Cavity ring fiber chemical sensors

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CAVITY RING FIBER CHEMICAL SENSORS

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School of Chemical and Biomedical Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Doctor of Philosophy

2008

To my family

Statement of Originality

I hereby certify that the work embodied in this Thesis is the result of original research done by me and has not been submitted for a higher degree to any other University or Institute.

12-Dec-2008
Date

NINA

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Summary

In recent years, optical fiber chemical sensors are paid increasing attentions due to their electrical passivity, remote sensing potentials and miniaturization feasibility, relying on the specific properties of the optical fibers. Highly sensitive spectroscopic techniques are highly demanded for enhancing the sensitivities of the optical fiber chemical sensors. This thesis mainly reports optical fiber cavity ring-down (CRD) and cavity ring-up (CRU) based-sensors for chemical sensing and other applications.

The thesis begins with a comprehensive survey on the existing types and spectroscopic techniques for optical fiber chemical sensors. Following that, direct absorption spectroscopy, which is the most commonly used spectroscopic technique, is studied. The direct absorption spectroscopy-based optical fiber chemical sensors are analyzed based on a practical setup. Aiming at reducing the effects of the main noises in this kind of sensor, a digital finite impulse response (FIR) filter is designed to improve this chemical sensor's sensitivity. The simulation and experimental results have shown that the detection accuracy is enhanced by this digital signal processing (DSP) technique.

The success of introducing DSP technique into the sensing system motivates us to solve the challenge of identification of the unknown chemical mixture detected by an optical fiber chemical sensor using pattern recognition technique. An automatic chemical mixture recognition system by using support vector regression (SVR) technique is proposed. Using the recognition model, the chemical components and the corresponding concentrations could be identified automatically and a high measurement accuracy in terms of concentration is achieved.

Successively, CRD spectroscopy in fiber optics is studied. Passive CRD spectroscopy for optical fiber sensors, which is without the gain compensation, and active CRD spectroscopy with a gain provided are exploited respectively. The passive CRD spectroscopy applied for strain sensing is proposed. A long period grating (LPG) CRD strain sensor in a fiber loop is set up. The experimental results indicate that the LPG CRD sensor displays a good linear response over a wide strain region. Meanwhile, by using this sensing scheme, a good sensitivity and a small minimum detectable strain are obtained, which represents a new generation of fiber sensors for strain measurement.

After that, the active CRD fiber loop is investigated comprehensively for trace gas detection. The mathematical model of the CRD fiber loop is initially developed, and an experimental setup of the CRD fiber loop is built. A digital least mean square (LMS) adaptive filter is proposed to reduce the amplified spontaneous emission (ASE) noise. The simulation results show that by the well designed LMS adaptive filter, the detection error is greatly reduced.

Following the fully investigation of CRD spectroscopy, a novel concept of CRU spectroscopy is proposed for trace gas detection in a fiber chemical sensing system. A comprehensive theoretical model of CRU spectroscopy for trace gas detection has been presented. The effects of the amplifier, the input signal parameters and the intra-cavity loss to the features of CRU output signals are numerically simulated and discussed.

With the guidance of the simulation, CRU fiber chemical sensing system is built up. In this study, the characteristics of the CRU output power is investigated as a function of the EDFA pump current, input signal and the total intracavity loss. The

experimental results demonstrate the superiority of the CRU scheme and shows a promising potential for CRU fiber loop in the application of chemical sensing systems.

In our final part of work, CRD and CRU spectroscopic techniques are applied for bio-sensing area. LPG CRD/CRU refractive index sensors in the fiber loop are set up. The ring-down/up times and the LPG transmission loss with the changes of refractive index of the measurement material are investigated. By detecting the various decays of the attenuation losses at different ambient refractive indices, the sensitivities of the sensors are evaluated. The experimental results indicate good linear responses for the LPG CRD/CRU sensors. And by the analysis, the minimum detectable refractive index from the CRU is smaller than the CRD scheme, which presents a potential for the CRU fiber loop to the high-sensitive and highly demanded bio-sensing applications.

Acronyms

ANN	artificial neural networks
ASE	amplified spontaneous emission
CRD	cavity ring-down
CRU	cavity ring-up
CW	continuous wave
DFB	distributed feedback
DFT	discrete Fourier transform
DSP	digital signal processing
EDF	erbium doped fiber
EDFA	erbium doped fiber amplifier
EDFL	erbium doped fiber laser
FBG	fiber Bragg grating
FIR	finite impulse response
FMCW	frequency modulated continuous-wave
FWHM	full-width-half-maximum
ICLAS	intracavity laser absorption spectroscopy
IIR	infinite impulse response
LMS	least mean square
LPG	long period-grating
MIR	mid infrared region
NIR	near infrared region
OPO	optical parametric oscillator
OSA	optical spectrum analyzer
PB	passband
PC	personal computer
PD	photodetector
PLS	partial least squares
RLS	recursive least squares
RMS	root mean square
SB	stopband
SDM	spatial-division multiplexing
SNR	signal-to-noise-ratio
SVM	support vector machine
SVR	support vector regression
TDM	time-division multiplexing
TLS	tunable laser source
OSA	optical spectrum analyzer

Symbols

A	absorbance
b	amplified coefficient
c	light velocity in vacuum
C	concentration
$\Delta C_{\min}$	minimum detectable concentration
$\Delta C'$	minimum detectable concentration before LMS filtering
$\Delta C''$	minimum detectable concentration after LMS filtering
d_p	penetration depth
E	electric field
$\tilde{E}$	variable electric field
$\tilde{E}_n$	electric field of the noise
E_0	initial electric field
E_{in}	electric field of input pulse
ΔE_p	photon energy
f	frequency of light
$f(\mathbf{x}, \mathbf{w})$	predicted function of SVR
f_F	frequency distribution of ASE noise
F	Fourier transform function
$\overline{g_n}$	length-averaged gain coefficient
G	EDFA gain
G^s	EDFA stationary gain
h	Planck's constant
h_b	bound coefficient of SVR
$h(k)$	impulse response coefficient of digital filter
$H(z)$	transfer function of digital filter
I	intensity of light
$\tilde{I}$	contaminated intensity of light
I_0	initial intensity of light
$I_{0,dB}$	initial intensity of light in decibels
$I_{ASE-ASE}$	intensity of ASE-ASE interference
I_F	fluorescence intensity of light
I_{in}	input intensity
I_{out}	output intensity
I_{out}^s	output stationary intensity
I_R	reflected intensity of light
I_s	intensity of signal
I_{s-ASE}	intensity of signal-ASE interference

I_T	transmitted intensity of light
$I_{T,dB}$	transmitted intensity of light in decibels
l	effective path-length of the gas cell
L	length of the fiber cavity
L_{eff}	effective length of cavity
L_{EDF}	EDF length
$L_\varepsilon(\mathbf{x}, \mathbf{y}, f)$	ε -insensitive loss function
n	refractive index
n_1	refractive index of dense media
n_2	refractive index of rare media
n_{amb}	refractive index of ambient medium
n_{eff}	effective refractive indices of the fiber core mode
n_{clad}	effective refractive index of the fiber cladding mode
δn_{eff}	differential refractive index of the core and cladding
n_m^k	noise factor of LMS filter
n_{l1}	erbium ion populations of lower energy level 1
n_{u2}	erbium ion populations of upper level 2
n_{sp}	population inversion factor of EDFA
N	number of order of filter
$N_2(z, t)$	fraction of atoms in the excited state
$\overline{N_2}(t)$	length-averaged inversion level
P_p	output pump power
P_{p0}	initial pump power of the EDFA
P_s	peak amplitudes of output signal
P_{s0}	initial peak amplitude of input pulse
$P_n^+(z, t)$	forward power for the n -th input signal
$P_n^-(z, t)$	backward power for the n -th input signal
$P_i^+(0, t)$	input forward power
$P_i^+(L_{EDF}, t)$	output forward power
$P_i^-(0, t)$	output backward power
$P_i^-(L_{EDF}, t)$	input backward power
$P_{ASE}^+(L_{EDF}, t)$	ASE power
R	transmission factor
R'	coupling loss of the output coupler
R_M	reflectivity of the mirror
s_m^k	desired signals of LMS filter
S	cross-sectional area of the active fiber core

S_m	absorption strength
Sn	serial number of sample n
t	time
t_{th}	threshold time
t_M	maximum time
t_0	initial time
T	trip time
T_0	pulse width
T_p	pulse period
u_n	unit vector
w_m^k	LMS filter coefficient/weight
$\mathbf{w}$	weight parameter in SVR recognition system
$x(t)$	analog input signal
$x(n)$	digital input signal
x_m^k	input noise components of LMS filter
$\mathbf{x}$	independent variable in SVR recognition system
$\mathbf{X}$	database of in SVR recognition system
$y(n)$	digital output signal
y_m^k	contaminated input signal sequence in LMS filter
$\mathbf{y}$	dependent variable in SVR recognition system
ν	frequency or wavenumber of light
ν_m	wavenumber at center of the absorption line
ν_s	frequency of the signal
$\Delta\nu_{ASE}$	band-width of ASE noise
$\Delta\nu_F$	band-width of FBG filter
ω	angular frequency
ω_s	angular frequency of the input signal
λ	wavelength of light
λ_s	signal wavelength
$\Delta\lambda_{FWHM}$	full-width-half-maximum (FWHM)
λ_{ab}	absorption wavelength
λ_{ex}	excitation wavelength
λ_{fl}	fluorescence wavelength
θ	angel of incidence
θ_c	critical angle
κ	molar absorption coefficient
κ_m	absorption coefficient at the center of the absorption line
γ	full-width-half-maximum (FWHM)
ξ	slack variable
E	root mean square (RMS) error

E_{con}	root mean square (RMS) error in term of concentration
τ	ring-down time /decay time
τ_U	ring-up time
$\bar{\tau}_U$	statistical mean ring-up time
τ'	decay time before LMS filtering
τ''	decay time after LMS filtering
τ_s	spontaneous life of excited state
$\Delta\tau$	standard deviation of ring-down/up time
$\Delta\tau_{min}$	minimum detectable ring-down/up time
$\delta\tau$	ring-down/up time fluctuation
$\sigma\tau$	statistical uncertainty of ring-down/up time
χ	loss per reflection
β	total loss
β_A	loss of variable-attenuator
β_R	residual losses
β_T	transmission loss of LPG
α	net loss
α_U	net gain
$\bar{\alpha}_U$	statistical mean net gain
Λ	period of LPG
ε	insensitivity of SVR
$\Delta\varepsilon$	micro-strain
$\Delta\varepsilon_{min}$	minimum detectable micro-strain
μ	stability of LMS filter
ρ	erbium ion concentration
γ_n	emission coefficients of EDF
α_n	absorption coefficients of EDF
Γ_n	overlap integral
σ_F	variance of intensity
$\sigma_{ASE-ASE}$	variance of ASE-ASE intensity
σ_{s-ASE}	variance of s-ASE intensity
σ_n^e	emission cross-section
σ_n^a	absorption cross-section
ζ	saturation parameter

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Chapter 1

Introduction

1.1 Motivation

With the development of the global industrialization, chemical sensing systems have become increasingly important for safety and environmental monitoring in an industrial setting. In the last decade, optical fiber chemical sensors in the near infrared region (NIR) have been broadly exploited for trace gas detection. Compared to other sensing counterparts, optical fiber chemical sensors are paid particular attention because of their attractive features depending on the specific properties of the optical fibers such as high sensitivity, low cost, light weight as well as immunity to electromagnetic interference. Furthermore, optical fiber chemical sensors, operating around 1550nm region, which is the optical communication window, may allow safe and remote location of the chemical sensors combined with the availability of optical fiber components, such as erbium doped fiber amplifiers (EDFAs), optical couplers, optical filters, etc..

However, the major disadvantage of optical fiber sensors to operate in NIR for trace gas detection is that the chemical molecular absorptions are typically two or three orders of magnitude weaker than those operating in the mid infrared region (MIR). Therefore, a variety of sensitive spectroscopic techniques such as intracavity absorption spectroscopy [1-6], wavelength modulation technique [7-10], frequency modulated continuous-wave (FMCW) technique [11-15] etc. were proposed for optical fiber chemical sensing. Among them, cavity ring-down (CRD) spectroscopic

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technique is caught extreme attention. This spectroscopic technique compares favorably with other spectroscopic techniques by its low susceptibility to laser noise and immunity from external loss contributions. CRD measures the decay time but not the intensity decay and thus the output signal is free from laser pulse-to-pulse variations. In a fiber CRD setup, a fiber loop replaces the high-reflectivity mirror resonant cavity in bulk optics. However, the sensitivity is not satisfactory comparing with the bulky counterparts due to the intrinsic noises in the fiber loop.

Although fiber CRD loop was first proposed for trace gas detection in 2001, little research work has been done on a systematical and comprehensive study of the fiber CRD loop accounting for the noise factors. This part of the work, however, is extremely important for improving the optical fiber chemical sensor's performance and making it competitive with its bulk optics counterparts. Therefore, we start from the theoretical exploration of CRD by means of mathematical modeling to analyze the problems occurred inside the fiber CRD scheme, and we realize this optical fiber sensing system experimentally to prove the theoretically analysis we obtained. Aiming to the main problems we find, appropriate approaches can be applied to improve the sensor's performance.

By this original study, it is found that the amplified spontaneous emission (ASE) noise induced by the erbium doped fiber amplifier (EDFA) is the principle noise resource to contaminate the CRD signals. To overcome the performance limitation of the optical devices, without modifying the experimental setup, digital signal processing (DSP) technique is proposed to retrieve the CRD signal from noisy results. The attraction of DSP technique comes from its key advantages such as no drift in performance with the ambient environment and great flexibility without the

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need to modify the hardware. Based on the characteristics of the specific noises and the CRD signals, the sort of filter algorithm is selected and the filter specifications are set. The DSP technique is also able to be employed to reduce the noise influences in other kinds of sensors such as direct absorption spectroscopy-based sensor, which will be shown in the thesis as well.

Furthermore, a modified CRD spectroscopic technique, named cavity ring-up (CRU) spectroscopic technique is proposed for chemical sensing application. Based on a rate equation approach, modeling of dynamic photon numbers and gain of an erbium doped fiber amplifier (EDFA) will be carried out to account for the time-evolving CRU signals in the fiber gas sensing loop. The effects of the EDFA pump power, the erbium doped fiber (EDF) length, the input signal parameters and the intra-cavity loss to the features of CRU output signals will be numerically studied. Experiments will be conducted and experimental results will be discussed and compared to the simulation results. Theoretical study and experimental investigation are implemented to verify its feasibility and superiority.

The superiority of the CRD and CRU fiber loop also motivates us to seek for other sensing applications, such as mechanical and bio-sensing, which will be shown in this thesis.

Finally, distinguishing the species of chemical mixture and their individual concentrations is always a big challenge for optical chemical sensors. This work is really hard to be realized by the experiment means. The success of introducing DSP technique into optical fiber sensing system motivates us to apply pattern recognition technique to identify the species. In our work, pattern recognition technique is

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proposed for recognizing the multi-gas components, with a good sensitivity achieved. All of the work is expected to fill the gaps of the research study.

1.2 Objective

The main objective of this thesis is to develop highly sensitive optical fiber chemical sensors. High sensitivities of the optical fiber chemical sensors could be achieved by highly sensitive spectroscopic techniques or appropriate signal processing techniques. Therefore, in this thesis, our work will focus on:

- To investigate the conventional spectroscopic techniques for trace gas detection. Direct absorption spectroscopic technique, which is the most commonly adopted spectroscopic technique in the optical fiber chemical sensors, will be studied. The main problems of that spectroscopic technique will be analyzed based on the practical setup.
- To apply a high sensitive spectroscopic technique for trace gas detection. Cavity ring-down (CRD) technique, which is a cavity-enhanced spectroscopic approach based on the direct absorption spectroscopic technique, will be exploited comprehensively. A mathematical model will be built up, including the noise factors that affect the sensor's sensitivity. Experiment of the CRD fiber loop for trace gas detection will be conducted.
- To propose a new cavity-enhanced spectroscopic approach. Cavity ring-up (CRU) spectroscopic technique will be proposed. Its characteristic will be addressed according to the theoretical analysis and experimental realization and its superiority will be demonstrated.

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- To employ the CRD and CRU fiber loop for other applications. Long period-grating (LPG) will be inserted into the CRD and CRU fiber loops for mechanical and bio-sensing applications.
- To adopt the appropriate signal processing technique to further enhance the measurement accuracy. Finite impulse response (FIR) filter and least mean square (LMS) adaptive filter will be designed to reduce the noises in the direct absorption sensor and CRD fiber loop respectively. Meanwhile, a gas mixture recognition system will be realized by using pattern recognition technique.

1.3 Major Contributions of the Thesis

This thesis makes the following contributions to the body of knowledge on the optical fiber sensors:

- Design a digital FIR filter to improve the detection accuracy of the optical fiber chemical sensors by direct absorption spectroscopy. The performance of the filter is discussed according to the characteristic of the chemical molecular absorption spectrum, the main noises types in the sensing system and the signal to noise ratios etc.. The analysis will guide the filter parameter selections for this type of chemical sensors.
- Propose an automatic gas mixture recognition system by using support vector regression (SVR) technique. By this SVR recognition model, up to 3 components of the gas mixture and the corresponding concentration could be identified automatically and a high measurement accuracy in term of concentration arrives.
- Set up an LPG CRD strain sensor based on passive CRD spectroscopy. The decay time, the sensitivity and minimum detectable strain of this sensing built-up

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are investigated. The experimental results indicate that the LPG CRD sensor displays a good linear response and shows a new type of sensor with a high sensitivity for strain measurement. This success may bring fiber CRD spectroscopic technique to broader sensing applications.

- Develop the mathematical model of the active CRD fiber loop initially. From this model, it is found that the amplified spontaneous emission (ASE) noise, induced by an erbium doped fiber amplifier (EDFA), is always a key problem for the measurement accuracy in a CRD fiber amplified loop chemical sensing system. By the analysis and simulations, it clearly demonstrates that the net loss, the output intensity, the decay time and thus the corresponding concentration will all be contaminated by the presence of this ASE noise.
- Design a digital least mean square (LMS) adaptive filter to reduce the ASE noise. This filter technique is applied to both simulation and experimental CRD signals. The simulation and experimental results before and after filtering at different net losses are compared and the minimum measurement concentrations of the filtered results are apparently decreased compared with the unfiltered results, which shows the feasibility of the designed filter for reducing the noise and retrieving the signal from the noisy environment.
- Propose a novel concept of cavity ring-up (CRU) spectroscopy for trace gas detection. A comprehensive theoretical model of CRU spectroscopy is exploited. The effects of the EDFA pump power, the EDF length, the input signal parameters and the intra-cavity loss to the features of CRU output signals are numerically simulated and discussed. The simulation results will have guidance for practical CRU setup.

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- Conduct a CRU fiber chemical sensing system. In this study, the characteristics of the CRU output power is investigated as a function of the EDFA pump current, input signal and the total intracavity loss. The experiments verify the simulation results that the EDFA, the input signal and the cavity parameter will all affect the CRU performance. The experiments also have indicated that minimization of the net gain is extremely important for achieving high measurement sensitivity in the fiber CRU scheme.
- Apply the proposed CRD and CRU spectroscopic techniques for bio-sensing area. LPG CRD/CRU refractive index sensor in the fiber loop is set up. The ring-down/up time and the LPG transmission loss with the changes of refractive index of the measurement material are investigated. By detecting the various decays of the attenuation loss at different ambient refractive indices, the sensitivity of this sensor is evaluated.

1.4 Thesis Organization

The thesis includes 8 chapters totally. The organization of the thesis is as follows:

- Chapter 2 is a literature review of optical fiber sensors. Principles of optical fiber sensors, especially the optical fiber sensors for chemical sensing are overviewed by categories. Highlights and drawbacks of optical fiber based sensors are discussed. The optical modulation techniques for optical fiber chemical sensors are reviewed chronically and the representative detecting schemes are presented.
- In Chapter 3, the direct absorption spectroscopy based fiber chemical sensor is studied. The basic principles of direct absorption spectroscopy are described followed by a list of noise factors which will influence the accuracy of the direct

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absorption spectroscopy system. The principle of digital signal processing technique is introduced. The work of accuracy enhancement by digital signal processing technique and multiple gas identification by pattern recognition are contributed respectively in the later parts of the chapter.

- In Chapter 4, the passive fiber cavity ring-down (CRD) spectroscopy is investigated. The principle of the CRD spectroscopy in bulk optics is described, and factors affecting the bulk CRD's sensitivity are indicated. The passive fiber CRD spectroscopy is presented and the application for the passive CRD spectroscopy into the optical fiber sensor is proposed and addressed.
- In Chapter 5, the active fiber cavity ring-down (CRD) spectroscopy is presented. The mathematical model of the active CRD fiber loop is derived. A digital least mean square (LMS) adaptive filter is employed to reduce the detection error aiming at the properties of the noises. Simulation and experiment are demonstrated respectively.
- In Chapter 6, a novel cavity ring-up (CRU) fiber chemical sensing system is proposed based on the CRD fiber loop. The CRU principle is described and the CRU model is presented. The CRU experiment is conducted and the experimental results are presented.
- The applications of active CRD and CRU fiber loop for bio-sensing are presented in Chapter 7. The long period grating (LPG) refractive index sensors based on CRD and CRU spectroscopy are proposed. The performances of the LPG sensors are discussed.

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- In the last chapter, the main achievement of the thesis is summarized and a conclusion is given. Future work is recommended for further improvement in the fiber chemical sensors and other sensing areas.

Chapter 2

Literature Review

2.1 Overview of Optical Fiber Sensors

The first low-loss optical fiber for sensor purpose was exploited in the early 1970s [16]. After this pioneering work, a range of optical-fiber based techniques which can be used for a variety of different sensor purposes have been produced and a number of relevant research papers were published [17]. The resulting optical fiber sensors have a series of attractive features depending on the specific properties of the optical fiber, which may be summarized as [18, 19]:

- Optical fiber based sensors can be used in difficult or hazardous locations due to the immunity to electromagnetic interference, safety against ignition and inflammables, and high corrosion resistance of cable;
- The low attenuation of optical fiber enables distributed and remote sensing, this property is beneficial for sensor multiplexing in a fiber sensing network;
- Optical fiber sensors can employ the high-quality components (fibers, sources, detectors, connectors, etc.) which are developed for the more mature optical fiber telecommunication technology;
- Lightweight and geometric flexible, optical fiber sensors are feasible of miniaturization.

Due to those merits, a wide variety of optical fiber sensors has been developed. Thanks to the complexity of the sensor systems which exist today, different approaches have been used in classification of optical fiber sensors. It could

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range from the essentially straightforward quantities, such as those based on the functions [20-32], or fiber types [22, 33-39]; or through the use of more precise subdivisions which focus on the modulation techniques [7, 8, 40-43], or even the sources [1, 23, 44, 45] employed (see Table 2.1). Due to the rapid development of the equipments and the optical measurement techniques, those kinds of classification methods may not be comprehensive and representative.

Table 2.1: Categories and examples of the optical fiber sensor types.

Categories	Examples of the optical fiber sensor types
Functions	Pressure, strain, temperature, displacement, refractive index, chemical, bio-sensing, biomedical...
Fibers	Single mode fiber, multi-mode fiber, fiber gratings, D-shaped fiber, photonic crystal fiber...
Modulation techniques	Wavelength/frequency modulation, intensity modulation, polarization modulation, ...
Light sources	Broadband light source, semiconductor laser source, laser diode, fiber laser source...

The most widely used classification nowadays, is to divide optical fiber sensors simply into extrinsic and intrinsic devices [43, 46]. Extrinsic fiber sensors are those in which the function of the optical fiber is merely to transmit the light to and from the sensing location. The optical fiber plays no role in the sensing mechanism. In contrast, the optical fiber plays an active role in intrinsic sensors, where the transmitted light is modulated by induced sensing interactions in the fiber core or, more usually in the fiber cladding. Tree schematic representations of the extrinsic and intrinsic optical fiber sensors are shown in Figure 2.1. For different applications,

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different types of fibers could be employed. In the next section, specifically, the extrinsic and intrinsic optical fiber sensors for chemical application are introduced.

Figure 2.1(a): Sorts of extrinsic optical fiber sensors and (b): sorts of intrinsic optical fiber sensors.

2.2 Principles of Optical Fiber Chemical Sensors

2.2.1 Classification of Optical Fiber Chemical Sensors

Sensors are devices that respond to a physical stimulus (such as heat and light) or their environment and transmit a resulting signal. Chemical sensors, which are to sense the chemicals, have broad and high-demanding applications for safety and environmental monitoring in an industrial setting. These sensors, not only are required to be sensitive to the detected chemicals, but also should be safe, inexpensive, reliable and durable. During the past 40 years, many solid-state sensor devices for detecting chemical components have been proposed based on various

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principles and materials. Several of them have grown to support our civil life in various respects. For example, semiconductor gas sensors using metal oxides such as SnO_2 and ZnO_2 , are applied to detect inflammable gases in air such as CH_4 and H_2 . In this kind of sensors, due to the absorption of gases on the solid surface reaction, the electrical conductivity changes are induced in semiconducting materials. Those sensors are currently used in a massive scale for gas leakage alarms in domestic houses. Oxygen sensors using stabilized zirconia have become indispensable for car emission control. Humidity sensors using ceramics or organic polymer electrolytes are very useful for air conditioning. These examples verify the high potentiality of chemical sensors in the modern technologies related to safety, process control and pollution surveillance. Yet these achievements satisfy only a part of the ever-expanding demands for chemical sensors.

In recent years, the number of chemical species to be covered with chemical sensors has increased dramatically. Toxic or bad-smelling gases such as H_2S and NH_3 frequently encountered in living circumstances, as well as explosive and hazardous gases such as HCN used for industrial processes have long been the targets of chemical sensors. The recent global issues of energy and environment are increasing the necessity of those sensors which can detect air-pollutants in environments such as NO_x , SO_x and CO_x or can be applied for detecting the combustion exhausts from stationary facilities and automobiles. Various chemical sensors should be developed for such new target chemicals. In addition, different sensors may be needed even for the same chemicals depending on the conditions of sensor operation. Based on these aforementioned reasons, a number of optical fiber sensing devices with different principles have been proposed. Optical fiber sensor is the sensor in which the light of

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the optical source is coupled to a transmitting fiber to undergo transduction or modulation in the sensor process. For an optical fiber chemical sensor, the process is to senses chemical properties, such species, pressure, concentration or pH etc..

Figure 2.2(a): Direct spectroscopic sensors and (b): reagent-mediated sensors.

Optical fiber chemical sensor could be classified conventionally into two categories, as shown in Figure 2.2:

- Direct spectroscopic sensors. Here the fiber acts as a simple light-guide which separates the sensing location from the monitoring instrumentation (source, detector, etc.). The fiber facilitates direct spectral analysis (e.g. absorption, reflection, fluorescence) of a sample at a distance.
- Reagent-mediated sensors (optrode). Here the optical fiber is combined with specific chemistry knowledge. For example, at the far end of the fiber, specific reagents are contained in a miniature reservoir attached to the fiber tip and are separated from the sample by means of an appropriate membrane. Alternatively, and more usually, as shown in Figure 2.2(b), suitable reagents may be

immobilized directly in a support matrix on the fiber tip or along the core of a de-clad optical fiber. A reagent is chosen to react sensitively and specifically to the analyte, and the resultant change in its optical properties is a direct measure of the analyte concentration. The term optrode is often used to describe reagent-mediated sensors and is derived from a combination of the term “optical-electrode”.

For optical fiber chemical sensors, such categories are more descriptive than the terms extrinsic and intrinsic which are used for general optical fiber sensors as described in the last section. The reagent-mediated sensors (optrode) could broaden the application to those analytes of interest which do not possess intrinsic spectral properties that facilitate the direct spectroscopic sensing approach. Although quite sensitive to the analyte, optrodes require specific reagents and thus more chemical relevant.

2.2.2 Principles of Optical Fiber Chemical Sensors

Figure 2.3: Principles used in optical fiber chemical sensors.

Most optical chemical sensors are based on a spectroscopic technique such as measurement of absorbance or fluorescence, whereby the detected signal is used to deduce the concentration of the target analyte. It is important, therefore, to consider the basic principles of the various spectroscopies used. The main spectroscopies used in optical fiber chemical sensors are illustrated schematically in Figure 2.3, which

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shows an incident beam with initial intensity of I_0 yielding transmitted (I_T), reflected (I_R) and/or fluorescence (I_F) signals, after interaction either directly with the analyte or with an immobilized indicator system. The principles of the interactions are described as below.

(1) Absorption

Figure 2.4: Schematic diagram of vibration-rotational transition of a chemical molecule.

As shown in Figure 2.4, a light with photon energy of $h\nu$ passes a chemical sample, if the photon energy of the light is equal to the energy difference of the chemical molecular vibration-rotational transition levels,

$$\Delta E_p = h\nu = h \frac{c}{\lambda_{ab}} \quad (2.1)$$

where h is the Planck's constant and c is the light velocity in vacuum, the energy will be absorbed by the chemical molecules and the chemical molecules will transit from the lower energy level to the higher energy level. The photon energy is related with the photon frequency ν or wavelength λ . Typically, the vibration-rotational energy levels associated with a molecule have a degree of superimposed fine structure, and thus the light at some specific wavelengths is absorbed (those wavelengths are called absorption wavelengths λ_{ab}) [47]. The absorbances at different

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wavelengths will be varied [48, 49]. Therefore, a molecular absorption spectrum, which consists of a series of closely spaced absorption lines, will be observed. Since the energy levels associated with a molecule are unique, the absorption serves as a “fingerprint” to identify a kind of chemical molecules. The transitions in vibration-rotational states of molecules occur at energies corresponding to the exact infrared band of the spectrum. Most chemicals have fundamental molecular vibration giving rise to strong absorption lines in mid-infrared region (MIR) around wavelengths of 3~10 μm , absorption can occur at frequencies that are harmonics or a combination of harmonics of the fundamental in the near-infrared region (NIR, around 1~2 μm), within the transmission window of optical fibers. According to Lambert Beer’s law [18], the absorbance of the light will be related to the concentration of the chemical sample, so by the molecular absorption spectrum, the chemical species and the corresponding concentration will be distinguished.

(2) Fluorescence

Although absorption is the dominant spectroscopic interaction on which optical chemical sensors are based, some other spectroscopies, such as fluorescence and evanescence are also reliable methods in particular applications. In fluorescence spectroscopy, the concentration of certain chemical may be measured through the fluorescence emitted from the chemical itself or from an intermediate fluorescent dye. Fluorescence occurs when a species in an excited state releases its energy through light emission which is called Stokes’ transition (Figure 2.5). Excitation is by absorption of photons from incident radiation at a wavelength λ_{ex} and the emitted fluorescence is at a longer wavelength λ_{fl} , where $(\lambda_{\text{ex}} - \lambda_{\text{fl}})$ is the Stokes’ shift.

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Figure 2.5: Stokes' transition.

Compared with direct absorption chemical sensors, fluorescence chemical sensors employ the fluorescence wavelength but not the excitation wavelength, which means the output signal can be measured against a zero background light level. Intrinsically, therefore, the fluorescence approach may yield a higher signal-to-noise ratio than absorption. But the intermediate fluorescent dyes are commonly required, and since the sensor is not self-calibrating, fluorescence sometimes requires other complex non-self-calibration procedure.

(3) Evanescence

Figure 2.6: Evanescent field.

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In evanescent wave sensors, the optical fiber itself is intimately involved in the sensing process. The evanescent field as shown in Figure 2.6 interacts either directly with the chemicals (monitoring absorption or index change) or with an intermediate dye, involving absorption or fluorescence as described before. The optical fibers themselves act as a sensing material. Control over the degree of penetration of the evanescent wave into the low-index medium is important in the evanescence wave sensors. This quantity is often characterized by the penetration depth, d_p , which is the perpendicular distant from the interface at which the electric field amplitude, E , has fallen to $1/e$ of its value, E_0 at the interface, that is [18]

$$E = E_0 \exp(-z/d_p) \quad (2.2)$$

The magnitude of the penetration depth is given by

$$d_p = \frac{\lambda_{ex}}{2\pi n_1 \left[\sin^2 \theta - (n_2/n_1)^2 \right]^{1/2}} \quad (2.3)$$

where λ_{ex} is the vacuum wavelength, θ is the angel of incidence to the normal at the interface, and n_1 , n_2 are the refractive index values of the dense and rare media, respectively. Although d_p is typically less than λ_{ex} by Equation (2.3), its value rises sharply as the angle of incidence approaches the critical angle $\theta_c = \sin^{-1}(n_2/n_1)$. This equation highlights the importance of the interface angle θ in the design of evanescent wave sensors.

Although the evanescent field is relatively weak as compared with direct absorption method, the effective path-length of the fiber can be quite long, and thus the sensitivity of the chemical sensing system will be guaranteed. However, both of fluorescence and evanescence methods may involve other chemical dyes, and have a

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special demand for the configuration of the optical fiber itself. Comparing with them, the experimental scheme by using direct absorption spectroscopic technique is quite simple and the light from the light source just interacts with the chemical itself. Furthermore, the optical fiber performs a purely passive role in transferring light to an chemical sample, but plays no part in sensing, and hence common low-cost sort of silica fiber can be used conveniently. In the following parts, the direct absorption spectroscopy-based optical fiber chemical sensors are focused.

2.2.3 Analysis of Optical Fiber Chemical Sensors

Advantages and specific characteristics are expected for optical fiber sensors compared with sensors treating electrical or electrochemical information, however, the drawbacks of them also cannot be neglected [19]:

- Parasitic optical signals can occur due to light scattering in the medium and stray ambient light. And also, the optical signal may be affected by contamination, fouling of the optical fibers, which can lead to a long-term instability of the chemical sensing system.
- Limited dynamic range. Due to Lambert-Beer's law, the linear relationship between the optical signal and the concentration of the detected chemical only has a limited dynamic range which we discuss in the next chapter, in contrast to the linear behavior of electrodes.
- Because most of optical components are designed for communication systems, how to modify them for chemical sensing is also a key problem to improve the whole sensors system performance.

Based on all of these reasons above, most of the optical fiber chemical sensors are still in the research level. Besides these, the major disadvantage of optical fiber

sensors to operate in NIR for the chemical detection is that the chemical molecular absorptions are typically two or three orders of magnitude weaker than those operating in MIR. Therefore, some high-sensitivity optical modulation techniques are proposed to improve the sensitivity of the optical fiber chemical sensors. Some representative techniques are reviewed in the upcoming section.

2.3 Optical Modulation Techniques of Optical Fiber Chemical Sensors

2.3.1 Intracavity Laser Absorption Spectroscopy

Intracavity laser absorption spectroscopy (ICLAS) first arose for trace gas detection in the early 1970. Seemingly to other optical modulation techniques, ICLAS was initially developed in bulk sensing system. The schematic of intracavity absorption measurement is as shown in Figure 2.7.

Figure 2.7: Schematics of measurement of intracavity absorption.

In this spectroscopic technique, the chemical absorber, as shown in Figure 2.7, is directly placed inside the laser cavity as well as the gain medium. The optical effective path L_{eff} is lengthened and short optical path confined by the practical dimension of the laser cavity is converted into a multi-pass system [50]. The sensitivity is significantly enhanced by Lambert-Beer's law. The main requirement of this ICLAS is that the homogeneous bandwidth of the laser gain medium is broader

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than the linewidth of the absorption material [51]. Many lasers that satisfy this requirement, such as Nd^{3+} lasers [51], dye lasers [52], color-center lasers [53], Ti:sapphire lasers [54, 55], diode lasers [45] and vertical-external-cavity surface-emitting semiconductor lasers [56] were successfully used for ICLAS measurements.

Figure 2.8: Experimental setup of intracavity absorption spectroscopy with a Nd^{3+} -doped fiber laser.

Since those lasers were bulky and costly, the alternative candidate fiber lasers were proposed to replace them. Fiber lasers operate continuously on numerous ionic transitions of various rare earth dopants, such as Nd, Yb, Pr, Tm, Er, Ho, in the range of 0.45 through $3.9\mu\text{m}$ [51]. The high concentration of the pump and laser light in a small channel (usually $2\text{-}5\mu\text{m}$ wide) allows efficient transfer of the pump power to the active ions and ensures high gain to be obtained. As a result, fiber lasers operate upon diode-laser pumping with their typical pump threshold below 1mW . The combination of laser and pump laser can be manufactured as a compact unit that consumes low power in accordance with the requirements of field measurements of intracavity absorption. Important advantages of fiber lasers over diode lasers are their low loss and the inhomogeneous broadening of their gain which allows for measurements of intracavity absorption over a broad spectral range with no spectral tuning. In 1993, a

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broadband Nd^{3+} -doped fiber laser has been reported in an external cavity by pumping with an Ar^+ -ion laser as shown in Figure 2.8. The sensitivity of intracavity absorption measured by this fiber laser has been found to yield $L_{\text{eff}}=130\text{km}$ [1].

Figure 2.9: Multi-point fiber system for methane gas detection by using wavelength modulation technique.

From 1997 to 1998, several optical fiber chemical sensors based on wavelength modulation technique were conducted [7, 8, 10]. In those schemes, distributed feedback (DFB) laser, with the advantage of high coherence was applied as the light source. The performances of the chemical sensors were improved than the previous use of the low-coherence counterparts [44, 57-60]. One of the experimental setups is as illustrated in Figure 2.9.

The wavelength of the DFB laser was modulated sinusoidally through the modulation of the injection current, while its average wavelength was stabilized at the

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center of the gas absorption line with a separated reference cell with 100% methane gas and feedback control electronics. The modulated light signal from the laser passed through a gas cell that contained a gas sample to be measured and was subsequently converted to an electric current through a photodiode. A lock-in amplifier was used to detect both the first- and second-harmonic signals. With scanning and digital signal processing technique, a good sensitivity was achieved. Another highlight of this experimental scheme is that it combined with multiplexing technique, some common expensive optical instruments such as laser source were shared within the network and the cost per sensing point was reduced. However, the multi-reflections occurring within the cells and from fiber joints/connectors gave rise to interference signals [7]. This undesirable interference produced harmonics in the output indistinguishable from the gas signal (etalon fringes) and set a limitation on this type of sensor's performance.

In 1998, a highly multiplexed (up to 128 points) realization of a optical fiber methane gas detection system designed for safety monitoring applications and detection up to the lower explosive limit (5% by volume) was reported [9]. This work expanded the laboratory experiment to field trials, and demonstrated the compatibility of the system performance, both technical and economic, with potential applications.

Excluding those spatial-division multiplexing (SDM) [9, 10], time-division multiplexing (TDM) [61] and frequency modulated continuous-wave (FMCW) technique [11-15] were also applied for multiplexing optical fiber chemical sensors. These multiplexing implements reduced the cost-per-sensing-point although some problems required to be solved e.g. the crosstalk in TDM which would affect the system performance.

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Figure 2.10(a): CW EDFL gas sensor with a linear cavity and (b): with a ring-cavity.

In 1999, a preliminary investigation of erbium doped fiber laser (EDFL) with bulky optic components for intracavity absorption of acetylene was addressed [62, 63]. The broad gain spectrum of the erbium doped fiber (EDF), from 1480-1620nm, covered the overtone absorption lines of a number of chemical gases e.g. C₂H₂, HCN, H₂S, CO, CO₂. This kind of laser permitted multi-gas detection with the same intracavity sensor, furthering cost reduction of the cost per type of gas. Continuous wave (CW)-operation EDFL, with linear cavity [6] and ring-cavity [4, 5]

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configuration, as shown in Figure 2.10(a) and Figure 2.10(b) respectively, were extensively studied. However, due to the long cavity length and the consequent close mode spacing of the cavity, the stable single-mode operation was difficult to achieve, especially if continuous tuning was required.

Figure 2.11: Intra-cavity multi-pass optical fiber sensing network using a mode-locked fiber ring laser.

In 2002, the alternative mode-locked EDFL for application to gas spectroscopy was proposed [3, 50, 64]. An intra-cavity multi-pass optical fiber gas sensor network has been demonstrated as shown in Figure 2.11. As a representative and recent example, this work is described in more detail. Several gas sensors made from micro-optic gas cells were connected in a ladder topology and further connected to a common optical path consisting of an EDFA, a tunable optical filter and an intensity modulator. The system could be regarded as several fiber ring laser cavities with different cavity lengths, which had different gas cells but shared the common gain medium and other devices. The intensity modulator with the cavity acted as a switch and could be controlled by a signal with variable repetition rate. The switch

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was closed only for very short duration so that continuous-wave (CW) oscillation was inhibited.

When the repetition rate was matched to the characteristic frequency of a cavity, say cavity i that contains sensor i , i.e.,

$$f = N_i f_i = N_i \frac{c}{L_i} \quad (2.4)$$

where L_i is the optical length of the i -th cavity that includes the optical length of the fiber and the gas cell, and N_i is an arbitrary integer, a pulse would circulate in the cavity, traversing the modulator with low loss on each pass because at that instant the switch was closed. The result was the generation of mode-locked pulses oscillating at a multiple of the characteristic frequency of i -th loop f_i . The dependence of mode-locking frequency on cavity length could be used to address different gas sensors. As gas cells were placed within cavities of different lengths, a cavity could only oscillate and provide lasing output when the repetition rate of the modulation signal was matched to that of the cavity. Therefore, interrogating the different cavities by various repetition rates, mode-locked pulses from each cavity in turn could be obtained.

The highlights of this kind of system were:

- Mode-locked operation was chosen in preference to CW operation for application to gas spectroscopy because not only, with CW operation in a long fiber loop, mode hopping readily occurred and complex feedback control loops were required for stabilization; but also although the line-width was much narrower with a single-mode stabilized CW laser, there was no need for ultra-narrow line-widths when making measurements of pressure-broadened gas absorption lines,

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which had a typical line-width of about 5GHz and mode-locked line-width normally with 1THz can be sufficient.

- The use of intra-cavity spectroscopy where a gas cell was directly placed within the cavity of a mode-locked fiber laser made the sensing system more stable than normal extra-cavity counterparts, and the absorption of the gas cell would not be affected by the reflection noises from the detector, so the accuracy of the gas sensing system were improved.
- The minimum detectable gas (acetylene) concentration of 781ppm [3] was achieved.

However, in the practical experiment, only two fiber cavities were built up [3, 50, 64]. The reason was that each gas cell was parallel connected to the oscillation cavity by a 50:50 coupler. However, each coupler had a 3dB insertion loss, which means that to the i -th gas cell, the input power from the fiber laser through it only could achieve $(1/2)^{i-1}$ times of that through the first gas cell, i.e. the input power to the fifth gas cell just had 1/16 times of that to the first gas cell, which was too small to detect and the signal-to-noise ratio would decrease dramatically. And also the cavity length for each cavity has to be carefully selected or else the crosstalk would occur and affect the accuracy of the sensing system greatly.

In 2004, wavelength modulation/second harmonic detection technique was applied to the fiber laser sensing system, and the experimental setup is shown in Figure 2.12 [65]. The filter was wavelength-modulated by a sinusoidal signal at frequency f , and at the same time, scanned slowly across a gas absorption line by a saw-tooth scanning signal. The presence of the gas absorption converted the wavelength modulation into an intensity modulation, which in general included the

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components of the fundamental harmonic and the second harmonic frequency. When the central wavelength was aligned to the peak of the absorption line, the second harmonic component of the modulation signal was maximized. The signal from the photodetector (PD) was lock-in detected to give an output voltage signal that was proportional to the amplitude of the second-harmonic. The second harmonic (lock-in output) was proportional to the gas concentration being measured and could therefore be used as a measure of gas concentration. This mechanism improved the stability of the input light to the gas cell and hence enhanced the detection accuracy of the system. The minimum detectable gas (acetylene) concentration of 1000ppm was reached. However, the etalon effects in optical fiber cells imposed some limits, which would limit both the wavelength and intensity detection sensitivities.

Figure 2.12: Wavelength modulation technique for the fiber optical gas sensor

Except the above mentioned techniques, other techniques were applied into the optical chemical sensors too, such as time-wavelength spectroscopy or reference gas cell technique [8, 66]. But in all these practical sensing systems, the setups were

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complex and the measurement errors were always induced by the intensity fluctuation due to the instability of pump laser sources and optical noises (e.g. interferometric noise [7], thermal noise [57]) from other optical components, such as the EDFA, optical filter, photodetector, etc..

2.3.2 Cavity Ring-down Spectroscopic Technique and Its Applications

Cavity ring-down (CRD) spectroscopic technique, is a highly sensitive cavity-enhanced method based on direct absorption spectroscopic technique. Although history of CRD could retrieve from 1960s [67, 68], Herbelin *et al.* (1980) [69] and Anderson *et al.* [70] were regarded as pioneers to the CRD technique. In 1988, O'Keefe and Deacon introduced this technique to trace gas detection by measuring the absorption spectrum of the gas molecules [71, 72]. Unlike previous work, a pulsed dye laser replaced the CW laser for solving the problems associated with mode coincidences [73]. In their scheme, the chemical sample was placed inside a high-finesse optical cavity consisting of two highly reflective mirrors. A short laser pulse was coupled into the cavity, the light was reflected back and forth inside the cavity; at each round, a small fraction of the light leaked out of the cavity. Instead of detecting the intensity magnitude of the transmission light, a decay time depending on the rate of absorption was measured. The sample's concentration related with the rate of absorption then was determined from the decay time. There are several advantages to this approach. Since the absorption is determined from the time behavior of the signal, it is independent of pulse-to-pulse fluctuations of the laser, which means the sensitivity of the system is no longer affected by the laser intensity noise. Furthermore, the effective absorption path length, which depends on the reflectivity of the cavity mirrors, can be very long (up to several kilometers), while the sample volume can be

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kept rather small. Compared with other absorption techniques, especially those using modulation schemes, CRD spectroscopy is rather simple to construct out of a few components, with additional advantage that the absorption is measured on an absolute scale.

Due to the radiation limitations of the lasers, before 1995, most of the CRD work was done at visible wavelength. After that, the CRDs in the infrared and UV region were developed. The first paper on a high-resolution mid-infrared CRD realization was published in 1995 by Scherer using a Fourier-transform-limited optical parametric oscillator (OPO) [74].

Although nowadays most CRD experiments are performed with pulsed lasers, in parallel, several schemes have been developed during the last decade in order to perform CRD spectroscopy with CW lasers. Advantages of CW CRD spectroscopy are a better spectral resolution due to its narrow line widths and a better wavelength reproducibility. The first two CW-CRD experiments were traced back to 1996. Engeln *et al.* (1996) reported a phase-shift CRD spectroscopy, in which the absorption spectrum was extracted from a measurement of the magnitude of the phase shift that an intensity-modulated CW light beam experienced upon passage through an optical cavity [75, 76]. Later, Romanini *et al.* (1997) used the other approach; the resonant cavity mode was swept over the CW laser line; then, when sufficient light was coupled into the cavity, the laser was switched off; subsequently, the CRD transient was recorded [77].

The first application of CRD technique into fiber optics for trace gas detection was reported 7 year ago by Stewart *et al* [78, 79], and schematic diagram of the experimental fiber cavity ring down system is shown in Figure 2.13. A fiber loop

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replaced the optical cavity in the bulky CRD scheme. The fiber loop consisted of an open path, micro-optic gas cell formed with GRIN lenses and two standard 10:90 fiber couplers where the light was coupled into and out of the system while the majority of the light remained in the loop. The input laser was DFB laser; where the wavelength could be precisely tuned to match a gas absorption line, giving high spectral power density. The current input was modulated via a signal generator to produce pulses. Erbium doped fiber amplifier (EDFA) was employed to compensate the insertion losses from the optical devices such as couplers, band-pass filters etc., and also the absorption loss from the gas molecules. A tunable narrow band-pass filter in the loop was necessary to restrict gain position to around the input signal wavelength. Scanning the input laser, on and off- resonant signal, the loss at the absorption wavelength could be determined and therefore the gas concentration could be obtained.

Figure 2.13: Cavity ring-down scheme in a fiber loop.

Although successfully introducing the CRD into optical fiber chemical sensors, there were still several problems affecting the sensor's performance. First,

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comparing with the high-finesse optical cavities in bulky CRD, the fiber components' sensitivities were limited by the fabrications. Fiber cavity produced by direct deposit of a highly reflective dielectric coating on the polished fiber end [80, 81] or fiber Bragg gratings (FBGs) were reported [82] to improve the sensor's sensitivities, but the techniques were not as mature as that in bulk optics. Second, in this sensing scheme, EDFA was used in the fiber loop. Although the system effectively employed the benefits of the EDFA, an unwanted amplified spontaneous emission (ASE) noise from EDFA was induced and could greatly influence the sensitivity of the system. Wavelength modulation spectroscopy [79] and even the CW-CRD were considered [78] for fiber chemical sensing but definitely the complexity of the setups was increased.

From 2002 to 2004, fiber CRD expanded to various applications including temperature [83], pressure [84, 85], strain [86], bending [81], liquid phase detection [87, 88], refractive-index sensing [82], large-scale bending radius measurement [81] and single-cell detection [89]. Fiber Bragg gratings (FBGs), biconical tapers and specialized fibers were inserted into the CRD fiber loop as the sensing materials. Good responses and sensitivities, it demonstrated a new concept for optical fiber sensors and a technical feasibility of developing a new generation of fiber sensors for those measurements.

Chapter 3

Direct Absorption Spectroscopy for Chemical Sensing

3.1 Introduction

In this chapter, direct absorption spectroscopy based fiber chemical sensor is studied. Direct absorption spectroscopy is a conventional and simple spectroscopic technique to sense the chemical species by measuring the light absorption due to the vibrational and rotational transitions of the sensed chemical molecules. In an optical fiber based direct absorption spectroscopic system, the fiber acts as a passive light-guide which remote connects the sensing location where the chemicals place from the monitoring instrumentation (light source, detector, etc.). The regions of the molecular absorption spectra that are efficiently transmitted by the inexpensive standard optical fibers extend from 1450nm to 1650nm, typically known as the fiber transmission window.

Although direct absorption spectroscopy based fiber sensors have attractive features relying on the specific properties of the optical fibers such as electrical passivity, remote sensing potentials and low cost, the noises inside the sensing system due to the devices and environmental interference may influence the system measurement accuracy. The use of digital signal processing (DSP) technique to enhance the measurement accuracy of a hydrogen cyanide (HCN) gas sensor is presented in this chapter. Compared to its real optical counterparts, the attraction of DSP technique comes from key advantages such as no drift in performance with the ambient environment and great flexibility without the need to modify the hardware.

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The direct absorption spectroscopy is not only fit for the single chemical detection, but for the chemical mixture detection as well. However, how to recognize the species of those chemicals and distinguish their individual concentrations are big challenges. In our work, a support vector regression (SVR) pattern recognition algorithm is proposed to be used for recognizing and measuring the chemical compounds characterized by molecular absorption spectrometry.

The organization of the chapter is as follows. The principle of direct absorption spectroscopy is described in Section 3.2, followed by an analysis of direct absorption spectroscopy system which is in Section 3.3. In Section 3.4 and 3.5, accuracy enhancement by DSP technique and multiple chemical identification by pattern recognition are presented respectively. Finally, a conclusion is given in Section 3.6.

3.2 Principle of Direct Absorption Spectroscopy

Figure 3.1: Block diagram of direct absorption spectroscopy technique.

The block diagram of direct absorption spectroscopic technique is as shown in Figure 3.1. For direct absorption spectroscopic technique, the optical fibers only perform as transmitting medium but play no role in sensing system. When a continuous wave (CW) light with initial intensity I_0 passes through a chemical sample in a gas cell, the chemical molecules absorb photons at specific wavelength λ or wavenumber,

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$\nu = 1/\lambda$ and transit from lower to higher vibration-rotational levels. Thus, the output transmitted light intensity denoted as $I_T(\nu)$ decays at corresponding wavenumber and the molecular absorption spectrum could be detected from the spectrometer, followed the Beer-Lambert's law [18],

$$I_T(\nu) = I_0 \exp[-\kappa(\nu)lC] \quad (3.1)$$

where l is the effective path-length (cm) of the gas cell, C is the gas concentration (atm^{-1}) and $\kappa(\nu)$ is the molar absorption coefficient ($\text{atm}^{-1} \cdot \text{cm}^{-1}$), which is a constant at room temperature for a specific species of gas in each wavelength.

Intensities I_0 and $I_T(\nu)$ are commonly scaled in decibels, so the above equation is modified to

$$A(\nu) = 10 \log_{10} \left(\frac{I_T(\nu)}{I_0} \right) = I_{T, dB}(\nu) - I_{0, dB} = -\kappa(\nu)lC \cdot 10 \log_{10} e \quad (3.2)$$

where $A(\nu)$ is called absorbance. Typically, the absorption spectra of most chemicals in the near infrared (NIR) region (fiber transmission window) consist of a number of closely spaced absorption lines corresponding to quantized vibration-rotational energy levels. (Usually, these lines are the second harmonic of the fundamental absorption spectra in the mid-infrared region (MIR). The most important practical consequence of Equation (3.2) is that when $\kappa(\nu)$ and l are known, the calculated absorbance $A(\nu)$ is directly proportional to the concentration C , thereby yielding a linear calibration.

The molecular absorption spectra or absorption band of the chemical, which composes of a series of absorption lines due to the molecular vibration-rotational transitions, could be obtained by reading different absorbance at different frequency

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using direct absorption spectroscopy. At a low pressure, the line shape of each absorption line, which is subjected to homogeneous broadening in which all the chemicals interact in the same way with the frequency range, could be described as a Lorentzian profile (pressure-broadened line) as [8]

$$A(\nu) = \kappa(\nu)lC = \frac{\kappa_m lC}{\left\{ \left(\frac{\nu - \nu_m}{\gamma} \right)^2 + 1 \right\}} \quad (3.3)$$

where κ_m and ν_m are the absorption coefficient and wavenumber at the center of the absorption line respectively and γ (cm^{-1}) specifies the pressure broadened linewidth or called full width at half maximum (FWHM), with a definition as shown in Figure 3.2. κ_m is related with absorption strength S_m ($\text{atm}^{-1} \cdot \text{cm}^{-2}$), and

$$\kappa_m = S_m / \pi\gamma \quad (3.4)$$

Strictly speaking, ν_m is dependent on the pressure due to the pressure shift. However, the phenomenon could be neglected when it is compared with the minimum detection of the detecting instrument. Absorption coefficient κ_m could be considered as constant at room temperature [90].

Figure 3.2: Definition of FWHM of a Lorentzian lineshape.

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The performance of the chemical sensor is often evaluated by its accuracy or sensitivity. The measurement accuracy (or called detection error) of the direct absorption spectroscopy-based sensor, which is usually represented in terms of gas concentration which is called minimum detectable concentration, could be derived from Beer-Lambert law. By differentiating Equation (3.2), we obtain

$$\Delta A(\nu) = \Delta I_{dB}(\nu) = \Delta I_{T,dB}(\nu) - \Delta I_{0,dB} = -\kappa(\nu)l\Delta C \cdot 10 \log_{10} e \quad (3.5)$$

The measurement accuracy ΔC , therefore, is directly proportional to the change of the absorbance $\Delta A(\nu)$ or the change of the light intensity $\Delta I_{0,dB}(\nu)$. Notice here $\Delta I_{dB}(\nu)$ includes the change of the initial light intensity $\Delta I_{0,dB}$ and the change of transmitted light intensity $\Delta I_{T,dB}(\nu)$. The sensitivities, which is defined as $\Delta C / C$, then could obtained by dividing Equation (3.5) to equation (3.2), so

$$\frac{\Delta C}{C} = \frac{\Delta I(\nu)}{I} \bigg|_{dB} \quad (3.6)$$

As a result, the minimum detectable concentration could also be obtain by

$$\Delta C = \frac{\Delta I(\nu)}{I} \bigg|_{dB} \times C \quad (3.7)$$

The accuracy and the sensitivity of the direct absorption spectroscopic sensor, will be influenced by changes of the light intensity and other system and environmental factors. Those influences will be described at the following sections.

3.3 Analysis of Direct Absorption Spectroscopy System

(1) The noises from light source

(a) Intensity noise

In direct absorption spectroscopy, broadband light source and semiconductor tunable laser source are often adopted as the light source due to their broad light emission region. The fundamental intensity noises of both light sources are induced by the spontaneous emission fluctuations. This intensity fluctuation ΔI is caused by the relaxation oscillation, which results from the different times required to reach the equilibrium state between electron and photon populations (The time different, about three orders of magnitude, is because of the different injection carrier lifetime and the photon lifetime) [91]. By Equation (3.2), the sensor's measurement accuracy in term of concentration ΔC is directly proportional to the change of the intensity ΔI . Broadband light source, though less expensive than tunable laser source, has a lower signal to noise ratio $I/\Delta I$, thus the performance of the direct absorption spectroscopy based chemical sensors by using broadband light source will be more greatly affected by the intensity noise factor.

(b) Linewidth noise and frequency noise

The linewidth of the incident beam $\Delta\nu$ should be very narrow, ideally approximating monochromatic radiation. Deviations from perfect Beer-Lambert's behavior increase as the linewidth increase, but are particular severe when the linewidth is greater than the spectral width γ of the absorption band of the absorption species. Such additions result in a nonlinear calibration for the sensor which, although usable in some

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instances, will result in a sensitivity which falls with concentration, and a consequent reduction in the useful measurement range. For a semiconductor laser source, the linewidth noise and the frequency noise are mainly due to the gain fluctuation of the semiconductor gain material [92]. If the linewidth of the laser source is comparable with that of the gas absorption lines, the absorption must be larger than the ideal condition. However, with nowadays rapid development of semiconductor laser technology, the linewidth of the laser source could be neglected comparing with the absorption linewidth.

(c) Wavelength stability

Wavelength of the semiconductor is dependent on the temperature. In practical use, the semiconductor lasers are temperature-stabilized by using Pelti-electronic cooler. A stability of about $\pm 0.01^{\circ}\text{C}$ is usually achieved. The stability of the oscillation frequency is about $\pm 100\text{MHz}$. Typically, the frequency shift of the semiconductor laser is about $1\text{GHz}/\text{mA}$. The current noise affects the linewidth broadening of a laser that has an extremely narrow linewidth less than 1MHz [91]. That is one reason that tunable semiconductor laser is preferred in high-sensitivity sensing schemes.

(2) Deviation due to the material saturation

Deviations from perfect Beer-Lambert behavior are observed in highly absorbing or scattering media. Both of these effects yield a limited range of the absorbance-concentration linearity. Furthermore, high concentrations of the absorbing species can also result in measurement problems due to reactions or complication taking place. In such circumstances, the optical characteristics of the absorbing material will differ significantly from those observed at low concentrations.

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(3) Interferometric noise

Interferometric noise is a type of noise caused by interference between signal waves and reflected waves and might set a limit on the sensor performance. For transmission-type sensors, while the first-order reflection will be directly fed back into the source, it may be assumed that they have no effect on the system performance when a proper isolator is used at the laser output port. The second-order reflection along the fiber, first backward then forward; however, might affect the system performance. In the output of the system, in addition to a primary beam, many second-order waves due to second-order reflections may exist [7, 8]. Reflections can occur at fiber connectors, fiber-cell joints, cell surfaces, etc [57, 93]. Multireflections occurring within the cells and from fiber joints/connectors give rise to interference signals which produce harmonics in the output indistinguishable from the gas signal as shown in Figure 3.3. This effect, however, could be reduced by the use of lenses with high quality anti-reflection coatings.

Figure 3.3: Second-order reflection waves in a transmission-type sensor.

(4) Noise from receivers

At the receiver end, the output intensity is usually converted to voltage by a photodetector. However, a shot noise is induced by this electronic device. Shot noise

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consists of random fluctuations of the electric current in an electrical conductor, which are caused by the fact that the current is carried by discrete charges (electrons). This occurs not only in p-n junctions but also in any conductor, and even in the case where the charge is not well localized. Shot noise is to be distinguished from current fluctuations in equilibrium, which happen without any applied voltage and without any average current flowing. These equilibrium current fluctuations are known as Johnson-Nyquist noise, which is widely known as thermal noise [57]. Both noises could not be evaded once using the electronic devices.

3.4 Accuracy Enhancement by Digital Signal Processing Technique

The noises mentioned in Section 3.3, will definitely limit the wavelength and intensity detection accuracy in the direct absorption spectroscopic systems. Therefore, high-sensitivity modulation techniques were proposed to enhance the measurement accuracy of the chemical sensing system in recent years, e.g., through the use of multi-pass intra-cavity spectroscopy technique and wavelength modulation technique by mode-locked fiber laser, with the minimum detectable gas (acetylene) concentrations of 781ppm and 1000ppm respectively [3, 65]. Whereas, both of their setups were complex and the measurement errors were always induced by the intensity fluctuations due to the instability of the pump laser sources and optical noises from other components, such as the erbium doped fiber amplifier (EDFA), optical filter, photodetector (PD), etc.. In this section, the use of digital signal processing (DSP) technique to enhance the measurement accuracy of hydrogen cyanide (HCN) gas sensor is reported. The principle of DSP technique is described in

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Section 3.4.1, the simulation results is shown in Section 3.4.2 and experiment and discussions are presented in Section 3.4.2.

3.4.1 Principle of DSP Technique

Digital signal processing (DSP) is concerned with the digital representation of signals and the use of digital processors to analyze, extract, or modify information from signals. Most signals in nature are analog in form, often meaning that they are quite continuously with time, and represent the variations of physical quantities, such as the variations of output optical signal corresponding to the absorption properties of the chemical molecules. The signals used in most popular forms of DSP are derived from analog signals which have been sampled at regular intervals and converted into a digital form.

Figure 3.4: The simplified block diagram of digital signal processing technique.

The specific reason for processing a digital signal may be, for example, to remove noises from the signal. In this part of work, DSP is considered for disposing the detected signals from the chemical sensing experimental system, and the simplified block diagram is shown in Figure 3.4. First, the analog signal $x(t)$ from the experimental system is converted to digital signal $x(n)$ and then recorded in a personal computer. After analyzed and improved its quality by a digital processor, the

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desired signal $y(n)$ is obtained for further use. DSP is now used in many areas where analog methods were previously used and in also other entirely new application which were difficult or impossible with analog methods [94]. The attraction of DSP comes from key advantages such as follows.

- Guaranteed accuracy. Accuracy is not affected by the ambient noises like analog devices.
- Perfect reproducibility. Identical performance is obtained since there are no variations due to component tolerances. For example, using DSP technique, a digital recording can be copied or reproduced several times over without any degradation in the signal quality.
- No drift in performance with temperature or age.
- Great flexibility. DSP systems can be programmed and reprogrammed to perform a variety of functions, without modifying the hardware. This is perhaps one of the most important features of DSP.
- Superior performance. DSP can be used to perform functions not possible with analog signal processing. For example, linear phase response can be achieved, and complex filtering algorithms can be implemented using DSP techniques.

DSP is not without disadvantages, such as time consuming to design DSP algorithms and the finite word-length problem which means serious degradation in system performance may result from limited number of sampling points.

In our system, the digital filter is chosen as the processor because of the demand of removing noises from the experimental results. A filter is essentially a system or network that selectively changes the wave shape, amplitude-frequency and /or phase-frequency characteristics of a signal in a desired manner. Common filter

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objectives are to improve the quality of a signal (for example, to remove or reduce noises), to extract information from the signals or to separate two or more signals previously combined. A digital filter, is a mathematical algorithm implemented in software on a digital input signal to produce a digital output for the purpose of achieving a filtering objective. The term digital filter refers to the specific hardware or software routine that performs the filtering algorithm. Digital filters often operate on digitized analog signals or just numbers which represent some variable that are stored in a computer memory.

Digital filters play very important roles in DSP. Compared to their real counterparts, the attraction of the digital filter comes from the following key advantages besides those of DSP techniques

- Digital filter can have characteristics which are not possible with analog filters, such as a truly linear phase response.
- Both filtered and unfiltered data can be saved for further use.
- In practice, the precision achievable with analog filters is restricted, while with digital filters the precision is limited only by the word-length effect.
- Digital filters can be used at very low frequencies, where the use of analog filters is impractical. Also, digital filters can be made to work over a wide range of frequencies by a mere change to the sampling frequency.

Digital filters are broadly divided into two classes, namely infinite impulse response (IIR) and finite impulse response (FIR) filters. Either type of filter, in its basic form, can be represented by its impulse response sequence, $h(k)$ ($k=0,1,\dots$). The input and output signal to the filter are related by the convolution sum, which is given in Equations (3.8) for the IIR and (3.9) for the FIR filter.

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$$\begin{aligned}
 y(n) &= \sum_{k=0}^{\infty} h(k)x(n-k) = \sum_{k=0}^N b_k x(n-k) - \sum_{k=1}^M a_k y(n-k) \\
 H(z) &= \sum_{k=0}^N b_k z^{-k} \left/ \left(1 + \sum_{k=1}^M a_k z^{-k} \right) \right.
 \end{aligned} \tag{3.8}$$

$$\begin{aligned}
 y(n) &= \sum_{k=0}^{N-1} h(k)x(n-k) \\
 H(z) &= \sum_{k=0}^{N-1} h(k)z^{-k}, z = e^{j\omega T}, k = 0, 1, \dots, N-1
 \end{aligned} \tag{3.9}$$

where $h(k)$ is the impulse response coefficient, $H(z)$ is the transfer function and N is the filter length, that is the number of filter coefficients. T is the sampling period and ω is the fundamental (first harmonic) angular frequency, which is equal to $2\pi / NT$. It is evident from these equations that, for IIR filters, the impulse response is of infinite duration whereas for FIR it is of finite duration, since $h(k)$ for the FIR has only N value. In practice, it is impossible for N to be infinite. Instead, the IIR filtering equation is expressed in a recursive form where a_k and b_k are the coefficients of the filter. As a result, in Equation (3.8), the current output signal, $y(n)$, is a function of past output as well as present and past input signals, that is the IIR is a feedback system of some sort as shown in Figure 3.5(a). This should be compared with the FIR equation in which the current output $y(n)$, is a function only of past and present values of the input and the block diagram is as shown in Figure 3.5(b).

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Figure 3.5(a): Block diagram representation of IIR filter and (b): FIR filter.

Note, however, that when a_k are set to zero, Equation (3.8) reduces to Equation (3.9), which means FIR is a special case of IIR filter. From the figures, we note that filtering is in fact the convolution of the signal and the filter’s impulse response $h(k)$ in the time domain. Z^{-1} represents a delay of one sample period.

Compared with IIR, FIR is preferred in our sensing system because of the following advantages:

- FIR filters can have an exactly linear phase response. The implication of this is that no phase distortion is introduced into the signal by the filter. This is an

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important requirement in many applications. Whereas, the phase responses of IIR filters are nonlinear, especially at the band edges.

- FIR filters realized non-recursively which is by direct evaluation of Equation (3.9), are always stable. However, the stability of IIR filters cannot always be guaranteed.
- The word-length effects are much less severe in FIR than in IIR.

Although IIR has its own special application such as in a sharp cutoff filter, FIR is indeed a better choice to keep the spectral shape, which is the most important for application in the chemical sensing systems. Furthermore, the stability of FIR is also a desired factor in the use of our filtering system.

3.4.2 Simulation Results

In our work, hydrogen cyanide (HCN) gas is detected. Hydrogen cyanide is a chemical compound with a linear triatomic molecule structure. Pure hydrogen cyanide is a colorless, volatile, and extremely poisonous gas at room temperature with a bitter almond odor. An HCN concentration of 300ppm (parts per million) of air will kill a human within a few minutes, and its toxicity is caused by the cyanide ion. Hydrogen cyanide gas in air is explosive at concentrations over 56,000ppm. Because of its deadly toxicity, HCN is often under surveillance in the environmental and safety monitoring systems.

The $2\nu_1$ band of HCN gas locates in the region of 1520-1580nm ($2\nu_1$ refers to the second harmonic of the fundamental symmetric vibration transitions). As a linear molecule, the HCN absorption spectrum is normally arranged in two branches, refer to as the P and R branches respectively. The absorption wavelength and the

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absorption coefficient for each absorption line could refer to the empirical formulas from numerous experiments by the chemists [49, 95]. With those values and the assumed experimental setting parameters, the HCN absorption lines are simulated as below.

Consider a direct absorption spectroscopy based HCN sensing system shown in Figure 3.1. Although the light power of an commercial laser is able to reach as large as 20dBm, concerning a practical gas multiplexing system [50], an optical input power for each gas cell is quite small, i.e. the corresponding signal-to-noise-ratio (SNR) is quite small, and hence this will increase the measurement error. Moreover, the noise from the laser source is regarded as white noise [92], which will contribute significant errors in the detection. In order to improve the measurement accuracy of the gas detection system, an effective technique is to employ a digital filter to remove these noises in such system [96]. By Beer-Lambert's law, it is clear to see that to maximize sensitivity, excluding smallest possible $(\Delta I / I)$ noise, a molecular transition with a large absorption coefficient $\kappa(\nu)$, as well as the longest possible effective path-length l should be selected, whereas l in practice is limited by the physical size for the apparatus. So in this simulation, R(7), the strongest absorption line of HCN gas in $2\nu_1$ band, is used for analysis [95], while the molar absorption coefficient κ_m is equal to $2.4488 \times 10^{-4} \text{Pa}^{-1} \text{m}^{-1}$. The central wavelength λ_m and the corresponding full-width-half-maximum (FWHM) of the absorption line γ are 1537.299nm and 60pm respectively. The length of the gas cell l is 22.5cm and the gas concentration C is 121000ppm, set according to experimental parameters. The input power of the laser source is assumed to be 1mW, while the absorption of the

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light intensity by HCN molecules is about 3dB as shown in Figure 3.6. The amplitude of noise is set to be 0.2mW, so the signal-to-noise-ratio (SNR) is about 5, which is much smaller than in some practical cases. To design appropriate parameters of the filter, the frequency spectrum of the signal with noises is obtained by using discrete Fourier transform (DFT) analysis [96]. The DFT spectrum demonstrates the maximum signal frequency is at 1mHz. Therefore, a digital FIR low-pass filter is designed by the optimal method [94]. The chosen passband (PB) frequency and stopband (SB) frequency of the filter are 1mHz and 400mHz respectively and the number of order (N) is 7. The simulation result is illustrated in Figure 3.6. The SNR of the signal after the FIR filter is about 48, 6.82dB larger than the contaminated signal without any filtering.

Figure 3.6: Spectra of R(7) absorption line.

In some practical cases, SNR should be around 10000~100000, dramatically larger than that simulation study. The relationship between SNR after filtering and the error in terms of the gas concentration is shown in Figure 3.7, where the

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aforementioned filter is used for this simulation. It demonstrates clearly that when SNR is larger than 10000, the error can be reduced to below 1ppm.

Figure 3.7: Signal-to-noise ratio vs. detection errors of gas concentration.

3.4.3 Experiment and Discussions

Figure 3.8: Experimental schematic diagram.

The experimental configuration of the HCN gas sensor by direct absorption spectroscopy in NIR region is shown as Figure 3.8. To obtain the whole HCN molecular absorption spectrum, the input light from a tunable laser source (ANDO-AQ4321D) with initial power of 1mW, which was scanned from 1520nm to 1580nm

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with a step wavelength of 1pm, was passed to a NIST Standard Reference Material HCN absorption cell ($2\nu_1$ band, 22.5cm path length, 13.3kPa pressure, corresponding to concentration of 121000ppm of HCN gas [97]); After the absorption of HCN molecules, the light from the gas cell was detected by a broadband photodetector (PD) with an amplifier, whose gain was 3.9V/mA; Finally, the spectrum was recorded by a personal computer (PC).

Figure 3.9: Absorption spectrum of HCN gas.

The entire HCN absorption spectrum is shown in Figure 3.9. The depth of the R(7) absorption line at 1537.299nm was about 1.6V, corresponding to the gas concentration of 121000ppm in the cell by Beer's Law. The amplitude of the noise around the dip of R(7) was found to be 2×10^{-5} V. The SNR was about 80000, corresponding to the minimum detectable gas concentration of $\Delta C_{\min} = 1/\text{SNR} \times 12.1\% = 1.5\text{ppm}$ [65] according to Equation (3.7). After the use of the aforementioned FIR filter for the contaminated R(7) absorption line, the minimum

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voltage fluctuation around the dip reached to about 1×10^{-6} V, corresponding to the minimum detectable gas concentration up to about 0.1ppm.

To show the effect of the FIR filter more prominently, input power from the laser source was reduced to $10 \mu\text{W}$, and then the SNR became rather smaller. The P(35) absorption line at 1572.387nm, the distinguishably weakest peak in Figure 3.9 was used to analyze. The PB and SB frequency of the filter were set to be 1.5mHz and 450mHz respectively, and the order of the filter N was set to be 7. The experimental result is shown in Figure 3.10. It can be seen that the spectrum after filtering was significantly smoother. The SNR is increased from 8 to 160, with 13dB enhancement after the use of the well-designed FIR filter. Moreover, Figure 3.11 shows a linear relationship between the unfiltered and filtered SNR of P(35) absorption line with the input power of the light source, which indicates the input power will not affect the capability of the designed filter.

Figure 3.10: Spectra of P(35) absorption line.

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Figure 3.11: Signal-to-noise ratio of P(35) absorption line vs. optical input power.

From the above simulation and experimental results, a feasible scheme is proposed to improve the sensitivity of the HCN gas sensor by using digital signal processing technique. Both simulation and experimental results have shown that the detection accuracy is enhanced to 0.1ppm at the absorption wavelength of 1537.299nm while the input power is 1mW by using the well designed digital FIR filter. Furthermore, the weakest absorption gas lines can also be detected by using this technique while they cannot be detected by using other methods.

3.5 Multiple Gas Identification by Pattern Recognition

In some industrial applications, blends of chemicals instead of one are detected and the compositions of the chemicals are unknown. More difficultly, the spectra of those chemicals may even overlap with each other and the identification of the compositions of the chemicals will be more challenging in the optical spectroscopic field. Regular digital signal processing techniques, e.g. DFT transform mentioned in Section 3.4 is not suitable to distinguish individual chemical from chemical mixture

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because of their frequency similarities from the DFT transform distribution (i.e., for almost all the chemical gases, most spectral energy distributes in the low frequency band). In this case, FIR filter based on DFT transform cannot be used to identify and distinguish chemical components.

Alternatively, pattern recognition, defined as a collection of supervised learning methods, is a scientific discipline broadly applied to various industrial fields such as image analysis, signature authentication, text retrieval and face and speech recognition [98]. It aims to classify objects (or known as the generic term “patterns”) into a number of categories or classes based on either a priori knowledge or on statistical information extracted from the patterns. Each species of gas, in the respect of laser spectroscopy, possesses unique molecular absorption spectrum (or “pattern”) in the NIR band. Thus, the absorption spectrum can be used for trace gas detection such as a “fingerprint” used for humans. This characteristic “fingerprint” can be used as “feature” in a pattern recognition system, and then can be recognized by some machine learning methods. Amongst all the machine learning methods, support vector machine (SVM) which is a supervised learning method based on the statistical learning theory, attracts great attentions due to its outstanding advantages such as special generalization ability, especially for small sample size problems, no trouble of local minimum problem, and reliability in the multivariate problem or even high noise conditions [99]. Owing to those merits, SVM has been applied in chemical sensing areas such as electronic olfactory system [100] and gas chromatography-mass spectrometry [101].

In this section, automatic identification and measurement of chemical mixture by a SVR recognition system are investigated. The principles of the molecular

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absorption spectroscopy for multiple chemical gases and SVR are described in Section 3.5.1, followed by the experiment and discussions which are given in Section 3.5.2.

3.5.1 Principles

Figure 3.12: Block diagram of direct absorption spectroscopic chemical sensor.

The molecular absorption spectra of the multiple chemical gases could be obtained by direct absorption spectroscopy, as shown in Figure 3.12. In a laboratory condition, a tunable laser source (TLS) and an optical spectrum analyzer (OSA) are adopted as the light source and the receiver respectively due to their high-resolutions. A gas cell containing a gas sample is connected with the TLS and the OSA by two sections of optical fibers.

The absorption Equations (3.1) and (3.2) are under the assumption of a single chemical to be detected. Actually, Beer-Lambert's law is also available to be applied on multiple chemicals absorption with the assumption that there is no chemical reaction amongst the blend of chemicals [102]. For a gas mixture with n components stored in one gas cell, Equation (3.2) could be modified to,

$$A(\nu) = I_{T, dB}(\nu) - I_{0, dB} = -10 \log_{10} e \cdot \sum_{i=1}^n \kappa_i(\nu) l C_i \quad (3.10)$$

The absorption coefficient of each species of gas varies at different wavenumber and thus the output intensity and the corresponding absorption change

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with wavenumber too. So Equation (3.10) represents a system of equations rather than a single equation. It could also be depicted as a matrix form of

$$\begin{bmatrix} A(\nu_1) & A(\nu_2) & \cdots & A(\nu_k) \end{bmatrix} = -(10 \log_{10} e) \cdot l \cdot \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{bmatrix}^T \begin{bmatrix} \kappa_1(\nu_1) & \kappa_1(\nu_2) & \cdots & \kappa_1(\nu_k) \\ \kappa_2(\nu_1) & \kappa_2(\nu_2) & \cdots & \kappa_2(\nu_k) \\ \vdots & \vdots & \ddots & \vdots \\ \kappa_n(\nu_1) & \kappa_n(\nu_2) & \cdots & \kappa_n(\nu_k) \end{bmatrix} \quad (3.11)$$

or

$$\mathbf{y} = b \mathbf{w}^T \mathbf{x} \quad (3.12)$$

with the definition of

$$\mathbf{y} = \begin{bmatrix} A(\nu_1) & A(\nu_2) & \cdots & A(\nu_k) \end{bmatrix}, \quad b = -(10 \log_{10} e) \cdot l$$

$$\mathbf{w} = \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{bmatrix}^T, \quad \mathbf{x} = \begin{bmatrix} \kappa_1(\nu_1) & \kappa_1(\nu_2) & \cdots & \kappa_1(\nu_k) \\ \kappa_2(\nu_1) & \kappa_2(\nu_2) & \cdots & \kappa_2(\nu_k) \\ \vdots & \vdots & \ddots & \vdots \\ \kappa_n(\nu_1) & \kappa_n(\nu_2) & \cdots & \kappa_n(\nu_k) \end{bmatrix} \quad (3.13)$$

where k is number of sampling data, and customarily is much larger than the number of compounds in the gas mixture n (i.e. $k \gg n$), so solving this equation is a multiple linear regression problem. Vector $\mathbf{y}$ is named as a dependent variable, $\mathbf{x}$ is an n -dimensional independent variable, b is an amplified coefficient only related with the effective length l and $\mathbf{w}$ is the weight parameter to be solved.

Numerous regression algorithms, such as partial least squares (PLS) regression, artificial neural networks (ANN) and support vector machine (SVM), were developed in recently years aiming at various problems in chemistry, biomedical and biological engineering. PLS regression extends multiple linear regression without imposing the restrictions employed by discriminant analysis, principal components regression, and canonical correlation [103]. Therefore, PLS is especially useful where the number of independent variables is comparable to or greater than the number of

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compounds (data points) and/or there exists other factors leading to inter-correlated variables. ANN, often just called a "neural network" (NN), is a mathematical model or computational model based on biological neural networks. In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. So ANN always attracts researchers who are interested in predication of a dynamic system problem or non-linear statistical data modeling [104]. Support vector machine (SVM), which is based on the strict mathematical theory, is outstanding solving the multivariate problem, or even reliable at underfitting, overfitting or high noise conditions. SVM, which is a supervised learning method based on the statistical learning theory, highlights due to its outstanding advantages such as special generalization ability, especially for the small sample size problems, no trouble of local minimum problem, and reliability in the multivariate problem or even high noise conditions [99]. Owing to those merits, SVM has been applied in chemical sensing areas such as electronic olfactory system and gas chromatography-mass spectrometry [100, 101]. For our direct absorption spectroscopy sensing system, it is a linear statistical regression problem and it has no inter-correlated variables by Equation (3.13), so SVM will be more suitable compared with the other two algorithms .

The support vector regression (SVR) algorithm is described below for solving the regression problem as Equations (3.12) and (3.13).

The training data set $\{[\mathbf{x}(i), y(i)] \in \mathcal{R}^n \times \mathcal{R}, i = 1, 2, \dots, k\}$ consists of k pairs of $(\mathbf{x}_1, y_1), (\mathbf{x}_2, y_2), \dots, (\mathbf{x}_k, y_k)$, with $\mathbf{x}_i \in \mathbf{x} \subseteq \mathcal{R}^n, (n = 3), y_i \in \mathbf{y} \subseteq \mathcal{R}$. If based on the minimization least square loss function by traditional regression method, unique solution of the weight coefficients $\mathbf{w}$ could be obtained. This selection is actually

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based on the assumption that all the experimental data are infinitely accurate. But actually, all the experimental data must have some errors due to the noise, the measurement limitations, etc.. If the loss function is minimized very strictly, the mathematical model should contain not only the true relationship among the variables, but also include the errors from the experiment. So in order to avoid fitting the values of the experimental errors into the mathematical model, an ε -insensitive loss function $L_\varepsilon(\mathbf{x}, \mathbf{y}, f)$ that ignores errors within a certain distance of the true value is introduced in the SVR algorithm, and

$$L_\varepsilon(\mathbf{x}, \mathbf{y}, f) = |y - f(\mathbf{x}, \mathbf{w})|_\varepsilon = \begin{cases} 0 & \text{if } |y - f(\mathbf{x}, \mathbf{w})| \leq \varepsilon \\ |y - f(\mathbf{x}, \mathbf{w})| - \varepsilon & \text{otherwise} \end{cases} \quad (3.14)$$

where f is the predicted function, in the linear regression, taking the form

$$f(\mathbf{x}, \mathbf{w}) = b\mathbf{w}^T \mathbf{x} \quad (3.15)$$

The objective of the support vector is to find a function $f(\mathbf{x}, \mathbf{w})$ that has the least deviation which is larger than ε from the actually obtained target $\mathbf{y}$ for all the training data as shown in Figure 3.13. In other words, the errors as long as less than ε are not considered, but any deviation larger than that will not be accepted.

Figure 3.13: Support vector regression function.

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From Equation (3.14), if the residue is no larger than the small value ε , the loss function will be zero. In that case, infinite number of solutions but not a unique solution are obtained. In order to get an optimal unique solution, it is noticed that when the values of the weights become smaller, the error of the calculated value of a dependent variable (Δf) and the experimental errors of the independent variable ($\Delta \mathbf{x}$) in the regression equation can be expressed as follows:

$$\Delta f = b\mathbf{w}^T \Delta \mathbf{x} \quad (3.16)$$

So the error of the calculated value can be depressed by minimization of the sum of the square of the weight coefficients of regression ($\|\mathbf{w}\|^2 = \mathbf{w}^T \mathbf{w}$). This is a convex optimization problem, slack variables ξ_i , ξ_i^* are introduced to seek the optimal regression function by the minimization of the functional,

$$\Phi(\mathbf{w}, \xi, \xi^*) = \frac{1}{2} \|\mathbf{w}\|^2 + h \sum_{i=1}^k (\xi_i + \xi_i^*) \quad (3.17)$$

subject to

$$\begin{aligned} b\mathbf{w}^T \mathbf{x}_i - y_i &\leq \varepsilon + \xi_i \\ y_i - b\mathbf{w}^T \mathbf{x}_i &\leq \varepsilon + \xi_i^* \end{aligned}$$

and

$$\xi_i, \xi_i^* \geq 0, h_b > 0$$

where the constant h_b determines the trade-off between the flatness of f and the amount up to which deviation larger than ε are tolerated. Eventually, the weight vector could be obtained by solving Equation (3.17) with the use of Lagrangian algorithm [99].

The procedures of the use of SVM to automatically identify and measure the multi-components of the target gas mixture are described as in Figure 3.14.

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Figure 3.14: Flow chart of automatic identification and measurement system.

The database used in the gas identification system is based on HITRAN molecular spectroscopic database, which has been regarded as the international standard for providing the necessary fundamental spectroscopic parameters for diverse atmospheric and laboratory transmission and radiance calculations [105]. According to the absorption strengths and linewidths provided in HITRAN database, database X is built up which composes absorption coefficients of 60 samples of 8 species of gases with significant absorption in the NIR infrared region. The sampling rate and the length of each sample must be identical with those of the training data set. The number of sample m exceeds to that of the species of gases because a sort of gas may correspond to multiple samples due to absorption of same species of gas

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differing at different transmission bands or different isotopes. The species of gases, the corresponding number of samples and the serial number of samples in database **X** are as listed in Table 3.1.

Table 3.1: List of the gas species, the corresponding number of samples and the serial numbers of samples in database **X**.

Gas species	C ₂ H ₂	CH ₄	CO	CO ₂	H ₂ O	HI	N ₂ O	O ₂	HCN
Number of samples	4	3	3	27	12	2	7	1	1
Serial number (Sn)	1-4	5-7	8-10	11-37	38-49	50-51	52-58	59	60

Background correction of the raw spectrum is necessary to have a more interpretable signal, allowing to determine the peak wavenumbers and the amplitudes of peaks more accurately. The background signal forms due to a scattering of infrared beam caused by heterogeneities in a solid, external light or a source of non-specific absorption. The background signal could be estimated by a least-squares polynomial fitting function [106]. Subtracting the estimation of the background from the raw data, the output data are ready for the process of resampling.

Resampling is the other crucial problem in the data preprocessing. The data length, the sampling rate of the processed data must keep consistent with those of the database. Both oversampling and undersampling will enhance the error of the recognition system. The sampling rate and length depend on both the experimental resolution and the database resolution.

Next, the regression modeling is built up, which is based on SVR algorithm. When the number of the samples m and the number of components n in the gas mixture are known, the number of execution could be obtained, which is equal to m^n .

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To guarantee the reasonability of the solution, constrained conditions are employed. Both the concentration of each component and the total concentration of the training set must be between 0 and 1atm or 0 and 100% respectively. The negative solutions or those values larger than 100% are deserted and beyond consideration.

To obtain a unique solution of the components in the gas mixture, except constrained conditions, the root mean square (RMS) error of each solution from the regression model is evaluated:

$$E = \left[\left(\sum_{i=1}^k L_e^2(\mathbf{x}_i, y_i, f_i) \right) / k \right]^{\frac{1}{2}} = \left[\left(\sum_{i=1}^k |y_i - f_i(\mathbf{x}, \mathbf{w})|_e^2 \right) / k \right]^{\frac{1}{2}} \tag{3.18}$$

The solution with the minimum RMS error is obtained and by the corresponding serial number of the sample S1, S2,..., Sn, the components of the gas mixture are also recognized.

3.5.2 Experiment and Discussions

Table 3.2: Specification of Gas Cell 1.

Gas	Pressure (Torr)	Concentration =Pressure/1atm
HCN	10	1.33%
C ¹² O	150	19.7%
C ¹³ O	150	19.7%

The experimental setup is as shown in Figure 3.12. A NIST standard Gas Cell 1 (Wavelength reference, with the specifications shown in Table 3.2) was used for detection. The length of Gas Cell 1 was 15cm, 5 multipass and thus the effective path length was 5 times of the length of the gas cell, 75cm totally. The cell with fiber ports

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were connected to a tunable laser source (TLS, Ando AQ4321D) with CW emitting light from 1520 to 1620nm and an OSA (Ando AQ6317, with resolution of 0.01nm) operating in the synchronized scanning mode with the TLS.

(a)

(b)

Figure 3.15 (a): Experimental raw gas spectrum. (b): Processed gas spectrum.

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The detected spectrum is illustrated in Figure 3.15(a). The input power of the TLS was set to be 0dBm. Due to the insertion loss of the gas cell and the existence of background signal, the backline of the spectrum deviated more than 1dBm. The x-axis was scaled by wavenumber (cm^{-1}) instead of wavelength (cm), which was identical with the scale of the database. A slight overlap between 6270 cm^{-1} and 6290 cm^{-1} was observed, and the curve was unsmooth because of the environmental interference, the resolution of the laser source and detector and the interferometric noise induced at both ends of the gas cell.

A least-squares polynomial fitting was used to determine the nonlinear background superimposed on the molecular absorption spectrum. Performed on a subset of points above a threshold, which represented a wide class of background, the fitting curve was estimated and the background was removed by using this estimation. Afterwards, the signal was resampled with a sampling interval of 5 cm^{-1} , which was identical with that in Database X such that the operation was less burdensome and time-consuming while the spectrum kept the inherent curve profile. The gas spectrum after background removal and resampling is shown in Figure 3.15(b). After background removal, the backline of the spectrum became quite flat, with a value of near to 0, representing there were no absorptions at those points. The graph also presented that the absorption lines distributed in the whole detecting region, and the largest absorption peak was observed around 6535 cm^{-1} , normalized to -1.

The spectrum was passed to the aforementioned SVR model. The insensitivity ε and the bound coefficient h_b were set to be 0.001 and 10 respectively, and the amplified parameter b was computed as 65.1442 when the effective length was 75cm. Because it was a three multiple regression problem, the solved RMS error was

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an $m \times m \times m$ matrix (m was the total number of sample, equal to 60). The minimum error was computed as 0.0012, the components were recognized as S8, S9, S60 ($C^{12}O$, $C^{13}O$ and HCN correspondingly from Table 3.2) with the concentrations of 19.5%, 18.9% and 1.40% respectively, close to the datasheet provided by the product supplier. The variances may be due to the gas cell fabrication problems (such as the practical length or concentrations of the gas cell are not exactly as standard).

To visualize the relationships of the samples and corresponding RMS errors, the RMS errors while one component of the mixture is fixed are illustrated in Figure 3.16(a)-(c). For instance, Figure 3.16(a) shows when S8 is fixed, the RMS error is minimized when the other two components are S9 and S60 respectively. On those graphs, the contours are also displayed to show the values of the error by different colors based on the error values. The RMS detection error is scaled in term of concentration by $E_{con} = w \times E_y / y$ [65] and it could be read from graphs as 0.01%.

(a)

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(b)

(c)

Figure 3.16(a): RMS detection error based on S8 is known (The minimum RMS error is obtained when the other components are S9 and S60 respectively). (b): RMS detection error based on S9 and (c): S60 is known

To further proving the reliability of the proposed recognition system, Gas Cell 2 ($C^{12}O$ inside, at the pressure of 700Torr, corresponding with concentration of

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92.1%) instead Gas Cell 1 was inserted into the gas detecting system. The input power of the TLS was kept 0dBm. The raw spectrum is demonstrated in Figure 3.17. Following the aforementioned procedures, the nonlinear background was removed and resampled.

Figure 3.17: Raw absorption spectrum of Gas Cell 2.

The processed data were passed to the same SVR model. The parameters were kept as same as before. The target was recognized as a single gas component, carbon monoxide ($C^{12}O$, S8) and the concentration was 92.8%, quite close to the specifications of Gas Cell 2. The RMS detection error in term of concentration was 0.03%. The absorption per unit effective length vs. absorption coefficient of $C^{12}O$ is illustrated in Figure 3.18. With the help of ε -tube, the regression curve was predicted, and the slope value of the predicted curve was equal to the concentration of the gas.

From the above satisfactory results of Gas Cells 1 and 2, this SVR model demonstrated a good ability to identify and measure gas mixture with up to 3

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components automatically with high measurement accuracy. Actually, because the measurement accuracy is independent on the number of components of the gas mixture from Equation (3.18), SVR also could be employed to recognize the multiple components from the gas mixture even when the number of the components is more than 3 due to its reliability in the multivariate problem [99]. Therefore, it shows a promising feasibility to be applied in the environmental monitoring such as toxicological evaluation of complex gas mixture or the gas identification systems.

Figure 3.18: Absorption coefficient vs. absorption per unit length.

3.6 Conclusion

In this chapter, the direct absorption spectroscopy for optical fiber chemical sensor is studied. The principle of direct absorption spectroscopy is described and the noises affecting the measurement accuracy are discussed. Aiming to the main noises, a feasible scheme is contributed to improve the sensitivity of the direct absorption spectroscopy sensor by using digital signal processing technique. Both simulation and experimental results have showed that the detection accuracy is enhanced by using the

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well designed digital finite impulse response (FIR) filter. The weakest absorption gas lines even could be detected and corrected by using this proposed approach.

The other contribution of this chapter is to propose an automatic gas mixture recognition system by using support vector regression (SVR) technique. The gas mixture spectra are obtained by a simple direct absorption spectroscopic fiber sensing system, and after the recognition model, the gas components and the corresponding concentration are obtained. By this SVR model, up to 3 components of the gas mixture could be identified automatically and a high measurement accuracy in terms of concentration is obtained. Therefore, this recognition system shows a promising potential to be employed in recognizing unknown gas mixture.

Chapter 4

Passive Cavity Ring-down Spectroscopy

4.1 Introduction

In last chapter, the optical fiber chemical sensor based on direct absorption spectroscopy technique is studied. Due to the weak absorptions of the chemical molecules in the near infrared region, digital signal processing technique is proposed to improve the sensitivity of the sensing system. An alternative approach to achieve high-sensitivity measurement is to employ highly sensitive modulation techniques. Cavity ring-down (CRD), which is a high sensitive modulation method to measure small fractional absorption in a resonant cavity [107], is studied in this chapter. Unlike conventional direct or multi-pass optical spectroscopy technologies, CRD measures the ring-down time of the resonant cavity rather than the decay of intensity. Proportional to the loss in the cavity, the ring-down time is both independent of excitation intensity, resulting in lower susceptibility to laser noise, and immune from external loss contributions, furthering enhancing sensitivity [86]. The optical fiber CRD, where a fiber loop replaces the high-reflectivity mirror resonant cavity in bulk optics, has been implemented in trace gas detection [78], refractive-index sensing [82], biconical tapers strain sensing [86] and other pressure [84, 85], temperature [83] measurements in the last couple of years. By without/with the existence of the gain amplifier, fiber CRD spectroscopy is categorized to passive and active CRD spectroscopy [108]. In passive CRD spectroscopy, no amplified material is inserted in the fiber cavity and no gain is applied to compensate the total loss of the cavity. So

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the passive CRD is usually used for small fraction loss detection. The active CRD spectroscopy, with the appearance of the amplifier, on the other hand, could be applied for a fiber cavity with relative larger loss. The active CRD spectroscopy in fiber optics will be addressed in the next chapter.

In this chapter, the passive fiber CRD spectroscopy is focused. First, the principle of the CRD spectroscopy in bulk optics is described, and predominant problems affecting the bulk CRD's sensitivity are indicated. Next, the passive fiber CRD spectroscopy is presented and the application for the passive CRD spectroscopy in a long period grating (LPG) fiber strain sensor is addressed. A conclusion of this chapter is given in the last section.

4.2 CRD Spectroscopy in Bulk Optics

Figure 4.1: Schematic diagram of the bulk cavity ring-down experiment.

Figure 4.1 shows the schematic diagram of the experimental implementation of cavity ring-down (CRD) spectroscopy in bulk optics. CRD is easy to visualize in the pulsed form [109]. If a temporally narrow pulse of light is injected into a cavity containing a chemical sample, it will be reflected back and forth within the cavity and its intensity will gradually decay with time as light energy leaks out of the cavity. The decay arises from losses in the mirror coatings of the cavity and absorption by the chemical sample contained between the mirrors. In a case of an empty cavity without the

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chemical sample, the output intensity will decrease exponentially according to the following relationship [107]

$$I(t) = I_0 \exp \left[-2\chi \left(\frac{tc}{2l} \right) \right] \quad (4.1)$$

I_0 is the intensity of the initial pulse, and $I(t)$ is the output intensity coupled out of the cavity through one of the mirrors after time t . In the exponent in Equation (4.1), the term -2χ represents the loss of the reflections of two mirrors in the cavity. The term $tc/2l$ depicts the number of round trips in time t , where c is the velocity of light in vacuum and l is the length of the cavity. For a empty cavity, the loss per reflection $-\chi$ is only involving the loss in the mirror coatings of the cavity, taken as $-(1-R_M)$, where R_M is the reflectivity of the mirror, so Equation (4.1) could be rewritten as

$$I(t) = I_0 \exp \left[-(1-R_M) \frac{tc}{l} \right] \quad (4.2)$$

Consider now a cavity that contains a chemical species that absorbs the light at the wavelength of the radiation injected into the cavity. For a round trip in the cavity, the loss per reflection $-\chi$ due to the chemical absorption is given by $-\kappa lC$ according to Beer-Lambert's law in Equation (3.1). Then the total loss symbolized as β in the cavity containing the absorbing species will be

$$\beta = -2(1-R_M) + 2(-\kappa lC) = -2[(1-R_M) + \kappa lC] \quad (4.3)$$

and Equation (4.1) can be rewritten as

$$I(t) = I_0 \exp \left\{ -[(1-R_M) + \kappa lC] \frac{tc}{l} \right\} \quad (4.4)$$

If we define a time constant τ and at the point $t = \tau$,

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$$I(\tau) = I_0/e \quad (4.5)$$

So

$$\tau_1 = \frac{l}{c(1 - R_M)} \quad (4.6)$$

for the empty cavity and

$$\tau_2 = \frac{l}{c[(1 - R_M) + \kappa l C]} \quad (4.7)$$

for the cavity with chemical sample [110]. Then a general formula for a CRD output will be

$$I(t) = I_0 \exp\left(-\frac{t}{\tau}\right) \quad (4.8)$$

and from Equations (4.6) and (4.7), the concentration of the chemical species will be given by [111]

$$C = \frac{1}{c\kappa} \left(\frac{1}{\tau_2} - \frac{1}{\tau_1} \right) \quad (4.9)$$

Figure 4.2: Schematic representation of the ring-down pattern produced by a short laser pulse injected into the cavity.

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A schematic representation of a CRD pattern is illustrated in Figure 4.2. The constant τ which is usually called decay time or ring-down time, is the most important parameter in CRD process, and by reading the decay time at empty cavity and the cavity containing the chemical sample, the concentration of the detected chemical sample could be determined according to Equation (4.9).

In direct absorption spectroscopy technique, the longer path-length of the light intensity gives the higher sensitivity according to Beer-Lambert's law. In CRD spectroscopy, the ring-down cavity can be viewed as having an effective path-length of $l/(1-R_M)$ from Equation (4.6). Since mirrors are commercially available today with reflectivity on the order of 99.999% [112], the effective optical path-length of the cavity is increased by 10^5 times over the physical dimensions of the device. Thus an absorption path-length of 10-100 kilometers is achieved on the order of one meter physical length. This can be compared with traditional "multiple pass" cavities [111], where effective path-lengths of 10-100 meters are the practical limit.

It is clear from the foregoing discussion that cavity ring-down spectroscopy is a sensitive means of measuring fractional absorption in chemical samples from sub-ppm levels out to the 10^3 ppm range. The primary advantages of the technique are high sensitivity and freedom from pulse-to-pulse variations of the laser ($\Delta I/I_0$) because it only measures the decay time τ .

Potential problems that may degrade the performance of this technique in real-world environments include [109]:

- The effect of turbulence-induced change in refractive index on beam direction within the cavity;

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- The presence of particular matter in the cavity that can result in scattering of the beam;
- Cavity alignment problems due to thermal lensing;
- Transverse mode competition, that can lead to non-exponential ring-down curves.

4.3 Principle of Passive Fiber CRD Spectroscopy

Figure 4.3: Cavity ring-down scheme in a fiber loop.

In 2001, the first CRD based optical fiber sensor was proposed [79]. In optical fiber CRD spectroscopy, a fiber loop replaces the high-reflectivity mirror resonant cavity in bulk optics, as shown in Figure 4.3. The fiber cavity is composed by two optical fiber couplers, a long segment of fiber with a target sample inserted. In a CRD process, an input pulse is coupled in from Coupler 1, rings around in the fiber cavity and is coupled out by the other coupler Coupler 2. Due to the loss in the fiber cavity, the output pulses decay exponentially, which obey Equation (4.8). As shown in Figure 4.3, the total loss in the fiber cavity, composes of the couplers' losses, the fiber loss and the sample's insertion loss. This total loss is equal to the pulse intensity change in a round trip time (the time the pulse travels in one fiber loop), which could be expressed mathematically by

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$$-\alpha \cdot I = \frac{dI}{dt} \cdot T \quad (4.10)$$

where α is the total loss in the fiber cavity, dI/dt is the rate of pulse intensity change, and T is the trip time, which could be obtained by

$$T = \frac{nL}{c} \quad (4.11)$$

equal to the length of the fiber cavity L over the speed of light in fiber core c/n , where n is the refractive index of the fiber core.

If Equation (4.10) is integrated over t ,

$$\int_{I_0}^I \frac{dI}{I} = - \int_0^t \frac{\alpha}{T} dt$$

we get

$$\ln I \Big|_{I_0}^I = - \frac{\alpha}{T} t \Big|_0^t$$

so

$$\ln \left(\frac{I(t)}{I_0} \right) = - \frac{\alpha}{T} t \quad (4.12)$$

or

$$I(t) = I_0 \exp \left(- \frac{\alpha}{T} t \right) \quad (4.13)$$

If the ring-down time τ is defined to

$$\tau = - \frac{T}{\alpha} \quad (4.14)$$

Equation (4.13), which is the fiber CRD formula, has the exactly same format as the CRD Equation (4.8) for bulk optics.

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Like bulk CRD, the ring-down time τ deals with the loss in the cavity, so the ring-down time is independent on excitation intensity. So the fiber CRD has lower susceptibility to laser noise. The intra-cavity sample also results immune from external loss contributions, further enhancing sensitivity. The merits of the fiber CRD include no alignment problems and transverse mode competition as in the bulk optics (see Section 4.2), attributed to the specific properties of the fiber.

However, in fiber CRD, the total loss in the fiber cavity cannot be kept as small as that in the bulk optics, due to the fiber transmission loss and the insertion losses of the fiber devices. For example, to keep the total loss minimum, couplers with minimum coupling ratio of 1:99 are usually adopted, the two coupler's insertion losses will be 0.1dB, whereas, only 1% of the light is able to be coupled in, and 1% of the light could be coupled out, so the output pulse intensity will be very small. If 50:50 couplers are applied, then at least 6dB loss is introduced for an empty fiber cavity. Assume a gas cell is inserted to the fiber cavity, normally, the insertion loss of the gas cell will be 1dB, and if the absorption of the gas in the excitation wavelength is 2dB, then the second output pulse will decrease 3.1dB from the first output pulse even we use 1:99 couplers with the price of the large consumption of the pulse intensity. In this case, the output pulses will decay quickly below the minimum detectable power of the detectors and only a few pulses could be captured and thus the ring-down time is difficult to detect. Even worse, a large total loss will shorten the ring-down time due to Equation (4.14), which will reduce the sensitivity of the fiber CRD sensor. For bulk CRD, however, due to the mature craftworks of the cavity mirror, only 4×10^{-4} dB loss is induced for an empty cavity, so the ring-down time could be much longer than that in fiber optics. Although the ring-down could be

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increased by enhancing the trip time by Equation (4.14), and the trip time of the fiber CRD could be longer than that in bulk CRD by lengthening the fiber loop, but more undesirable fiber transmission loss will be induced as well.

Therefore, for trace gas detection, an optical amplifier has to be employed to provide a gain to compensate the large loss in the fiber cavity. To distinguish the fiber CRD with and without the gain, the definitions of active CRD and passive CRD are introduced. For passive CRD, without the gain compensation, it may not be used for chemical sensing, whereas, there are other ample applications for this passive CRD scheme. In the following section, the passive CRD spectroscopy for fiber strain sensing is presented.

4.4 Experimental Passive Fiber CRD for Strain Sensing

Over the past decade, strain sensing systems have become increasingly important in wide applications including geography, aerospace, structural monitoring, chemical and biomedical sectors. Optical fiber strain sensors outperform mechanical and other sensing counterparts with their specific features due to high sensitivity, low cost, light weight as well as immunity to electromagnetic interference. Long period gratings (LPGs), which are formed by inducing periodic refractive index modulations in the core of hydrogen-sensitized germanosilicate fibers, are proposed as simple yet versatile fiber strain sensors. Compared with fiber Bragg grating-based sensors, LPGs highlighted by their high-sensitivity, broad strain-induced shift and economical fabrications. Moreover, since fiber Bragg gratings (FBGs) are based on coupling of light to the reverse-propagating guided mode, optical isolators are required to prevent back-reflection-induced source oscillation and thus their applications are limited to

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some specific conditions [113].

As all-fiber components, LPGs could be compatible with cavity ring-down (CRD) spectroscopic technique for improving sensitivity, which has been implemented in biconical tapers strain [86], pressure [85], temperature [83] measurements in the last couple of years. In this section, alternatively, an LPG is inserted in a CRD fiber loop for investigating the strain measurement capability. The principle of LPG is described in Section 4.4.1. The experimental scheme and theoretical analysis of the cavity ring-down LPG fiber loop are presented in Section 4.4.2, followed by the experiment and discussions which are given in Section 4.4.3.

4.4.1 Principle of Long Period Grating

Figure 4.4: Schematic of a long period grating (LPG).

Long-period gratings (LPG) are formed by inducing a periodic refractive index modulation in the core of a photosensitive optical fiber. The spatial periodicity Λ of this index variation can range from tens to hundreds of micrometers. The caused phase matching between the mode propagating in the core of the fiber and a forward-propagating cladding mode is achieved at the resonant wavelength, λ , with the expression

$$\lambda = (n_{eff}(\lambda) - n_{clad}^m(\lambda))\Lambda \quad (4.15)$$

where $n_{eff}(\lambda)$ is the effective refractive index of the propagating guided mode at the

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resonance wavelength, $n_{clad}^m(\lambda)$ is the refractive index of the m -th cladding mode and Λ is the period of the LPG, as shown in Figure 4.4. The fiber itself consists of two waveguide structures—one being the high-index core surrounded by the lower-index cladding, the other being the cladding, surrounded by the ambient medium. The differential effective index is a function of the optical fiber parameters and hence the coupling wavelengths can simply be varied by selecting appropriate fibers and grating periodicities. The cladding modes lose power rapidly on propagation due to surface defects and absorption by the protective jacket. Hence the transmission spectrum of a typical long-period grating consists of a series of loss bands centered at discrete wavelengths, as shown in Figure 4.5. Each resonant band corresponds to the coupling of the guided mode to a cladding mode of a distinct order m .

Figure 4.5: The typical transmission spectrum of an LPG.

When an LPG is strained, its resonant wavelength will shift along the resonant bands. Consider the LPG with period Λ under the influence of axial strain $\Delta\epsilon$, where $\Delta\epsilon$ is known as micro-strain, the ratio of the change in length and the original length

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($\Delta\varepsilon = \Delta d/d$). This strain performance is described by the classical expression of the wavelength shift per unit strain change $d\lambda/d\varepsilon$ [114],

$$\frac{d\lambda}{d\varepsilon} = \frac{d\lambda}{d(\delta n_{eff})} \left(\frac{dn_{eff}}{d\varepsilon} - \frac{dn_{clad}}{d\varepsilon} \right) + \Lambda \frac{d\lambda}{d\Lambda} \quad (4.16)$$

As above, the wavelength shift due to axial strain is a function of material and waveguide effects, represented by the first and the second terms on the right-hand side of Equation (4.16) respectively. The material contribution results from the change in transverse dimensions of the fiber due to Poisson's effect and the change in the differential refractive index of the core and cladding ($\delta n_{eff} = n_{eff} - n_{clad}$, n_{eff} and n_{clad} are the effective refractive indices of the core mode and cladding mode) arising from the strain-optic effect shown in the first term, while the waveguide contribution results from the change of the period of the LPG as shown in the second term. The overall shift in a resonant band due to a particular magnitude of axial strain is a function of the fiber properties, the grating period and the order of the corresponding cladding mode. By selecting the appropriate periodicity in a given LPG, it will thus allow the generation of attenuation bands with desired sensitivity [115].

For simplification, the total terms on the right hand side of (4.16) can be defined as A , and

$$d\lambda = A d\varepsilon \quad (4.17)$$

4.4.2 Experimental Scheme and Theoretical Analysis

The experimental setup of the cavity ring-down LPG fiber loop for the strain measurement is based on the schematic diagram shown in Figure 4.6. The cavity was composed by two standard 2×1 1:99 optical fiber couplers, a long segment of fiber

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and an LPG. The CW light from a tunable laser source (Anritsu MG 9541A, 1510-1640nm) entered into an acousto-modulator (Brimrose AMM100-10-1550) and was modulated via a signal generator (Agilent 33250A 80MHz) to produce a train of optical pulses. Those modulated pulses were coupled into the loop via 1% arm of Coupler 1, passed through the fiber cavity, coupled out by 1% arm of Coupler 2 such that the majority of the pulse power were kept inside the fiber loop and continued to ring around the ring-down fiber loop. The output periodic trains of pulses were detected by an amplified photodetector (Thorlabs PDA400, 10MHz bandwidth). In each cavity decay process (a duration defined as a period of input pulses train including only one input pulse), the amplitude of the output pulses decayed temporally due to the total existing loss α . This total loss α , comprised fiber loss, coupler insertion losses and LPG transmission loss in this case [87], which could be evaluated from the relationship of α and τ in the Equation (4.14).

Figure 4.6: Block diagram of the experimental setup of LPG cavity ring-down strain sensor.

The both ends of the LPG, which has been inserted in the fiber loop, are glued onto two separated translation stages (with a resolution of 20nm and a translation range of 1000 μ m each) apart of a distance of d shown in Figure 4.6. For a strain sensor, micro-strain $\Delta\epsilon$ is depend on the ratio of the change in length Δd and the original length d ($\Delta\epsilon = \Delta d/d$).

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In the CRD configuration, the strain-induced wavelength shift of the LPG was expressed as an attenuation variation of the LPG and thus a total loss change at the wavelength of the input pulse. Due to the change of the total loss, the ring-down time varied correspondently. Based on Equation (4.14), the relationship of the change of total loss and the change of decay time is

$$\frac{d\tau}{\tau} = -\frac{d\alpha}{\alpha} \quad (4.18)$$

By Equation (4.17), the change of LPG strain-induced loss could be derived as

$$d\alpha' = \frac{d\alpha'}{d\lambda} A d\varepsilon = B d\varepsilon \quad (4.19)$$

Because the change of the total loss is only caused by the attenuation variation of LPG, $d\alpha' = d\alpha$. The parameter B comprises the terms of A and $d\alpha'/d\lambda$. The term A is again affected by the material and waveguide contribution. The other term $d\alpha'/d\lambda$, which is the slope of the LPG transmission dip, is dependent on the corresponding LPG spectral depth and bandwidth. In the LPG fabrication, the last two terms are related to the power of the UV laser and the duration of writing. Combining Equations (4.18) and (4.19), the change of the decay time per unit strain $d\tau/d\varepsilon$ is

$$\frac{d\tau}{d\varepsilon} = -\frac{\tau}{\alpha} \cdot B \quad (4.20)$$

This change of decay time per unit strain is called the sensitivity of the LPG CRD sensor, which is a reflection of the LPG strain-induced performance in the CRD loop. Detecting the decay time at different strain levels, the sensor's sensitivity could be evaluated. Moreover, from this equation, it shows that, this sensitivity is not only determined by the grating's configuration represented by the parameter of B , but also related with values of total loss α and the decay time τ . For a given LPG embedded

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in a CRD strain sensing system, a small total loss α and a long decay time will expect to bring the strain sensor a higher sensitivity. The accuracy of the sensor, depicted as minimum detectable micro-strain $\Delta\epsilon_{\min}$, correspondingly, is

$$\Delta\epsilon_{\min} = -\frac{\alpha}{\tau} \cdot \frac{1}{B} \Delta\tau_{\min} \quad (4.21)$$

according to Equation (4.20), comparing to that in a conventional direct LPG strain sensor by Equation (4.17)

$$\Delta\epsilon_{\min} = \frac{1}{A} \Delta\lambda_{\min} \quad (4.22)$$

where $\Delta\lambda_{\min}$ is the minimum detectable wavelength.

4.4.3 Experiment and Discussions

Figure 4.7: The transmission spectrum of the LPG with periodicity of 280 μ m and length of 16mm.

The LPG was fabricated using the amplitude mask technique on a section of H₂-loaded SMF-28 fiber. It was manufactured by using a UV laser with an amplitude mask of appropriate periodicity of 280 μ m in order that its resonant band was around 1510-1640nm (the detectable region of the tunable laser source). The growth of the

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LPG spectrum was monitored throughout the whole fabrication process by an optical spectrum analyzer (OSA Ando AQ6317) and a tunable laser source (Anritsu MG 9541A 1510-1640nm). During the fabrication, the power of the UV laser was carefully controlled so that the attenuation induced from LPG was kept small to guarantee there were enough output decay pulses to be coupled out and detected by the broadband photodetector. Its transmission spectrum is illustrated in Figure 4.7.

From Figure 4.7, the largest transmission loss in this resonant band of the LPG was around -0.77dB while its resonant wavelength located around 1625nm. A large value of $d\alpha/d\lambda$ was observed in the broad region from 1600nm to 1618nm on the left slope of LPG transmission spectrum and this sharp slope could be used as the operating region for high sensitive strain measurement from Equation (4.19).

For this reason, when this LPG was inserted into the CRD fiber loop, the wavelength of the input light pulse was set to be 1600nm. The length of the fiber loop was estimated around 1km and the light propagated at 2.08×10^8 m/s in the fiber (the values is usually calculated by the light speed c in vacuum over the refractive index n of fiber core, typically, $c=2.99 \times 10^8$ m/s and $n=1.44$ respectively), so the corresponding trip time was about 4.8 μ s. To avoid the pulses overlapping with each other to cause distortions, each input pulse from the laser source must decay completely before the next input pulse to couple in, so the modulating pulse period and the width were set to be 400 μ s and 1 μ s respectively. The gain of photodetector was 10dB. Without any strain applied on the LPG, a series of periodic output pulse trains coupled out of the CRD loop were detected by the photodetector and displayed in an oscilloscope. The decay curve from one cavity ring-down decay is illustrated in Figure 4.8(a).

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(a)

(b)

Figure 4.8(a): Cavity ring-down result with an unstrained LPG. (b): $t - \ln(I(t)/I_0)$ and fitted cavity ring-down curves.

From the graph, the output pulses decay with time as expected. The trip time was read to be $4.667\mu\text{s}$, so the actual loop length was 972m. Around 30 output pulses could be observed under the minimum detections of the photodetector and the

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oscilloscope. To obtain the decay time, the peak output voltages of the pulses are fitted with the convenient linear expression

$$\ln(I(t)/I_0) = -t/\tau \quad (4.23)$$

By using this formula, the exponential decay curve from the experiment was logarithmized and fitted by a linear equation and the fitting result is shown in Figure 4.8(b). The ring-down time, obtained from the inverse slope of the curve, is 29.707 μ s. The total loss of the CRD loop is 0.742dB by Equation (4.14), including two couplers' insertion loss (about 0.04dB each), the LPG attenuation (0.231dB at 1600nm), splice loss and fiber transmission loss.

Figure 4.9: CRD strain response.

During strain process, one end of the LPG was fixed on Translation Stage 1, while the other end was strained by tuning the micrometer on Translation Stage 2. The original distance between two translation stages was set to be 4cm. Translation Stage 2 was tuned step by step at a stepwise fashion of 10 μ m and a total distance up to 120 μ m was moved. From the readings taken from the oscilloscope, with the strain,

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both the amplitude and the number of the output pulses from the CRD loop decreased. Those meant that the attenuation of the LPG increased and thus the resonant wavelength had a blue shift via the LPG transmission spectrum of Figure 4.7. The corresponding decay times were recorded at different strain levels and the relationship is indicated in Figure 4.9.

From Figure 4.9, the ring-down time presents a good linear response to the change of the strain. This linear response is due to the LPG strain feature (linear response $d\lambda/d\varepsilon$) [114] and also the linear relationship between the total loss and wavelength in the detecting region (from 1600nm to 1618 nm by Figure 4.7). Compared with the biconical tapered CRD strain gauge [86], which had a nonlinear strain decay time to strain response, the LPG CRD sensor with a linear response is quite superior to biconical taper to be applied in the strain sensing applications.

The sensitivity of the sensor, defined as $d\tau/d\varepsilon$, is 1.261ns/ $\mu\varepsilon$. The minimum detectable decay time, which is defined as twice of the standard error over 10 ring-down decay periods, is mainly due to the wavelength instability of the laser source, the temperature sensitivity of the LPG and even the minimum detection of the detectors. The temperature sensitivity of the LPG is related to the period, the material and the order of cladding mode. Designed with appropriate specifications, the embedded LPG with a highly wavelength-stable laser source and high-resolution detection system will dramatically reduce the minimum detectable decay time $\Delta\tau_{\min}$. In our experiment, $\Delta\tau_{\min}$ is equal to 0.04%, corresponding to 0.011 μ s approximately. Then by Equation (4.21), the corresponding minimum detectable strain $\Delta\varepsilon_{\min}$ is around 9 $\mu\varepsilon$. By using Equations (4.17)-(4.19), this sensitivity corresponds to the

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change of the wavelength shift per unit strain $d\lambda/d\varepsilon$ of around $2\text{pm}/\mu\varepsilon$. So in a direct LPG strain sensing system [114], assuming the minimum detectable wavelength $\Delta\lambda_{\min}$, resulting from those limitation brought by resolution of the laser source and a fairly good OSA, is around 0.06nm , it corresponds to a minimum detectable strain of $30\mu\varepsilon$, 4 times larger than that in LPG CRD fiber loop. Furthermore, in the CRD configuration, expensive wavelength interrogation system such as OSA does not need to be used. A less-costing detecting system e.g. the photodetector and oscilloscope can be employed instead. Therefore, this LPG CRD strain sensing system indicates a promising potential for high-resolution strain sensors.

4.5 Conclusion

In this chapter, CRD spectroscopic techniques in bulk optics and fiber optics are studied. The principle of CRD spectroscopy is addressed, and its superiority over the conventional direct absorption spectroscopy is presented. Then we focus on the passive CRD spectroscopy for optical fiber sensors, which is without the gain compensation provided by the amplifier in the fiber cavity. After that, the passive CRD spectroscopy for application in strain sensing is proposed. A long period grating CRD strain sensor in a fiber loop is set up. The decay time, the sensitivity and minimum detectable strain of this sensing built-up are investigated. The experimental results indicate that the LPG CRD sensor displays a good linear response in a strain region from 0 to $3000\mu\varepsilon$ at the wavelength of 1600nm . Meanwhile, by using this sensing scheme, a sensitivity of $1.261\text{ns}/\mu\varepsilon$ and a minimum detectable strain of $9\mu\varepsilon$ are obtained. This type of sensor demonstrates a high sensitivity and develops a technical feasibility of a new generation of fiber sensors for strain measurement.

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However, without gain compensation, the application of the passive fiber CRD loop is restricted for chemical sensing. In this following chapter, the alternative CRD fiber loop, CRD amplified fiber loop will be studied for trace gas detection.

Chapter 5

Active Cavity Ring-down Spectroscopy

5.1 Introduction

In the previous chapter, passive cavity ring-down (CRD) fiber loop is investigated. In this chapter, the alternative CRD fiber loop, active CRD fiber loop is studied comprehensively. The significant difference of the active and passive CRD is that a gain is provided in the active CRD. Thanks to this merit, relative large absorption loss of the target gas could be compensated by the gain offered by the optical amplifier and it provides a solution to apply CRD fiber loop for chemical sensing system. Some works have been done to apply active CRD technique in the optical fiber chemical sensing system [78, 108]. In this scheme, an erbium doped fiber amplifier (EDFA) was used to compensate the insertion losses from some optical devices such as couplers, band-pass filters etc., and also the absorption losses from the chemical molecules. Although the system effectively employed the benefits of the optical fibers, an unwanted amplified spontaneous emission (ASE) noise from the EDFA was induced. In that case, the contaminated gain from the EDFA would be unstable and thus greatly influence the sensitivity of the system. Gain clamp compensation was considered to be applied [116, 117] to stabilize the gain of the EDFA, but the experimental results were still unsatisfactory and the complexity of the setup was enhanced.

In this chapter, the mathematical model of the active CRD fiber loop for trace gas detection is introduced. This model will help us to understand how the active

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CRD spectroscopy operates for fiber chemical sensing system and how the noises in the CRD fiber loop are formed. In order to enhance the measurement accuracy of the sensing system, digital signal processing (DSP) technique is also employed to reduce the detection error which is due to the ASE noise. Aiming at the properties of the ASE noise, a digital least mean square (LMS) adaptive filter is chosen to be used in this CRD gas sensing system. The principle of CRD is described in Section 5.2, the modeling and the simulation results are presented in Section 5.3, the experimental results are shown in Section 5.4 and finally the conclusion is given in Section 5.5.

5.2 Principle of Active Fiber CRD Spectroscopy

Figure 5.1: Active fiber CRD spectroscopic scheme.

The active fiber CRD spectroscopic scheme, as shown in Figure 5.1, is quite similar to the passive fiber CRD spectroscopic scheme shown in Figure 4.3. For trace gas detection, a gas sample is inserted into the cavity, which will induce a relative large total loss to the fiber loop. To add the gain of G to the fiber cavity, an erbium doped fiber amplifier (EDFA), which is a commonly used optical amplifier in fiber optics, is inserted into the fiber cavity [118]. A tunable band-pass-filter, whose central wavelength tuned to identical with the input pulse wavelength, is embedded after the EDFA to restrict the EDFA gain in the exact input wavelength. Additionally, it will

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suppress the unwanted amplified spontaneous emission (ASE) power from the EDFA (The influence of the ASE effect will be discussed in the next section). A variable attenuator is inserted to the cavity as well to adjust the total loss β (which includes fiber loss, component insertion loss, attenuation loss of the attenuator and absorption loss of the gas) so that the net loss α for each loop which is defined as

$$\alpha = \beta G - 1 \quad (5.1)$$

could be kept in minimum and/or at an optimum condition. The net loss deals with the trip time and ring-down time, as same as Equation (4.14). The only difference is in active CRD case, α stands for the net loss in the fiber cavity, and this loss is equal to the total loss after compensation by the gain; while in passive CRD scheme, the total loss is small enough and no gain is provided, so α stands for the total loss without gain compensation. The ring-down formula for active CRD, whereas, keeps the exact format as in passive one as shown in Equation (4.8), so Equation (4.8) is the general formula for CRD spectroscopy.

5.3 Modeling of Active Fiber CRD for Chemical Sensing

In last section, the active fiber CRD scheme is introduced. In this scheme (Figure 5.1), an EDFA is applied to provide the gain to compensate the total loss in the fiber cavity. Although the benefits of the EDFA are efficiently employed and a small loss is obtained by this way, an ASE noise from the EDFA is induced. ASE noise is a kind of amplified noise due to the spontaneous emission of the erbium ions [119-121]. The EDFA possesses a broad gain profile in the fiber transmission window, markedly from 1520-1580nm as shown in Figure 5.2. When the input signal at a specific wavelength rings around in the fiber cavity, only the signal at this wavelength is

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expected to be amplified; in practice, however, the background signals at other wavelengths which are considered as noises are also amplified by the EDFA. In that case, the gain provided by the EDFA for each round trip will be unstable and the net loss for each round trip is not a constant any more. The accumulated output powers (including ideal and noisy signals) will be detected by the detector and then the obtained CRD curve, as shown in Figure 5.3, will not be in a perfect first-order exponential format as shown in Figure 4.2, and definitely will not follow the CRD general Equation (4.8). If the ring-down time is still obtained by Equation (4.8), it will have a deviation with the ideal ring-down time, so the measurement error is caused. In this section, the modeling of active fiber CRD loop is carried out to account for the gain contamination of the ASE noise. In the later part, a least mean square digital filter is proposed for improving the contaminated signal. In the following Section 5.4, this CRD scheme is realized experimentally and the results will be compared with that by the simulated model.

Figure 5.2: ASE distribution of an EDFA.

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Figure 5.3: The contaminated CRD curve.

5.3.1 Modeling Buildup

Figure 5.4: Schematic diagram of cavity ring-down chemical sensing fiber amplified loop

The mathematical model of the fiber amplified CRD loop for the chemical

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measurement follows the CRD schematic diagram of Figure 5.4. A CW laser source is current modulated via a signal generator to produce a train of optical pulses. For each ring-down process, an input light pulse from the pulse train is coupled into the loop via a standard 50:50 optical fiber coupler, and then passes through a gas cell and an optical attenuator. Afterwards, it passes an EDFA with gain of G and a tunable narrow band-pass filter; after a trip time of T , finally it is coupled out by another 50:50 fiber coupler such that the remaining half of the light power of the pulse is kept inside the fiber loop for this repeatable process. The output pulse, which is coupled out from each round trip, is detected by a broadband photodetector. The pump monitor is applied to control the amplitude of gain of the EDFA. The rest of the pulse will continue to propagate around the ring-down trip until the power of the output pulse decays under the minimum detectable power of the photodetector.

When the spectral line-width of the laser is narrow enough to be neglected comparing with the gas spectral linewidth [111], the electric field of the pulse train from the modulated laser light is defined as

$$E(t) = \begin{cases} E_0 \exp(i\omega_s t), & t_0 < t \leq t_0 + T_0 \\ 0, & t_0 + T_0 < t \leq t_0 + T_p \end{cases} \quad t_0 = (k-1)T_p, \quad k = 1, 2, \dots \quad (5.2)$$

where E_0 is the amplitude of the electric field of the input light pulse, ω_s is the angular frequency of the input light, T_0 and T_p are the pulse width and period respectively. In this model, T_p must be much longer than the trip time T to guarantee that only one input pulse is kept inside the fiber loop in the whole ring-down process. In the meantime, the trip time T must be longer than T_0 in order to evade the ring-down pulse to overlap with itself and thus induce pulse distortions. Then the corresponding intensity of the pulse train should be

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$$I(t) = \begin{cases} \frac{1}{2} E(t) E^*(t) = \frac{1}{2} E_0^2 = I_0, & t_0 < t \leq t_0 + T_0 \\ 0 & , t_0 + T_0 < t \leq t_0 + T_p \end{cases} \quad (5.3)$$

The symbol ‘*’ represents conjugate. Due to the periodical repeatability of the input pulses from the laser source, let us consider only one period of pulse in the following analysis, i.e. the k -th pulse from the pulse train that enters into the CRD loop at the time of $t_0 = (k-1)T_p$. The initial electric field of this single input pulse before ringing in the cavity ring-down loop or called the input pulse of the first loop is defined as $E_{in}(t=t_0)$ or $E_{in,0}^k$, and

$$E_{in,0}^k = E_0 \exp(i\omega_s t_0) \quad (5.4)$$

So the corresponding initial intensity is $I_{in,0}^k = E_0^2/2 = I_0$. Considering the gain and the total loss of G and β respectively per loop, the light intensity of the decayed output pulse after one loop will be

$$I_s(t_0 + T) = \frac{1}{2} (\beta G)^{1/2} E_{in}(t_0 + T) \cdot (\beta G)^{1/2} E_{in}^*(t_0 + T) = \frac{1}{2} \beta G E_0^2 = \beta G I_{in}(t_0 + T) = \beta G I_0 \quad (5.5)$$

or simplified as

$$I_{s,1}^k = \frac{1}{2} (\beta G)^{1/2} E_{in,1}^k \cdot (\beta G)^{1/2} E_{in,1}^{k*} = \frac{1}{2} \beta G E_0^2 = \beta G I_{in,1}^k = \beta G I_0 \quad (5.6)$$

Here a set of symbols is defined, for any function $\Psi(t)$, $\Psi(t_0 + iT) = \Psi_i^k$ $i=0, 1, 2, \dots$

From Equation (5.6), the ideal output pulse intensity after first loop should be a constant only related with input pulse intensity. However, there is an unavoidable ASE noise induced by the EDFA of this CRD loop. The corresponding electric field

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of the noise is denoted as $\tilde{E}_n^k(t)$. The sign ‘ $\sim$ ’ denotes as a random variable. Then after the first loop, the total intensity of the output pulse with the ASE noise is [122]

$$\begin{aligned}\tilde{I}_{out,1}^k &= \frac{1}{2} \left((\beta G)^{1/2} E_{in,1}^k + \tilde{E}_{n,1}^k \right) \left((\beta G)^{1/2} E_{in,1}^k + \tilde{E}_{n,1}^k \right)^* \\ &= \frac{1}{2} \left(\beta G E_0^2 + \tilde{E}_{n,1}^k \tilde{E}_{n,1}^{k*} + (\beta G)^{1/2} E_{in,1}^k \tilde{E}_{n,1}^{k*} + (\beta G)^{1/2} E_{in,1}^{k*} \tilde{E}_{n,1}^k \right)\end{aligned}\quad (5.7)$$

Notice here subscript “out” is used to distinguish the output pulse intensity with the intensity of the pulse ringing in the loop. In the conventional CRD formula Equation (4.8), $I(t)$ represent the output pulse intensity; but for our dynamic modeling, $I_{out}(t)$ is the output pulse intensity while $I(t)$ is the pulse intensity inside the fiber loop before ringing out. The first term of the right hand side in Equation (5.7) is coincident with $I_{s,1}$ described in Equation (5.6), which is the ideal light intensity of the output pulse of the first loop. The second term is the term due to the ASE noise, and it is usually depicted by average intensity which is given by [123-125]

$$I_{ASE-ASE}^k = \left\langle \frac{1}{2} \tilde{E}_{n,1}^k \tilde{E}_{n,1}^{k*} \right\rangle = 2n_{sp} \beta \hbar \nu (G-1) \Delta \nu_{ASE} = I_{ASE-ASE} \quad (5.8)$$

where ν is the optical frequency of the input light pulse, $\Delta \nu_{ASE}$ is the band-width of the ASE noise, n_{sp} is the population inversion factor, which is defined as $n_{u2} / (n_{u2} - n_{l1})$, where n_{l1} and n_{u2} are erbium ion populations of the lower energy level 1 and upper level 2 respectively [126].

For the third term and fourth term of the right hand side of Equation (5.7), they are the interferences between the signal and the ASE noise, and

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$$\begin{aligned}
 I_{s-ASE,1}^k &= \frac{1}{2} \left\langle (\beta G)^{1/2} E_{in,1}^k \tilde{E}_{n,1}^{k*} \right\rangle + \frac{1}{2} \left\langle (\beta G)^{1/2} E_{in,1}^{k*} \tilde{E}_{n,1}^k \right\rangle \\
 &= \left\langle (\beta G)^{1/2} E_{in,1}^k \tilde{E}_{n,1}^{k*} \right\rangle \\
 &= \left\langle (\beta G)^{1/2} E_{in,1}^k \tilde{E}_{n,1}^{k*} \cdot (\beta G)^{1/2} E_{in,1}^{k*} \tilde{E}_{n,1}^k \right\rangle^{1/2} \\
 &= \left\langle (\beta G) E_{in,1}^k E_{in,1}^{k*} \cdot \tilde{E}_{n,1}^{k*} \tilde{E}_{n,1}^k \right\rangle^{1/2} \\
 &= 2 \left(I_{s,1}^k I_{ASE-ASE} \right)^{1/2}
 \end{aligned} \tag{5.9}$$

As a result, under those influences of this ASE noise, in the first loop, the total variance of $\tilde{I}_{out,1}^k$ from $I_{s,1}^k$ is

$$\left(\sigma_{F,1}^k \right)^2 = \sigma_{ASE-ASF}^2 + \left(\sigma_{s-ASE,1}^k \right)^2 = I_{ASE-ASE}^2 + 4 I_{ASE-ASE} I_{s,1}^k \tag{5.10}$$

The frequency distribution of ASE noise is considered as a sort of Gaussian white [122], with the pattern of

$$f_{F,1}^k(\nu) = \frac{1}{\sqrt{2\pi}(\sigma_{F,1}^k)^2} \exp \left[\left(-\frac{1}{2} \right) \left(\frac{\nu}{\sigma_{F,1}^k} \right)^2 \right] \tag{5.11}$$

By using an inverse Fourier transform, the corresponding function $\tilde{F}_1^k(t)$ in the time domain can be obtained. Eventually, $\tilde{I}_{out,1}^k$ can be expressed by

$$\tilde{I}_{out,1}^k = \beta G I_0 + \tilde{F}_1^k \tag{5.12}$$

From this above equation, the net loop loss is defined as

$$\tilde{\alpha}_1^k = \frac{\tilde{I}_{out,1}^k - I_0}{I_0} = \beta G - 1 + \tilde{F}_1^k / I_0 \tag{5.13}$$

Due to the ring-down condition, the pulse intensity $\tilde{I}_{m,m+1}^k$ in the beginning of the $(m+1)$ -th loop is equal to the pulse intensity in the end of the m -th loop $\tilde{I}_{out,m}^k$ ($m = 0, 1 \dots M$). M is determined by the sensitivity of the photodetector. So, referring to the first loop, the model of the $(m+1)$ -th CRD loop has formats below:

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$$\begin{aligned}
 \tilde{I}_{in,m+1}^k &= \tilde{I}_{out,m}^k \\
 \tilde{I}_{s,m+1}^k &= \beta G \tilde{I}_{in,m+1}^k \\
 (\sigma_{F,m+1}^k)^2 &= I_{ASE-ASE}^2 + 4I_{ASE-ASE} I_{s,m+1}^k \\
 f_{F,m+1}^k(\nu) &= \frac{1}{\sqrt{2\pi(\sigma_{F,m+1}^k)^2}} \exp\left[\left(-\frac{1}{2}\right)\left(\frac{\nu}{\sigma_{F,m+1}^k}\right)^2\right] \\
 \tilde{F}_{m+1}^k(t) &= f_{m+1}^{-1k}(\nu) \\
 \tilde{I}_{out,m+1}^k &= \beta G \tilde{I}_{in,m+1}^k + \tilde{F}_{m+1}^k \\
 \tilde{\alpha}_{m+1}^k &= \frac{\tilde{I}_{out,m+1}^k - \tilde{I}_{in,m+1}^k}{\tilde{I}_{in,m+1}^k} = \beta G - 1 + \tilde{F}_{m+1}^k / \tilde{I}_{in,m+1}^k
 \end{aligned} \tag{5.14}$$

So the output pulse signal could be considered as a sequence of discrete-time signal $\{Y_m^k\}$ at regular interval of T . With the relationship of the net loss $\tilde{\alpha}_{m+1}^k$ and the output pulse intensity $\tilde{I}_{out,m+1}^k$ at the $(m+1)$ -th loop from the above bunch of Equations (5.14), the fiber CRD model is further described to a general format:

$$\tilde{\alpha}_{m+1}^k = \frac{\tilde{I}_{out,m+1}^k}{\tilde{I}_{out,m}^k} - 1 = \beta G - 1 + \tilde{F}_{m+1}^k / \tilde{I}_{out,m}^k \tag{5.15}$$

After m -th loop ($m=0, 1, 2 \dots M$), by integrating both side of Equation (5.15), the output pulse intensity is

$$\sum_{i=0}^m \left(\frac{\tilde{I}_{out,i+1}^k}{\tilde{I}_{out,i}^k} - 1 \right) = \sum_{i=0}^m (\beta G - 1) + \sum_{i=0}^m \left(\frac{\tilde{F}_{i+1}^k}{\tilde{I}_{out,i}^k} \right) \tag{5.16}$$

When the net loss is small, $\tilde{\alpha}_{i+1}^k = \left| \tilde{I}_{out,i+1}^k / \tilde{I}_{out,i}^k - 1 \right| \ll 1$,

$$\tilde{I}_{out,i+1}^k / \tilde{I}_{out,i}^k - 1 \approx \ln \left(\tilde{I}_{out,i+1}^k / \tilde{I}_{out,i}^k \right) \tag{5.17}$$

Substituting Equation (5.17) into the left hand side of Equation (5.16), finally,

$$\ln(\tilde{I}_{out,m}^k / I_0) = -mT / \tau_0 + mT / \tilde{\delta}^k = -mT / \tilde{\tau}^k \tag{5.18}$$

where

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$$\begin{aligned}\tau_0 &= T / (1 - \beta G) \\ \tilde{\delta}^k &= mT / \sum_{i=0}^m (\tilde{F}_i^k / \tilde{I}_{out,i}^k) \\ \tilde{\tau}^k &= \tau_0 \tilde{\delta}^k / (\tilde{\delta}^k - \tau_0)\end{aligned}\tag{5.19}$$

For convenience, let $\tilde{y}_m^k = \ln(\tilde{I}_{out,m}^k / I_0)$ in the following analysis.

For one input optical pulse from the laser source, e.g. the k -th input pulse, the consequent sequences of the output pulses $\{\tilde{y}_m^k\}$, $m=1, 2, \dots, M$, could be recorded by the oscilloscope as shown in Figure 5.4.

From the above equations, it clearly demonstrates that, due to the influence of ASE noise, when the CRD process is repeated, the decay time is no longer a constant. The corresponding net loss turns into a variable too. When τ_0 and α_0 denote the ideal decay time and net loss respectively, the difference of $\tilde{\tau}$ with τ_0 has a linear relationship with the variance of the net loss through Equation (4.14)

$$\begin{aligned}\frac{\Delta \tilde{\tau}}{\tau_0} &= \frac{\Delta \tilde{\alpha}}{\alpha_0}, \quad \alpha_0 = \beta G - 1, \\ \Delta \tilde{\alpha} &= \tilde{\alpha} - \alpha_0, \quad \Delta \tilde{\tau} = \tilde{\tau} - \tau_0\end{aligned}\tag{5.20}$$

This change of the net loss, on the other hand, could be described in the gas concentration C by Beer-Lambert's law (refer to Equation (3.1))

$$\Delta \tilde{\alpha} = \kappa(\nu) l \Delta \tilde{C}\tag{5.21}$$

Thus, the error in term of gas concentration has such a relationship as below:

$$\Delta \tilde{C} = \frac{\alpha_0}{\kappa(\nu) l} \cdot \frac{\Delta \tilde{\tau}}{\tau_0}\tag{5.22}$$

5.3.2 Theoretical Analysis and Principle of LMS Filter

To reduce the ASE noise effect, the gain clamp compensation was considered to be

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applied to stabilize the gain of the EDFA, but the experimental results were still unsatisfactory and the complexity of the setup was enhanced [78]. Digital filter is considered to be applied for this sensing scheme. Due to the ASE noise's nature, the spectra of the CRD signal and the ASE noise distribute over the same frequency region and cannot be distinguished by the conventional digital frequency-selective filters such as low-pass or band-pass sort. The adaptive filter which is a type of digital filter with self-adjusting characteristics is considered to apply in this system. The principle of digital adaptive filter is illustrated in Figure 5.5.

Figure 5.5: Block diagram of a least mean square (LMS) adaptive filter.

A group of optical output pulses $[y_1^k, y_2^k, \dots, y_m^k, \dots, y_M^k]$ from the k -th ($k=1, 2, \dots, K$) input pulse of the laser source enters into the filter simultaneously. The loop number of m in the CRD model does mean the sampling number. This contaminated input signal sequence y_m^k includes both desired signals s_m^k and noises n_m^k , and s_m^k are expected to be obtained by subtracting n_m^k from y_m^k after a proper type of filter. n_m^k are given by

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$$n_m^k = \sum_{i=0}^{N-1} w_m^k(i) x_{m-i}^k, \quad N < M \quad (5.23)$$

where N is the filter length, x_m^k are the input noise components of the filter and $w_m^k(i)$, $i=0,1,\dots, N-1$ are the filter coefficients (or weights), which can be evaluated by several filter algorithms. The common algorithms for the adaptive filter have been found widespread applications such as the least mean square (LMS), the recursive least squares (RLS), and Kalman filter algorithms. In terms of computation and storage requirements, the LMS algorithm is the most efficient compared with others. Furthermore, it does not suffer from the numerical instability problem inherent in the other two algorithms [94]. The LMS is based on the steepest descent algorithm where the weights are updated from sample to sample as follows:

$$\begin{aligned} w_{m+1}^k &= w_m^k + 2\mu s_m^k x_{m-i}^k \\ s_m^k &= y_m^k - n_m^k \end{aligned} \quad (5.24)$$

where μ controls the stability and rate of convergence and s_m^k are the filtered output signal. By using this algorithm, the weights improve gradually as the filter learns the characteristics of the signals. Eventually, the weights converge with m and the error of the desired signal is minimized.

5.3.3 Simulation Results

The simulation is based on the schematic diagram as shown in Figure 5.4. The detected gas is assumed to be acetylene (C_2H_2), which is an important industrial product used in the chemical synthesis. Inhaling acetylene may cause dizziness, headache and nausea and mixtures with air containing between 3% and 82% acetylene are explosive on ignition. Its absorption spectrum in near infrared region locates from 1510-1540nm, with the strong absorption line in 1530.30nm. So gain the

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maximum sensitivity, the input wavelength of the laser pulse is set exactly at this absorption line, with a power of 1mW.

The amplitude of ASE noise can be estimated through Equations (5.8) and (5.9). The broad band-width of ASE noise $\Delta\nu_{ASE}$ ($\sim 40\text{nm}$) is decreased to $\Delta\nu_F = 0.5\text{nm}$ by the use of the narrow band-pass filter after the EDFA ($\Delta\nu_F$ is the bandwidth of the filter, as illustrated in Figure 5.2), which could not be omitted comparing with typical values of gas spectral linewidth which are below 0.1nm from HITRAN database [105]. the population inversion factor [119] n_{sp} is typically 3 and Planck constant h is equal to $6.626076 \times 10^{-34}\text{J}\cdot\text{s}$, the amplitude of ASE noise can be achieved to 0.02dB. For comparison, the simulation is to simulate Stewart's work [78]. So the other parameters, such as the total loop length ($L=58\text{m}$) and the ideal net loss α_0 of -0.48dB are all based on the experimental results in Ref.[78].

From those assumptions, the trip time T of 290ns and ideal decay time of $2.7715\mu\text{s}$ by Equation (4.14) are obtained. The ideal output intensity with time is detected by setting ASE amplitude as zero. The detection of the output pulses will be terminated when the light intensity of the output pulse is below the sensitivity of the photo-detector whose value is normally around 10^{-3} mW . The simulation result is shown in Figure 5.6. The peak intensity values of the output pulses are fitted with the convenient linear expression of

$$\ln(I_{out}(t)/I_0) = -t/\tau, \quad t = mT, \quad m = 0, 1, \dots, M \quad (5.25)$$

By using this formula, the ring-down time is obtained from the inverse slope of the curve. The ideal decay time is found identical with the above theoretical result of τ_0 , which verifies that the CRD model is reliable.

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(a)

(b)

Figure 5.6 (a): $t - \ln(I_{out}(t)/I_0)$ curves of ideal vs. noisy signal and (b): $t - \ln(I_{out}(t)/I_0)$ curves of unfiltered and filtered results. The sampling time is identical with the trip time, equal to 290ns.

After that, the noisy intensity of the output pulse versus time in the cavity ring-down fiber loop is investigated. The ASE amplitude switches to 0.02dB while all the other parameters of the CRD loop are the same as mentioned before. The

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contaminated decay curve is indicated in Figure 5.6(a). It illustrates that, the contaminated curve retains the curve shape because the ASE noise is relative small compared to the net loss; however, due to the existence of the noise, the contaminated signal fluctuates and deviates from the ideal signal more and more severely with time. This is because the m -th pulse rings around the cavity for m times and thus this pulse will be contaminated, i.e. $(m - 1)$ times more than the first output pulse.

Through the linear curve fitting by Equation (5.25), $\tau' = 2.7103\mu\text{s}$ for the noisy signal is obtained. In this case, when absorption coefficient of the C_2H_2 gas κ is 0.2cm^{-1} [78] and the length of the gas cell in the experiment l is 5cm, the error $\Delta C'$ of the contaminated signal is about $2.31 \times 10^3 \text{ppm}$ by Equation (5.22), and this is close to the experimental result from Ref [78].

Table 5.1: The specifications of the designed filter.

Sampling rate $1/T$	1/290ns	Filter length N	13
Convergence factor μ	4×10^{-7}		
Weight	$[w(0), w(1), w(2), \dots, w(12)]$		
Final weights w (10^{-3})	[-1.5143, -2.6498, -3.7853, -4.9209, -6.0567, -7.1926, -8.3287, -9.4650, -10.6020, -11.7390, -12.8760, -14.0130, -15.1510]		

An LMS adaptive filter is designed to remove the noise from the noisy signal shown in Figure 5.6(a). By LMS algorithm, the characteristics of the signals (here is the linear slope or say the decay rate of the CRD system) are recognized and the final weights vector is obtained while the error of the desired signal is minimized. The values of the sampling rate, filter length N and the other parameters i.e., convergence factor μ and the final weights of the designed filter are given in Table 5.1. After filtering, the filtered signal in Figure 5.6(b) is apparently smoother and the filtered

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decay time is closer to the ideal one than that of the noisy signal. The decay time τ'' becomes 2.7637 μ s after filtering, corresponding to the error $\Delta C''$ of 294ppm, 9dB smaller than the unfiltered signal.

Due to the random nature of the ASE noise, the decay time obtained is varied with different input pulses. As a result, the RMS value is adopted in the following analysis, while the ideal decay time, however, is kept invariable. When 10 input pulses from the laser source pass the CRD loop, the ten sequences of the output pulses enter to the well-designed filter. The RMS values of decay time before and after filtering are evaluated, 2.7423 μ s and 2.7690 μ s respectively, and the corresponding RMS errors in term of concentration are 1102ppm and 92ppm. The error after filtering reduces 11dB compared with that before filtering and that proves the ability of the designed filter to reduce the ASE noise and increases the sensitivity of the CRD fiber loop system effectively.

Figure 5.7: RMS detection error before and after filtering (log scale) vs. the net loss and the ASE noise amplitude.

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From Equations (5.20)-(5.22), it is quite apparent that only the amplitudes of the net loss and ASE noise determine the measurement accuracy when the detected sample is fixed. So, with the aforementioned designed filter, the RMS errors before and after filtering are detected by altering the net loss α and the amplitude of ASE noise $\Delta\alpha$). The investigation results among the net loss, the ASE amplitude, and the RMS error before and after filtering are illustrated in Figure 5.7. Through the unfiltered and filtered errors, the error ratio (which is defined as the ratio of unfiltered to filtered errors in decibels) is relatively stable with the minimum value of 6 when α and $\Delta\alpha$ are -0.1dB and 0.04dB and the maximum of 14 while α and $\Delta\alpha$ are -0.5dB and 0.03dB respectively, which demonstrates that the designed filter presents a good linear response. From Figure 5.7, it also shows that, the smaller either the net loss or the ASE noise amplitude, the smaller of the correspondent RMS error before and after filtering, i.e. the minimum detection error of 16ppm is achieved while the net loss is -0.10dB and the ASE amplitude is 0.01dB.

Physically, the larger the ASE amplitude $\Delta\alpha$, the more severe the signal is contaminated, and thus the larger of the error of $\Delta C'$ and $\Delta C''$. On the other hand, about the relationship of the error with net loss, because the pulse will ring down in the cavity longer with a small value of α , α has an inverse proportional relationship with the number of the ring-down loops m , while the input intensity and the minimum detection are fixed. The larger the number of the ring-down loops or called sampling number m , the better result it should be. Therefore, the detection errors of $\Delta C'$ and $\Delta C''$ are also proportional to α . So combining with the well-designed adaptive filter, the net loss and the ASE noise amplitude should also be kept as small

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as possible in the setup of the CRD fiber loop to obtain a high-accuracy chemical sensing system.

5.4 Experimental Active Fiber CRD for Chemical Sensing

Figure 5.8: Schematic diagram of cavity ring-down chemical sensing fiber amplified loop.

The experimental setup of the cavity ring-down fiber amplified loop for chemical sensing was based on the schematic diagram shown in Figure 5.8. The cavity was composed by two standard 2×2 50:50 optical fiber couplers (Coupler 1 and 2) and a long segment of fiber. The light from a tunable laser source (Anritsu MG 9541A, 1510-1640nm) entered into an acousto-modulator (Brimrose AMM55-8-1550) and was modulated via a signal generator (Agilent 33250A 80MHz) to produce a train of optical pulses. For each ring-down process, an input light pulse from the pulse train was coupled into the loop via one arm of Coupler 1, and then went through a NIST standard gas cell (Wavelength reference, C₂H₂-12-700) and an optical variable attenuator. Afterwards, it passed to an tunable gain EDFA (Opto-Link Corporation Limited, EDFA-MR) and a tunable fiber Bragg grating (FBG) filter with a central wavelength of 1529.98nm and a full-width half maximum (FWHM) of 0.1nm; after a trip time of T , finally it was coupled out by Coupler 2 such that the remaining half of

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the light power of the pulse was kept inside the fiber loop for this repeatable process. The output pulse, which was coupled out from each round trip, was detected by a broadband photodetector (Thorlabs PDA400 10MHz bandwidth). The detection of the output pulses would not be considered when the light intensity of the output pulse was below the minimum detection of the photo-detector whose value was around 10^{-3} mW.

The absorption gas spectrum of C_2H_2 was detected by using a tunable laser source (TLS, Ando AQ4321D) and an optical spectrum analyzer (OSA, Ando AQ6317) before the gas cell was connected to the cavity ring-down loop. The spectrum showed that the largest absorption line positioned at 1530.30nm, with an absorption loss of -9.716dB, identical with literature values. To achieve a high sensitivity (refer to Equation (5.22)), in the CRD setup, the input wavelength of the laser source and the central wavelength of the FBG filter were tuned to be identical to this strongest absorption line of the C_2H_2 gas [78, 127, 128]. The input power of the laser source was set to be 10mW, the maximum power that the laser source could achieve, to guarantee ample number of pulses would be obtained in each cavity ring-down process. The length of the fiber loop was around 1km, with a corresponding trip time of $5\mu s$. Because in the whole ring-down process, only one input pulse was allowed to be kept inside the fiber loop; and in the meantime, the trip time T must be longer than pulse width in order to evade the ring-down pulse to overlap and induce distortions, the pulse width and period were set to be $2\mu s$ and $500\mu s$ respectively. The pump current of the EDFA was increased to 151mA so that the gain of the EDFA was able to compensate the total loss in the CRD loop and the net loss in the loop would vary with the change of the attenuation by adjusting the variable attenuator. The ring-down curves with different attenuations of the attenuator are as shown in Figure 5.9.

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Figure 5.9: The cavity ring-down curves at different attenuator losses.

From the graph, the trip time is read to be $5.0663\mu\text{s}$. the ring-down times of each ring-down curve are computed by using Equation (4.14). The longest ring-down time of $101.1624\mu\text{s}$ is achieved when the attenuation is set to be 0dB, with a corresponding net loss of -0.218dB by the relationship of the ring-down time and the net loss from Equation (4.14). Comparing the ring-down curves at different attenuation losses, it is found that the smaller the attenuation loss is, the less shaper the ring-down curve becomes and the more pulses are obtained in each ring-down process, that means the less the net loss is in the ring-down loop. Afterwards, the linear relationship of the intensity ratio $\ln(I_{out}(t)/I_0)$ versus time is investigated. A ring-down curve when the attenuation of the variable attenuator is -0.80dB is shown in Figure 5.10(a). Again, based on Equation (4.14), a decay time of $21.7950\mu\text{s}$ is obtained and the net loss of -1.1481dB is correspondently computed. The graph also shows, due to the existence of the ASE noise in the cavity ring-down loop, the ring-

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down curve retains the linear curve shape; however, the signal fluctuates more and more severely with time.

(a)

(b)

Figure 5.10(a): The experimental $t - \ln(I_{out}(t)/I_0)$ curve of noisy signal vs. filtered signal. (b): The simulation $t - \ln(I_{out}(t)/I_0)$ curves of noisy vs. filtered signal.

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An LMS adaptive filter was designed to remove the noise from the noisy signal shown in Figure 5.10(a). The filter length N and the convergence factor μ were set to be 13 and 4×10^{-7} as shown in Table 5.1. After filtering, the filtered signal as indicated in Figure 5.10(a) was apparently smoother. The decay time τ became $23.150 \mu\text{s}$ after filtering, corresponding to the net loss of -1.072 dB .

To verify the reliability of the filter, a simulation was done by using CRD mathematical model. The parameters of the CRD modeling, e.g. the initial input power and the trip time were kept as same as the experiment. The net loss was set to be -1.07 dB to make the simulation curve most possibly close to the experimental result. The initial amplitude of the noise was set relating with the value of the initial intensity of the input pulse referring to the CRD mathematical model discussed in Section 5.3. Then the simulation output signal was filtered (the specifications of the filter were identical with those applied in the experimental signals) and the results before and after filtering are demonstrated in Figure 5.10(b). It illustrates that, the simulation results are quite identical with the experimental results, and the filtered signal is quite close to the ideal one, which demonstrates this type of filter could be used to remove the noise in the cavity ring-down curves.

As mentioned before, due to the random nature of the ASE noise, the obtained decay time varied at different ring-down processes. As a result, 10 ring-down processes were collected for each different net loss. Here, in each ring-down process, the contaminated ring-down curve was simulated based on the experimental results at different attenuations. The same filter was employed at both experimental and simulation ring-down results. For different attenuation losses, the measurement

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accuracies scaled by the RMS minimum measurement concentration of the contaminated signal before and after filtering are demonstrated in Figure 5.11.

Figure 5.11: measurement concentration before and after the filter vs. attenuator losses.

From Figure 5.11, both the experimental and simulation results show that the RMS minimum measurement concentration decays with the net loss in the ring-down loop, which is identical with the theoretical analysis in Section 5.3. The graph also demonstrates that, the RMS minimum measurement concentrations of the filtered results of both the experimental and simulation signals are definitely smaller than the original contaminated signal. For example, at the attenuation loss equal to -0.60dB, before filtering, the RMS minimum measurement concentrations of the experimental and simulation signals are 1018.10ppm and 986.32ppm respectively; after filtering, the minimum measurement concentrations decrease to 104.61ppm and 70.09ppm respectively, 8.2 and 14.5 times smaller than those before the filter. The filtered RMS minimum measurement concentration could achieve 14.78ppm when the attenuation loss is 0dB, with an approximate net loss of -0.22dB. Although before filtering, the minimum measurement concentrations of the simulation signal are quite close to

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those of the experimental signal; after filtering, the minimum measurement concentrations of the simulation signal are slightly smaller than the experimental signal. The difference may be due to the instability of the laser source during the experiment, and so other noises were induced excluding the main ASE noise from EDFA. Meanwhile, the decreased minimum measurement concentration values after filtering at different net losses also prove the reliability of the designed filter. Therefore, it indicates a promising potential to apply the LMS processing algorithm into high-resolution cavity ring-down chemical sensing systems for enhancing the measurement accuracy.

5.5 Conclusion

In this chapter, the active CRD fiber loop is investigated comprehensively. The mathematical model of the CRD fiber loop is initially developed. From this model, it is found that the amplified spontaneous emission (ASE) noise, induced by an erbium doped fiber amplifier (EDFA), is always a key problem for the measurement accuracy in a cavity ring-down (CRD) fiber amplified loop gas sensing system. By the analysis and simulations, it clearly demonstrates that the net loss, the output intensity, the decay time and thus the corresponding concentration will all be contaminated by the presence of this ASE noise. A digital least mean square (LMS) adaptive filter is proposed to reduce the ASE noise. The simulation results show by the well designed least mean square (LMS) adaptive filter, the detection error is reduced, e.g., the RMS detection error of 16ppm after filtering is achieved when the net loop loss is -0.10 ± 0.01 dB, and the error is reduced 14dB than that without filtering.

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After that, the experimental setup of the cavity ring-down (CRD) fiber loop is developed. The forgoing filter technique is applied to the experimental CRD curves. The experimental results before and after filtering at different net losses are compared and the RMS minimum measurement concentrations of the filtered results are apparently decreased compared with the unfiltered results. Simulation based on the CRD model is also executed and similar filtered results are obtained, which further proves that this designed filter could be applied to improve the accuracy of the CRD contaminated signals. Therefore, this proper digital signal processing technique shows a promising feasibility combining with the CRD sensing system to enhance the gas measurement accuracy.

Chapter 6

Cavity Ring-up Spectroscopy

6.1 Introduction

In Chapter 5, active CRD spectroscopy has been fully studied for trace gas detection. From the active CRD modeling, it is found possible error sources in the measurement of ring-down times originated partly from the ring-down time fluctuation by some fundamental noises, e.g. the amplified spontaneous emission (ASE) noise of the EDFA. Digital signal processing techniques is applied to denoise and retrieve the desired signals from the experimental results.

Another serious nuisance that might be encountered originated from the statistical uncertainty due to several technical reasons [129]. Because the net loss in the fiber loop could not be kept as low as that in the bulk optics [109] due to the relative low sensitivities of the fiber devices, the output signal dropped rapidly below the minimum detections of the photodetector and the oscilloscope. In that case, the number of the output pulses in fiber CRD will be much smaller than that in bulk optics [78]. This statistical uncertainty is hard to be distinguished by the conventional frequency-selective filters such as low-pass or band-pass sort. So the caused error is hardly removed and will reduce the measurement accuracy.

So in this chapter, a novel cavity ring-up (CRU) fiber gas sensing system is proposed based on the CRD fiber loop. In CRU, because the gain offered by the EDFA exceeds the total loss in the fiber loop, a net gain is induced in the fiber cavity and the light intensity grows with time and the corresponding ring-up time is

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measured. Therefore, this nuisance due to the relative large fraction loss in the fiber cavity and the resolution of the detector could be evaded. The principle of fiber CRU spectroscopy is described in Section 6.2, the CRU modeling and the simulation results are demonstrated in Section 6.3. The experiment and result of CRU is presented in Section 6.4 and the conclusion is given in Section 6.5.

6.2 Principle of Fiber CRU Spectroscopy

Fiber cavity ring-up (CRU) has the same experimental scheme as the active fiber CRD illustrated in Figure 5.1. Unlike CRD, in CRU spectroscopy, the gain of the EDFA exceeds the total loss in the fiber cavity and a net gain

$$\alpha_U = \beta G - 1 \quad (6.1)$$

is obtained.

In that case, the intensity of the output pulse increases after ringing around the fiber cavity. With the enhancement of the output intensity, however, the gain will decay due to the gain saturation. That is the distinct difference with the CRD scheme. In the CRD spectroscopy, because the output intensity decays with time, the rule of small signals is obeyed and the gain of the EDFA is estimated as a constant without the consideration of the ASE noise contamination. Therefore, the gain of the EDFA in the CRU loop needs to be redefined.

6.3 Modeling of Fiber CRU for Chemical Sensing

6.3.1 Modeling Buildup

The behavior of the EDFA is described on a basis of a two-level model previously reported by Sun *et al* [130]. Beams travel along the z direction between 0 and L_{EDF} ,

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which is the length of the EDF. The rate equation for the fraction of atoms in the excited state $N_2(z, t)$ at location z and time t is

$$\frac{dN_2(z, t)}{dt} = -\frac{N_2(z, t)}{\tau_s} - \frac{1}{\rho S} \sum_{i=1}^N u_i \frac{dP_i^\pm(z, t)}{dz} \quad (6.2)$$

where the forward and backward power for the n -th input signal $P_n^\pm(z, t)$ which is expressed by photon number is

$$\frac{dP_n^\pm(z, t)}{dz} = u_n [(\gamma_n + \alpha_n) N_2(z, t) - \alpha_n] P_n^\pm(z, t) \quad (6.3)$$

Here τ_s is the spontaneous life of the excited state, normally around 10ms, ρ is the erbium ion concentration, S is the cross-sectional area of the active fiber core, u_n is the unit vector along the propagation axis z of the active fiber ($u_n = \pm 1$ depending on the direction of the n -th optical input to the active fiber. The light travels from 0 to L_{EDF} , indicated by $u_n = +1$; while on the contrary, from L_{EDF} to 0, $u_n = -1$). γ_n and α_n are the emission and absorption coefficients respectively, represented by

$$\begin{aligned} \gamma_n &= \rho \Gamma_n \sigma_n^e \\ \alpha_n &= \rho \Gamma_n \sigma_n^a \end{aligned} \quad (6.4)$$

where Γ_n is the overlap integral, $\Gamma_n < 1$, and $\sigma_n^{e,a}$ are the emission and absorption cross-sections, respectively.

A saturation parameter is defined here

$$\varsigma = \frac{\rho S}{\tau_s} \quad (6.5)$$

Substitute Equation (6.5) into Equation (6.2) and integrate Equation (6.2) over z from 0 to L_{EDF} ,

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$$\begin{aligned} \left(\tau_s \frac{d}{dt} + 1 \right) \overline{N}_2(t) = & -\frac{1}{\zeta L_{EDF}} \sum_{i=1}^N [P_i^+(L_{EDF}, t) - P_i^+(0, t)] \\ & -\frac{1}{\zeta L_{EDF}} \sum_{i=1}^N [P_i^-(0, t) - P_i^-(L_{EDF}, t)] \end{aligned} \quad (6.6)$$

where $P_i^+(L_{EDF}, t)$ and $P_i^-(0, t)$ are output forward and backward optical powers, $P_i^+(0, t)$ and $P_i^-(L_{EDF}, t)$ are input forward and backward optical powers, $\overline{N}_2(t)$ is the length-averaged inversion level,

$$\overline{N}_2(t) = \frac{1}{L_{EDF}} \int_0^{L_{EDF}} N_2(z, t) dz \quad (6.7)$$

A length-averaged gain coefficient is defined as

$$\overline{g}_n(t) = \frac{1}{L_{EDF}} \ln \left[\frac{P_i^+(L_{EDF}, t)}{P_i^+(0, t)} \right] = \frac{1}{L_{EDF}} \ln \left[\frac{P_i^-(0, t)}{P_i^-(L_{EDF}, t)} \right] \quad (6.8)$$

The gain of the amplifier is $G = \overline{g}_n(t) L_{EDF}$. On the other hand, $\overline{g}_n(t)$ can be obtained by dividing Equation (6.3) by $P_n(z, t)$ and integrating over z ,

$$\overline{g}_n(t) = (\gamma_n + \alpha_n) \overline{N}_2(t) - \alpha_n \quad (6.9)$$

Substituting Equation (6.8) into the Equation (6.6),

$$\begin{aligned} \left(\tau_s \frac{d}{dt} + 1 \right) \overline{N}_2(t) = & -\frac{1}{\zeta L_{EDF}} \sum_{i=1}^N P_i^+(0, t) \left\{ \exp[\overline{g}_i(t) L_{EDF}] - 1 \right\} \\ & -\frac{1}{\zeta L_{EDF}} \sum_{i=1}^N P_i^-(L_{EDF}, t) \left\{ \exp[\overline{g}_i(t) L_{EDF}] - 1 \right\} \end{aligned} \quad (6.10)$$

If a single pulse inputs into the CRU loop with an initial peak amplitude of P_{s0} , the pump power of the EDFA is kept as P_{p0} , the peak amplitudes of output signal P_s and output pump power P_p will be

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$$\begin{aligned} P_{p,s}^+(L_{EDF}, t) &= P_{p,s}^+(0, t) \exp \left[\overline{g_{p,s}}(t) L_{EDF} \right] \\ P_{p,s}^-(0, t) &= P_{p,s}^-(L_{EDF}, t) \exp \left[\overline{g_{p,s}}(t) L_{EDF} \right] \end{aligned} \quad (6.11)$$

and

$$\begin{aligned} \rho S \left(\frac{d}{dt} + \frac{1}{\tau_0} \right) \overline{N_2}(t) &= P_{s,p}^+(0, t) \left\{ 1 - \exp \left[\overline{g_{s,p}}(t) L_{EDF} \right] \right\} \\ &+ P_{s,p}^-(L_{EDF}, t) \left\{ 1 - \exp \left[\overline{g_{s,p}}(t) L_{EDF} \right] \right\} \end{aligned} \quad (6.12)$$

with boundary conditions [131]

$$\begin{aligned} P_p^+(0, t) &= P_p^-(L_{EDF}, t) = P_{p0} \\ P_s^+(0, 0) &= P_{s0} \\ P_s^+(0, t) &= R' R P_s^+(L_{EDF}, t) \\ P_{ASE}^+(L_{EDF}, t) &< \delta \end{aligned} \quad (6.13)$$

where R' is the coupling loss of the output coupler (Coupler 2 in Figure 5.1), coupling loss of the output coupler R is the transmission factor describing the loss from the input port of coupler 1 to the beginning length ($z = 0$) of the EDF. In the setup of the CRU scheme in Figure 5.1, R is equal to the total loss excluding the coupling loss of Coupler 2, $RR' = \beta$. The ASE power $P_{ASE}^+(L_{EDF}, t)$ is kept below δ in simulation corresponding that in practice, 99% of the ASE power could be blocked by a narrow band-pass filter.

An iterative solution of the propagation-rate equations is implemented based on a Runge-Kutta iterative procedure. Finally, the peak amplitude of optical power at the output port of the CRU scheme can be described in decibels as

$$I_{out}(t) = 10 \log_{10} \left[10^3 \times h \nu_s \times (1 - R') P_s^+(L_{EDF}, t) \right] \quad (6.14)$$

where ν_s is the frequency of the signal and h is the Plank's constant.

6.3.2 Theoretical Analysis

Figure 6.1: Transient dynamics of the EDFA normalized gain ($G - G^s$) and the normalized output power ($\ln I_{out}(t) - \ln I_{out}^s$). The number of round times is defined as t / T .

Consider an input pulse enters into a CRU loop with a cavity length of 100m. The signal wavelength of this pulse is $\lambda_s = 1540 \text{ nm}$, with an initial power of -10 dBm. The pulse width is set to be $0.4 \mu s$, smaller than the trip time of the fiber loop (the trip time is decided by the cavity length by Equation (4.11)). The trip time and the pulse width

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only determine the time interval of the temporal signals. The incident forward and background pump power of the EDFA is 40mW at the pump wavelength of 980nm, the length of the EDF is kept as 10m, and the saturation parameter is $3.5 \times 10^{15} \text{m}^{-1}$. The values of the overlap integral, the absorption and emission cross-sections are followed the datasheet provided by the product supplier. The transmission factor R and R' of the fiber cavity are 0.24 and 0.5 respectively. The ASE output power is kept below -30dBm. Transient dynamics of the gain of the EDFA and the peak amplitude of the output power $I_{out}(t)$ normalized by their stationary values G^s and I_{out}^s are as shown in Figure 6.1.

The characteristic of the ring-up signal is divided by three time regimes. In the first time regime, when $t < t_{th}$, the gain $G < G^s$, $I_{out}(t)$ decays with time. During $t > t_M$, the gain of the EDFA and the output power keep at their stationary values G^s and I_{out}^s respectively.

While in the second time regime, $t_{th} < t < t_M$, the output power grows linearly in decibels until the gain is depleted to its final saturation value $G = G^s$ at $t = t_M$. The ring-up time which is defined as

$$\tau_U = \frac{T}{\alpha_U} \quad (6.15)$$

could be calculated as the inverse slope of fitting line, which is estimated by

$$\tau_U = \frac{1}{\zeta} \quad (6.16)$$

By the above equation, τ_U is read as 3.145 μs , corresponding to a net gain 0.66dB by Equation (6.15). This dynamic CRU process even can be demonstrated in wavelength domain, as shown in Figure 6.2. It shows the ASE power varies at different

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wavelengths but keeps below -30dBm while the signal power changes with time dramatically.

Figure 6.2: Transient dynamic of the output spectrum.

6.3.3 Sensitivity Analysis

In Section 6.3.1 and Section 6.3.2, the modeling of CRU fiber loop scheme is conducted and analyzed numerically. However, it only considers the ideal signals. In practice, the detecting accuracy of the CRU gas sensing system should be noticed. In this section, the detecting accuracy of the CRU fiber loop is defined.

The detecting accuracy in CRU scheme could be scaled by the minimum detectable ring-up time $\Delta\tau_U$. Consulting to the detection accuracy definition in CRD fiber loop (Equations (5.20)-(5.22)), when $\bar{\tau}_U$ and $\bar{\alpha}_U$ are denoted as the statistical mean ring-up time and net gain respectively, the difference of the ring-up time $\Delta\tau_U$ has a linear relationship with the variance of the net variable through Equation (6.15)

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$$\frac{\Delta\tau_U}{\bar{\tau}_U} = \frac{\Delta\alpha_U}{\bar{\alpha}_U} \quad (6.17)$$

$$\Delta\alpha_U = \alpha_U - \bar{\alpha}, \Delta\tau_U = \tau_U - \bar{\tau}_U$$

The minimum detectable concentration of fiber CRU has such a relationship as below:

$$\Delta C = \frac{\bar{\alpha}_U}{\kappa l} \cdot \frac{\Delta\tau_U}{\bar{\tau}_U} \quad (6.18)$$

Comparing with CRD scheme (Equations (5.20)-(5.22)). The change of the ring-down time $\Delta\tau$ includes the ring-down time fluctuation $\delta\tau$ by fundamental noises and the statistical uncertainty $\sigma\tau$ due to technical reasons. The main fundamental noise is composed of an amplified spontaneous emission (ASE) noise induced by an erbium doped fiber amplifier (EDFA) and interferometric noise caused by interference between transmitted signal and reflected signal [7]. Those fundamental noises can be reduced by EDFA gain clamp compensation technique [116, 117, 132] or digital signal processing techniques. The statistical uncertainty $\sigma\tau$ is due to technical reasons such as the sensitivities of the optical devices and detectors. With an existence of net loss, the intensity of the output pulses will drop with time. When the output intensity is close to the minimum detection of the photodetector and oscilloscope, the recorded data by the oscilloscope is not accurate any more. When the intensity is below the minimum detection of the detectors, the output signal cannot be captured and thus the number of the data able to be used in the statistic fitting is limited. This kind of uncertainty is hard to be distinguished by the conventional frequency-selective filters such as low-pass or band-pass sort. So the caused error is hardly removed and the measurement accuracy is reduced. In CRU, because the gain offered by the EDFA exceeds the total loss in the fiber loop, a net gain is induced in

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the fiber cavity and the light intensity grows temporally. Therefore, this nuisance due to the relative large fraction loss in the fiber cavity and the minimum detection of the detector can be evaded. So the minimum detectable ring-up time is expected smaller than the minimum detectable ring-down time, and thus the corresponding minimum detectable concentration in CRU is no larger than that in CRD, which generates CRU a higher sensitivity spectroscopic technique for trace gas detection.

6.3.4 Simulation Results

From Figure 6.1 and Figure 6.2, the signal convergence and the pulse amplitude are dependent on the parameters of the CRU loop such as the pump power, the erbium doped fiber (EDF) length, the input signal and the cavity loss etc.. The effects of those parameters are presented as follows.

(1) Influence of the EDFA factors

Figure 6.3(a) shows the simulation results of the CRU output signal at different EDFA pump powers from 1 to 80mW for $L_{EDF}=10\text{m}$, $P_{s0}=-10\text{dBm}$, $\lambda_s=1540\text{nm}$, $R=0.24$, $R'=0.5$. It can be seen that as the pump power is below 9mW, the output signals decay with number of round times, which means net loss exists. The gain provided by the EDFA is smaller than the total loss in the fiber loop and CRD instead of CRU phenomenon performs. When the pump power increases, the gain of the EDFA exceeds the total loss and the output signal grows due to the enhancement of the net gain. The increase of the pump power and the corresponding enhancement of the net gain induce the steep slope of the CRU curves and rapid saturation of the output signal. Thus, the calculated ring-up time decreases by Equation (6.15). The short ring-up time will induce the low sensing sensitivity of the CRU fiber loop by

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Equation (6.18) so the pump power of the EDFA should be adjusted above but close to the threshold in order to obtain an optimum net gain in the fiber loop for maximizing the sensing sensitivity.

(a)

(b)

Figure 6.3(a): Simulated output power and (b): gain versus number of round times at different pump powers for $L_{EDF}=10\text{m}$, $P_{s0}=-10\text{dBm}$, $\lambda_s=1540\text{nm}$, $R=0.24$, $R'=0.5$.

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The choice of the pump power is visualized by the various curves of EDFA gain G with pump power as well, as shown in Figure 6.3(b). When the pump power is below 9mW, the gain of the EDFA is always below a threshold value G^s , which is the gain to totally compensate to the total loss β in the fiber cavity at stationary level, $G^s = -\beta = -R'R = 9.21\text{dB}$. When the pump power is above the threshold, the gain in the second time regime ($t_{th} < t < t_M$) is over the total loss, thus the CRU condition is satisfied. With the increase of the pump power, the second time regime shortens and the net gain enhances. The corresponding ring-up time undesirably decreases and the CRU sensitivity reduces.

The changes of the signal power of the CRU are also resulted from the EDF lengths. Figure 6.4(a) shows the results of signal power for ten different EDF lengths. The length of the EDF varies from 5m to 15m with a step size of 1m. Comparing to the simulation results with the change of the EDFA pump power, the increase of the EDF length does not only change the net gain of the fiber cavity, but also induces the signal fluctuation. The reason is that with a long EDF length, the EDFA requires a longer time to reach a stationary level and the cavity loss will affect this equilibrium of the gain and the loss significantly. With the increase of the number of round times, the final output power will reach a constant, but the fluctuation of the signal is not desirable because it will influence the determination of the ring-up time. Therefore by the graph, only when the EDF length L_{EDF} is equal to 10m, the CRU signal is on an optimum status.

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(a)

(b)

Figure 6.4(a): Simulated output power and (b): simulated gain versus number of round times for different EDFA lengths. P_{p0} =40mW, P_{s0} =-10dBm, λ_s =1540nm, R =0.24, R' =0.5.

The changes of gain with number of round times at different EDF lengths (from L_{EDF} =5m to L_{EDF} =15m) are as illustrated in Figure 6.4(b). From the graph, it is found that the gain of the EDFA is quite sensitive to the change of the length of the

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EDF. Not until $L_{EDF}=10\text{m}$, there is the net gain in the fiber cavity; but at $L_{EDF}=12\text{m}$, the second time regime is quite short already. That means that the net gain in the fiber cavity only is kept as a constant in a limited number of round times, which is undesirable because it will enhance the fitting uncertainty of the CRU curve and thus induce the difficulty of finding the ring-up time. Once the EDF length L_{EDF} is above 10m, the net gain will increase rapidly with the change of the EDF length; at $L_{EDF}=15\text{m}$, the net gain could reach around 5dB contrasting to 0.5dB at $L_{EDF}=10\text{m}$, the corresponding ring-up time at $L_{EDF}=15\text{m}$ will be 10 times larger than that at $L_{EDF}=10\text{m}$, so the corresponding sensitivity will reduce 10 times. From this simulation, it could be concluded that the length of the EDF will affect the CRU performance significantly.

(2) Influence of the input signal factors

The input signal will affect the CRU performance as well. This influence could be due to the initial input signal wavelength and intensity. In Figure 6.5(a) and (b), the relationship of CRU output power with the input power of the signal, and the relationship of the EDFA gain with the input power are demonstrated respectively. The input power differs from -20dBm to 20dBm. Two cases are being considered. When the input power is a small signal (the input power is between -20dBm to 0dBm), the output power accelerates to a saturation status with the increase of the input power. This situation also shows clearly in Figure 6.5(b). The amplitudes of the gain keep the same for different input powers while the duration of the gain (the second time regime) is shorten gradually with the grows of the input power. Due to the uniform gain while the total loss is constant, the ring-up time keeps constant,

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which means the sensitivity of the CRU scheme is insensitive with the small input signal power.

(a)

(b)

Figure 6.5(a): Simulation results of output powers and (b): gains versus number of round times at different input powers. $P_{p0}=40\text{mW}$, $L_{EDF}=10\text{m}$, $\lambda_s=1540\text{nm}$, $R=0.24$, $R'=0.5$.

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However, for the case of large input signal power (the region of the input power is from 0dBm to 20dBm), the curves of gain versus number of round times at different input power levels may not vary greatly, but the shapes of the curves differ a lot comparing with those at small signal powers. t_{th} is longer with the increase of input power and the output power drops greatly at first time regime. After that, the output power saturates to a power value, which is smaller than the input power. The reason is, the larger the input signal power is, the smaller the gain of the EDFA is provided to the signal. For a fixed cavity loss, at equilibrium of gain and loss, the final gain is equalized with the total cavity loss, which is a fixed value too. So the input signal power has to decrease in the first time regime, and then drop to a small signal power where the EDFA could provide a large gain to compensate the total cavity loss. The shortcoming of this type of curve is because the second time regime is quite short, it is difficult to decide the ring-up time. Therefore, large input power should be evaded in CRU processes.

As well known, the EDFA power spectral density varies considerably with a marked peak near 1530nm. Due to the uneven EDFA gain spectrum, the value of the EDFA gain across the EDFA gain spectrum varies at different wavelengths. Therefore, CRU curve will vary with different input wavelengths. Our numerical modeling results at different input signal wavelengths support this prediction. Figure 6.6 is the simulation results of the output power and gain profiles at different input wavelengths ($\lambda_s \in [1500\text{nm}, 1610\text{nm}]$). It can be seen that, with the same input power, the gain provided near 1530nm is much larger than those provided at other wavelengths. As a result, at 1580nm, for example, the gain in the fiber cavity is

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always smaller than the total loss, a cavity ring-down process occurs instead of a cavity ring-up process.

(a)

(b)

Figure 6.6(a): Simulation result of output power profiles and (b): gain profiles at different input wavelengths. P_{p0} =40mW, L_{EDF} =10m, P_{s0} =-10dBm, R =0.24, R' =0.5.

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However, at $\lambda_s=1520\text{nm}$, with the same input power, it could be seen from Figure 6.6(b), the gain is over the total loss, and correspondingly a cavity ring-up curve could be observed from Figure 6.6(a). This is due to the EDFA gain mechanism; for eliminating this problem, gain flattening technique [133, 134] could be applied in the practical CRU setup.

(3) Influence of the cavity loss factors

The total loss in the fiber cavity could be adjusted by two factor, transmission factor R and the coupling loss R' of the output Coupler 2. The transmission factor R includes the absorption loss of the detected gas, the coupling loss from the input Coupler 1, the insertion loss of the optical devices in the fiber cavity, the attenuation loss from the variable attenuator and even the splicing loss and fiber attenuation. Varying those losses, the behavior of the CRU will be affected. In the modeling, assume the transmission factor R shifts from 0 to 1 with a step size of 0.01. The corresponding performance of the CRU scheme is demonstrated in Figure 6.7. The coupling loss R' is given to be 0.5. From output power curves, when the transmission factor is smaller than 0.2, most powers are depleted in the cavity, and output power decays with number of round times. With a larger transmission factor, the gain is over the total loss $\beta = R'R$ gradually and CRU begins. At the same number of round times, the gain offered by the EDFA decreases with the increase of the transmission factor, but the output power enhances comparing with those at small transmission factor. It is also observed that with a large transmission factor, the fluctuation of the output power at second time regime becomes severe. In this case, degrading the gain of the EDFA should be considered.

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(a)

(b)

Figure 6.7(a): Simulation result of output power curves and (b): gain curves at different transmission factors. $P_{p0}=40\text{mW}$, $L_{EDF}=10\text{m}$, $P_{s0}=-10\text{dBm}$, $\lambda_s=1540\text{nm}$, $R'=0.5$.

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(a)

(b)

Figure 6.8(a): Simulation result of output power and (b): gain at different coupling losses. $P_{p0}=40\text{mW}$, $L_{EDF}=10\text{m}$, $P_{s0}=-10\text{dBm}$, $\lambda_s=1540\text{nm}$, $R=0.24$.

Total loss could be altered by the coupling loss as well. The coupling loss changes from 0.05 to 1, with a step size of 0.05. A transmission factor $R=0.24$ is preset. Comparing Figure 6.7 with Figure 6.8, the trends of output power and gain spectra with coupling losses and those with transmission factors present quite similar

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formats. The reason is that both altering the coupling loss and transmission factor will affect the total loss. The only difference is the coupling loss has another influence to output power of the CRU since it decides how much output powers are coupled out by Equation (6.14).

From the above analysis, it is concluded that the dynamic gain, the cavity loss and the input signal will have effects on the CRU performance. The significances of these effects have been evaluated by the modeling simulations. Optimum values of the above parameters are compulsory with various demands of the CRU setup. For example, for a sort of gas with a broad absorption band in the fiber communication window, the choices of the input signal factors are not only decided by the absorbance at absorption wavelength, but also are influenced by the EDFA gain provided as discussed above. For the CRU setup with a fixed cavity loss, the length of the EDF and the pump power should also be selected cautiously to balance the total loss in the fiber cavity in order to obtain the higher sensing measurement sensitivity.

6.4 Experimental Fiber CRU for Chemical Sensing

Table 6.1: Absorption wavelength and the corresponding absorption of C₂H₂ in 1530nm-1538nm.

Wavelength	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
λ (nm)	1530.30	1531.51	1532.76	1534.04	1535.33	1536.65	1537.99
Absorption	A_1	A_2	A_3	A_4	A_5	A_6	A_7
A (dB)	-9.716	-9.594	-9.099	-8.049	-7.093	-6.014	-4.813

The experimental scheme of fiber CRU is illustrated in Figure 5.8. A NIST standard gas cell (Wavelength reference, C₂H₂-12-700) was inserted into the CRU loop. From

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the product supplier's datasheet shown in Table 6.1, acetylene had the strongest absorption line at $\lambda_1=1530.30\text{nm}$ in C band. In order to achieve a high sensing sensitivity, the input wavelength of the laser λ_s was set to be λ_1 , with an initial power of $I_0=-10\text{dBm}$. The length of the fiber cavity was relative long with an approximate value of 850m and a corresponding long trip time of $4.08\mu\text{s}$ was obtained by Equation (4.11). This long trip time would induce a long ring-up time and thus enhance the sensing sensitivity according to Equations (6.15) and (6.18). The central wavelength of the FBG filter was always tuned identical to the laser wavelength. The pump current of the EDFA P_{p0} was adjusted to provide a gain to compensate the total loss in the fiber cavity. The output pulses decayed with time and CRD curves were observed when the EDFA pump current was below 66mA. Once the EDFA's current was over 66mA, the output pulses began to grow with time, which meant the gain of the EDFA was over the total loss in the fiber cavity, and 66mA, might be the threshold current of EDFA, where the gain is equal to total loss β of the fiber cavity. The CRU curves were investigated when the EDFA current P_{p0} changed from 67mA to 73mA with a step of 2mA while the attenuation of the variable attenuator was fixed to an optimum condition. Figure 6.9(a) shows the experimental results of the CRU output signals at different EDFA pump currents. It should be pointed out that for clearness only the peak amplitudes of the output pulses are displayed in the graph. An approximate 0.5V baseline was induced by the offset amplitude of the function generator. The conversion from optical power to electrical voltage would not influence the calculation of the ring-up time. It can be seen that the output pulses grow with time to a stationary states, which accorded with our predication in the CRU

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model. The larger of the pump current, the larger of the stationary or saturation output is, e.g, for pump current of 67mA, the output signal voltage saturated at 2V, but for pump current of 73mA, the output voltage could reach to 3.1V. The fast increase of the output voltage with time may not be desired.

Figure 6.9(a): Output voltage versus time and (b): Logarithmized value of output voltage versus time at different pump currents for $I_0 = -10\text{dBm}$, $\lambda_s = 1530.30\text{nm}$.

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One reason is the photodetector inclined to be saturated and beyond its operation condition if the output voltage was too large. The other reason is the rapid enhancement of the output voltage meant a large net gain in the fiber cavity, which was reflected by the steep slope of the CRU curves and rapid saturation of the output signal. As discussed in our previous section, a small net gain will bring a large ring-up time and a high sensitivity, which could be found from Equation (6.18). So the pump power of the EDFA should be adjusted above but close to the threshold in order to obtain an optimum net gain in the fiber loop for maximizing the sensing sensitivity.

For convenience, the natural logarithmized value of output voltage is considered in Figure 6.9(b), so will be the following discussions. The baseline caused by offset of the function generator was ready to be removed because it wouldn't be related with the CRU process. From the Figure 6.9(b), the slopes of the curves in middle time regime were fitted by linear equation and ring-up times were calculated by using Equation (6.16). The ring-up times at different pump currents were 40.74 μ s, 35.77 μ s, 31.73 μ s, and 28.79 μ s respectively, decreasing with the enhancement of pump current. The corresponding net gains were 0.42dB, 0.47dB, 0.53dB, 0.58dB according to Equation (6.15). The standard deviation $\Delta\tau$ could reach 0.03 μ s in repeated processes. For the case of the net gain α_v equal to 0.42dB, the minimum detectable concentration was around 300ppm (the gas absorption coefficient κ of C₂H₂ is equal to 0.2cm⁻¹ at absorption wavelength 1530.30nm [78] and the length of the gas cell l is 5cm). This value is 4 times smaller than that from CRD experimental results in Chapter 5. This reduction of the minimum concentration could be due to the following reasons: In CRD, output pulses decayed with time. When the pulses were below the minimum detectable of the photodetector, those pulses with tiny amplitudes

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would not be recognized by the photodetector. So the numbers of the output pulses was limited. Unlike CRD, because the output power grew instead of decayed, more output pulses survived and large numbers of pulses were able to be collected in one CRU process and thus the statistic error in the fitting process decreased a lot. Another advantage of CRU is the input power could be quite small due to the growth of the output pulses; on the contrast, in the CRD process, large input power was required or else the output pulses would decay below the minimum detectable of the photodetector too rapidly. So expensive high power laser is not demanded in the CRU fiber loop, and the cost of the chemical sensing system could be reduced.

According to the simulation results, the CRU performance was resulted from the input signal factors as well. This influence could be due to the initial input signal intensity or the input wavelength. The relationship of the CRU output voltage with the input power of the signal, and the CRU output voltage vs. the input wavelength of the signal were investigated individually. As we discussed, the ring-up time may be long when the EDFA was above but close to the threshold value, so the EDFA's current P_{p0} was set to be 67mA. The input power I_s differed from -20dBm to 0dBm. The input wavelength λ_s was kept as 1530.30nm.

The transit responses of output voltages at different input powers are as shown in Figure 6.10. It is shown that output power decreased the acceleration rate to a saturation status with the increase of the input power. Moreover, the output voltages finally saturated to the same voltage value no matter how much the input power was. By calculations, the ring-up times increased with the enhancement of the input power. Although long ring-up times were preferred from our previous discussion, the “waste” of the input power could not be ignored. For example, when the input power was

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0dBm, the ring-up time was 3 times larger than that at the input power of -20dBm, with the price that the input power enhanced up to 20dB. Even more, the final stationary value of the output voltage, however, was decreased from the beginning 1.5 to 0. The changes of the curves at different input powers resulted from the different gains at different input powers. At small input power, e.g., $I_s = -20\text{dBm}$, the gain was larger than that at the large input power. So for the cases of the small input power, the gain provided by the EDFA would be larger than that at the large input power; and thus when the total loss was fixed, the net gain in the case of the small input power increased and the corresponding ring-up time decreased. Changing the total loss in the cavity is one solution for small input signals. If the total loss was enhanced, the net gain of the fiber cavity would decrease, longer ring-up times were able to be obtained.

Figure 6.10: Output voltages versus time at different input powers. $P_{p0} = 67\text{mA}$, $\lambda_s = 1530.30\text{nm}$.

As well known, the EDFA power spectral density varies considerably with a marked peak near 1530nm. Due to the uneven EDFA gain spectrum, the value of the EDFA gain across the EDFA gain spectrum varies at different wavelength. Therefore,

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CRU curve would vary with different input wavelengths. In Figure 6.11, the CRU curves at absorption wavelengths of C_2H_2 in 1530nm-1538nm are illustrated. The central wavelength of the FBG was always strained to be identical as the input wavelength. Input power was kept as -10dBm, and the pump power was 67mA. From the graph, the ring-up time was definitely maximized at the absorption wavelength of 1530.30nm. The reason is although the gain provided near 1530nm was larger than those provided at other wavelengths, the absorption of the C_2H_2 gas at 1530.30nm was largest too, which could be read from Table 6.1. Therefore, the net gain in that absorption wavelength was kept minimum. At other absorption wavelengths, especially when the absorption line was over 1534.04nm, due to the relatively large net gain, the CRU curves gradually fluctuated. Those fluctuations were not desired, because the decay time would be hard to be determined. So minimizing or optimizing the net gain was vital no matter how the input wavelength varied.

Figure 6.11: Output voltage profiles at different input wavelengths. P_{p0} =67mA, P_{s0} =-10dBm.

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Finally, the total loss of the fiber cavity would alter the CRU curves as well. The experimental results are as shown in Figure 6.12. The investigation was studied at absorption wavelength of 1530.30nm. The total loss increased 0.2dB, 0.4dB and 0.6dB by adjusting the various attenuator from previous setting. The results were quite straightforward. The pump current of the EDFA was fixed, so the gain offered by EDFA was a constant. The net gain was enhanced due to the increase of the total loss, and thus the corresponding ring-up times were shortened.

Figure 6.12: Output power profiles at different attenuation losses. $P_{p0}=67\text{mA}$, $P_{s0}=-10\text{dBm}$, $\lambda_s=1530.30\text{ nm}$.

A comparison is made between the active CRD and CRU method to show the superiority of the CRU. In the comparison, the pump current of EDFA, the input wavelength and power are kept unchanged. Only the loss of the attenuator is varied to keep the ring-up time and ring-down time approximately equivalent. The minimum detectable concentrations by CRD and CRU are tabulated. As shown in Table 6.2, the minimum detectable concentrations in both CRD and CRU decrease with the grows of the ring-down and ring-up time as expected. At different ring-down and ring-up

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times, the minimum detectable concentrations in CRD are typically 3-4 times larger than those in CRU, which presents the higher sensitivity of the CRU method.

Table 6.2: Comparisons of minimum detectable concentrations by CRD and CRU methods at different attenuation losses. P_{p0} =67mA, P_{s0} =-10dBm, λ_s =1530.30 nm.

CRD	$\bar{\tau}_D$ (μ s)	19.35	25.01	30.67	40.62
	ΔC_D (ppm)	2674	2058	1425	1154
CRU	$\bar{\tau}_U$ (μ s)	19.30	25.04	30.59	40.72
	ΔC_U (ppm)	728	643	454	301

Comparisons are also made between the CRD and CRU methods at different pump currents P_{p0} , signal input powers P_{s0} and wavelengths λ_s , as shown in Table 6.3-Table 6.5. From Table 6.3, with the increase of the pump current P_{p0} , both the minimum detectable concentrations of the CRD and CRU will increase due to the enhancement of the net loss/ net gain and the corresponding decays of the ring-down/ring-up time. The minimum detectable concentrations of CRU could keep 3-4 times smaller than those of CRD, which shows the superiority of CRU over CRD will not been influenced by the changes of the pump current.

Table 6.3: Comparisons of minimum detectable concentrations by CRD and CRU methods at different pump currents. P_{s0} =-10dBm, λ_s =1530.30 nm.

	P_{p0} (mA)	67	69	71	73
CRD	ΔC_D (ppm)	1154	1329	1567	1738
CRU	ΔC_U (ppm)	301	354	403	457

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At different signal powers P_{s0} , as shown in Table 6.4, the minimum detectable concentrations of CRD and CRU both decrease with the increase of the signal powers. This is due to that the gain provided by the EDFA will decrease with the enhancement of the signal power, and thus the net loss/net gain will increase, so the ring-down/ring-up time will be shorten. The smaller the ring-down/ring-up times are, the larger the minimum detectable concentrations of CRD and CRU will be. At $P_{s0}=-20$ dBm, the minimum detectable concentration of CRD ΔC_D is as large as 2510ppm. This large ΔC_D is also due to the small input power and the caused limited number of the input pulses.

Table 6.4: Comparisons of minimum detectable concentrations by CRD and CRU methods at different signal powers. $P_{p0}=67$ mA, $\lambda_s=1530.30$ nm.

	P_{s0} (dBm)	-20	-15	-10	-5	0
CRD	ΔC_D (ppm)	2510	1733	1154	732	607
CRU	ΔC_U (ppm)	721	523	301	283	266

Table 6.5: Comparisons of minimum detectable concentrations by CRD and CRU methods at different signal wavelengths. $P_{p0}=67$ mA, $P_{s0}=-10$ dBm.

	λ_s (nm)	1530.30	1531.51	1532.76	1534.04	1535.33	1536.65	1537.99
CRD	ΔC_D (ppm)	1154	1251	1321	1375	1392	1462	1753
CRU	ΔC_U (ppm)	301	385	411	432	459	542	612

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The influences of EDFA gain to ΔC_D and ΔC_U at different signal wavelengths are as shown in Table 6.5. Due to the different gains provided at different wavelengths, ΔC_D and ΔC_U will be different as well. For our case, ΔC_D and ΔC_U have the minimum values at $\lambda_s=1530.30$ nm, and have the maximum values at $\lambda_s=1537.99$ nm.

6.5 Conclusion

A novel concept of cavity ring-up (CRU) spectroscopy is proposed for trace gas detection in a fiber chemical sensing system in this chapter. Based on a rate equation approach, a comprehensive theoretical model of CRU spectroscopy for trace gas detection with dynamic gain of EDFA taken into account has been presented. The formulation of rate equations to model CRU events allows a quantitative numerical analysis on the general features of CRU output signals. The effects of the EDFA pump power, the EDF length, the input signal parameters and the intra-cavity loss to the features of CRU output signals are numerically simulated and discussed. The simulation results indicate that minimization of the net gain is extremely important for achieving high measurement sensitivity in a fiber CRU scheme. Therefore, adjusting the net gain by the cavity loss and even the input signal factors are fully analyzed. Meanwhile, optimization of the active fiber length enables to degrade the power fluctuation and to keep the CRU in the best performance.

Then CRU fiber chemical sensing system is conducted. In this study, the characteristics of the CRU output signal is investigated as a function of the EDFA pump current, input signal and the total intracavity loss. The experiments verify the simulation results that the EDFA, the input signal and the cavity parameter will all

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affect the CRU performance. The experiments also have indicated that minimization of the net gain is extremely important for achieving high measurement sensitivity in a fiber CRU scheme. The minimum detectable concentration of 300ppm is achieved at the net gain of 0.42dB, which proofs the superiority of the CRU scheme and shows a promising potential for CRU fiber loop in the application of chemical sensing systems.

Chapter 7

Cavity Ring-down/up Spectroscopy for Bio-sensing

7.1 Introduction

In Chapter 4, application of passive CRD spectroscopy for strain sensing was presented. LPG is adopted as the sensing material in that sensing scheme. The potential for LPG-based CRD fiber sensor was proved already by this previous work.

LPG not only has excellent high sensitivity to the response of temperature and strain [115, 135], but also outperforms FBG counterpart since it even could be applied to be bio-sensors, by sensing the refractive index change of the ambient bio-materials [136] surrounding the fiber cladding. In an LPG refractive index sensor, the fundamental guided mode propagating along the core of a single-mode fiber is coupled to forward-propagating cladding modes through a grating photowritten along the core of the fiber. The spectral resonant peaks of the LPG are shifted by the refractive-index change of the ambient around the cladding.

In the following section, the LPG CRD fiber loop for investigating the refractive index measurement capability is presented. By detecting the ring-down curves at different ambient refractive index levels, the performances of the LPG sensor are studied. In Section 7.3, the LPG refractive index sensor based on the novel CRU spectroscopy is proposed. The priority of the CRU over the conventional CRD technique will be shown. Finally, a conclusion is presented in Section 7.4.

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7.2 Experimental Fiber CRD for Bio-sensing

Figure 7.1: CRD experimental scheme for refractive index sensing.

The experimental scheme of cavity ring-down LPG fiber loop for the refractive index measurement is based on the schematic diagram shown in Figure 7.1. The fiber cavity was composed by two optical fiber couplers (Coupler 1 and 2) and a long segment of fiber. An LPG (period $\Lambda=300\mu\text{m}$, the transmission loss β_{T0} was -22.4dB at resonant wavelength $\lambda_0=1580.2\text{nm}$) was inserted into the fiber cavity, followed by a variable optical attenuator to adjust the total loss β in the fiber cavity (in this scheme, the total loss composed of the transmission loss of the LPG β_T , the attenuation loss from the variable attenuator β_A and other residual losses β_R such as fiber loss and components' insertion losses). A tunable gain erbium doped fiber amplifier (EDFA, Opto-Link Corporation Limited) was applied to provide a gain for compensating the large total loss β in the fiber cavity. A fiber Bragg grating (FBG) filter with a Bragg wavelength of 1546.1nm and full width at half-maximum (FWHM) of 0.02nm was connected in cascade behind the EDFA to restrict the gain to locate at the input wavelength. The undesirable amplified spontaneous emission (ASE) powers brought

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by the EDFA, in the meantime, was minimized by the narrow FWHM of the FBG filter.

When the value of the total loss in the fiber cavity was larger than the value of the gain offered by EDFA, a net loss α was defined as the fraction loss in the fiber cavity,

$$\alpha = \beta + G \quad (7.1)$$

where G was the gain of EDFA in decibel and β was described in decibel too (notice G is always a positive value while β is negative). As the input signal kept small, the gain of the EDFA was ideally a constant value, and thus the corresponding net loss was constant too.

For the CRD scheme, τ has a relationship with the net loss α in decibel as [78],

$$\tau = -4.34T / \alpha \quad (7.2)$$

The factor 4.34 is due to the decibel expression of α .

For a bare LPG in air surrounding, the ambient refractive-index was approximately equal to 1 (the refractive index of the air $n_{amb} \approx 1$). The laser wavelength was located at the resonant wavelength of the LPG, with the initial power of 10dBm. The FBG filter's central wavelength was always adjusted identical to the laser wavelength. The pulse width and period were set according to the estimated length of the fiber cavity. In the initial state, there was no attenuation from the variable attenuator, $\beta_{A0} = 0$. When the pump current of the EDFA was enhanced to 85mA, the CRD curve displayed in the oscilloscope is as shown in Figure 7.2(a). It is found that the curve has an exponential profile as expected. The maximum output

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voltage, which is shown in the first output pulse, is around 6V and is followed by over 30 pulses ringing out with successive time intervals (or trip time T) of $4.3\mu\text{s}$.

(a)

(b)

Figure 7.2(a): Cavity ring-down result with a bare LPG. (b): $t - \ln(I(t)/I_0)$ and fitted CRD curves.

To obtain the decay time, the peak voltages of the output pulses are fitted with the convenient linear expression. By using this formula, the exponential decay curve

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in Figure 7.2(a) is logarithmized and fitted by a linear equation and the fitting result is shown in Figure 7.2(b). The obtained ring-down time is $\tau_0=27.03\mu\text{s}$. The net loss of the CRD loop by Equation (7.2), is -0.69dB.

Figure 7.3: The approximation constant ring-down times and net losses at different ambient refractive indices.

The LPG then was immersed to refractive index oil with the refractive index of 1.35. The LPG resonant peak would expect to shift backwards to λ_1 and the depth would decay to β_{T1} according to the LPG coupling modeling [135, 136]. The gain value of the EDFA provided to the signal was always kept constant. The variable attenuator was adjusted to keep the total loss below the gain value so that the CRD phenomena were always observed. When the input wavelength was set as 1567.5nm, the minimum decay time was obtained. As the attenuation loss was set to $\beta_{A1}=-12.07\text{dB}$, the ring-down time τ_1 is approximately equal to τ_0 as shown in Figure 7.3. Those results demonstrate when the refractive index was changed to 1.35, the resonant peak λ_1 was shifted to 1567.5nm, and the depth of the resonant peak β_{T1}

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would be the subtraction of β_{T0} with β_{A1} , equal to -10.33dB. So the change of the ambient refractive index would be reflected by the change of the attenuation loss to keep the same ring-down time. The mathematical analysis is shown as below.

In the CRD fiber cavity, the net loss in the fiber cavity is related with the transmission loss of the LPG by Equation (7.1). For LPG, the transmission loss of the LPG strongly relies on the index of refraction (n_{amb}) of the ambient medium surrounding the cladding. Any change in this ambient index then serves to modulate the net loss α . Since the ring-down time is dependent on net loss through Equation (7.2), the change in n_{amb} will effectively vary the value of ring-down time, so the shift in a ring-down time is given simply by

$$\frac{d\tau}{dn_{amb}} = \frac{d\tau}{d\alpha} \cdot \frac{d\alpha}{dn_{amb}} \quad (7.3)$$

$d\tau/d\alpha$ could be derived from Equation (7.2) as

$$\frac{d\tau}{d\alpha} = \frac{4.34T}{\alpha^2} = -\frac{\tau}{\alpha} \quad (7.4)$$

So substitute the above equation to Equation (7.3), we get

$$\frac{d\tau}{dn_{amb}} = -\frac{\tau}{\alpha} \cdot \frac{d\alpha}{dn_{amb}} \quad (7.5)$$

When the ring-down time at different ambient refractive index is approximately invariable, such as $\tau_0 \approx \tau_1$, then

$$d\tau/dn_{amb} = -\frac{\tau}{\alpha} \cdot \frac{d\alpha}{dn_{amb}} \approx 0 \quad (7.6)$$

The ring-down time is not zero, so we can get

$$\frac{d\alpha}{dn_{amb}} \approx 0 \quad (7.7)$$

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The net loss is composed by the sum of gains and various losses, so Equation (7.7) could be rewritten as

$$\frac{d\alpha}{dn_{amb}} = \frac{dG}{dn_{amb}} + \frac{d\beta_A}{dn_{amb}} + \frac{d\beta_T}{dn_{amb}} + \frac{d\beta_R}{dn_{amb}} \approx 0 \quad (7.8)$$

In our experiment, the gain from the EDFA G and the loss β_R were kept unvariable, dG/dn_{amb} and $d\beta_R/dn_{amb}$ were both zeros, so

$$\frac{d\beta_A}{dn_{amb}} = -\frac{d\beta_T}{dn_{amb}} \quad (7.9)$$

Therefore, from Equation (7.9), by the change of the attenuator's loss, the change tendency of the ambient refractive index could be obtained. When the LPG was immersed to other refractive index oils orderly ($n_{amb}=1.37, 1.39, 1.41$ and 1.43), the relationship of the attenuator's loss and the values of ambient refractive index is as illustrated as Figure 7.4. The ring-down time for each case is kept around same, with a small deviation of 0.3% as shown in Figure 7.3. The corresponding net losses are as shown as well.

Figure 7.4: The relationship of the attenuation loss and the ambient refractive index.

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In Figure 7.4, the attenuation loss decreases with the enhancement of the ambient refractive index. From refractive index 1.35 to 1.43, the decay displays linearly, a decay of -7.16dB in the 1.35–1.43 index range is observed. The experimental results and analysis show that the ambient refractive index change is not only able to be detected by the LPG resonant wavelength shift, but also can be detected by the decay of the LPG resonant peak, which provides an alternative approach for sensing refractive index changes.

7.3 Experimental Fiber CRU for Bio-sensing

The experimental scheme of cavity ring-up LPG fiber loop for the refractive index measurement is also based on the schematic diagram shown in Figure 7.1. The same LPG was adopted in the CRU fiber loop, so the resonant wavelength and the transmission loss β_T remained same. Without inserting other components, the residual losses β_R was kept same as well.

If the value of the gain was over the value of the total loss in the fiber cavity, a net gain α_U was obtained as the fraction in the fiber cavity,

$$\alpha_U = \beta + G \quad (7.10)$$

and

$$\beta = \beta_T + \beta_A + \beta_R \quad (7.11)$$

For the CRU scheme, when the input signal power was small, the output intensity of the pulse was determined from a simple first order exponential function

$$I(t) = I_0 \exp(t / \tau_U) \quad (7.12)$$

where I_0 denotes initial intensity of the input pulse, τ_U is the ring-up time, which is

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the corresponding time when $I(t)$ increases to e times of I_0 . To obtain the ring-up time, the above function $I(t)$ is usually expressed as a natural logarithm format,

$$\ln(I(t)/I_0) = t/\tau_U \quad (7.13)$$

so ring-up time could be calculated by fitting the curve of $t - \ln(I(t)/I_0)$ (τ_U is equal to the inverse slope of the fitting line).

Referring to Equation (7.2), τ_U has a relationship with the net gain α_U as,

$$\tau_U = 4.34T / \alpha_U \quad (7.14)$$

In the CRU fiber cavity, the net gain α_U in the fiber cavity is related with the transmission loss of the LPG β_T by Equations (7.10) and (7.11). For the LPG, the transmission loss of the LPG strongly relies on the index of refraction (n_{amb}) of the ambient medium surrounding the cladding. Any change in this ambient index then serves to modulate the net gain α_U . Since the ring-up time is dependent on net gain through Equation (7.14), the change in n_{amb} will effectively vary the value of ring-up time, so the sensor's sensitivity could be represented by $d\tau/dn_{amb}$ and

$$\frac{d\tau_U}{dn_{amb}} = \frac{d\tau_U}{d\alpha_U} \cdot \frac{d\alpha_U}{dn_{amb}} \quad (7.15)$$

$d\tau_U/d\alpha_U$ could be derived from Equation (7.14) as

$$\frac{d\tau_U}{d\alpha_U} = -\frac{4.34T}{\alpha_U^2} = -\frac{\tau_U}{\alpha_U} \quad (7.16)$$

The other term $d\alpha_U/dn_{amb}$, could be rewritten as

$$\frac{d\alpha_U}{dn_{amb}} = \frac{d(G + \beta)}{dn_{amb}} = \frac{dG}{dn_{amb}} + \frac{d\beta_T}{dn_{amb}} + \frac{d\beta_A}{dn_{amb}} + \frac{d\beta_R}{dn_{amb}} \quad (7.17)$$

β_R was always invariable once the experimental setup was ready. When the gain of

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the EDFA and the loss of the variable-attenuator β_A are fixed,

$$\frac{d\alpha_U}{dn_{amb}} = \frac{d\beta_T}{dn_{amb}} \quad (7.18)$$

So Equation (7.15) becomes to

$$\frac{d\tau_U}{dn_{amb}} = -\frac{\tau_U}{\alpha_U} \cdot \frac{d\beta_T}{dn_{amb}} \quad (7.19)$$

The minimum detectable refractive index, correspondingly could be described by

$$dn_{amb} = -\frac{\alpha_U}{\tau_U} \cdot \frac{dn_{amb}}{d\beta_T} d\tau_U \quad (7.20)$$

When the bare LPG was exposed in air, the laser power was set to be -20dBm and the wavelength was located at the resonant wavelength of the LPG λ_0 . In the initial state, there was no attenuation from the variable attenuator, $\beta_{A0}=0$. When the pump current of the EDFA was enhanced to 89mA, the obtained CRU curve is as shown in Figure 7.5(a).

In Figure 7.5(a), a train of the output pulses display with successive time intervals (or trip time T) of $4.3\mu s$. The trend of the amplitude changes of the pulses tends to be divided into three time domains. To see clearly, a logarithmized form $t - \ln(I(t)/I_0)$ is adopted (see Figure 7.5(b)). To simplify, only the peak amplitudes of the pulses are plotted. In the first time domain, that is when the time is smaller than $20\mu s$, the signal decreases a little bit with time, which means the initial power of the input signal is too large for the EDFA to provide an appropriate value of gain (refer to simulation results in Section 6.3). With the time growing, the CRU curve, as shown in Figure 7.5(a), has an exponential profile as expected as Equation (7.12).

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Figure 7.5(a): CRU curve of a bare LPG. (b): $t - \ln(I(t) / I_0)$ and the linear fitted result.

In this region, the corresponding logarithmized CRU curve can be linear fitted; the inverse of the slope, which is exactly the ring-up time by Equation (7.13), is read as 44.84 μ s. The net gain of the CRU loop, then, by Equation (7.14), is 0.42dB. When the time is longer than 220 μ s, the signal output grows to so large that the gain

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provided decreases [121]. The signal output begins to saturate and the signal's growing speed slows down. The maximum output voltage can achieve 9.3V from this graph. This time region, however, is not completely shown in the graph because it will not have influences to obtain the ring-up time.

The LPG then was immersed to refractive index oils with different refractive indices n_{amb} . The LPG resonant peak would expect to shift backwards and the depth would decay according to the LPG coupling modeling. If the value of the EDFA gain and the attenuation loss were kept constant, the net gain would enhance by Equations (7.10) and (7.11). It could be expected that the ring-up process proceeded but the ring-up time was shortened according to Equation (7.14). The ring-up region was shortened and it further enhanced the difficulty to obtain the ring-up time from the CRU curve. So it is difficult to evaluate the sensitivity of this refractive index sensor by directly reading the ring-up times at different n_{amb} values. However, by Equation (7.19), the sensitivity not only could be represented by $d\tau_U / dn_{amb}$, but also could be described by $d\beta_T / dn_{amb}$ alternatively. Therefore, in our experiment, the attenuator was adjusted to compensate the decayed transmission loss β_T so that the net gain always kept invariable no matter how the ambient refractive index of the LPG changed,

$$\frac{d\alpha_U}{dn_{amb}} = 0 \quad (7.21)$$

By Equations (7.10) and (7.11), Equation (7.21) could be rewritten as

$$\frac{d\alpha}{dn_{amb}} = \frac{dG}{dn_{amb}} + \frac{d\beta_A}{dn_{amb}} + \frac{d\beta_T}{dn_{amb}} + \frac{d\beta_R}{dn_{amb}} = 0 \quad (7.22)$$

In our experiment, the EDFA gain G and the loss β_R were kept invariable,

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dG/dn_{amb} and $d\beta_R/dn_{amb}$ were both zeros, so

$$\frac{d\beta_A}{dn_{amb}} = -\frac{d\beta_T}{dn_{amb}} \quad (7.23)$$

Thus, the sensitivity of this CRU refractive index sensor could be obtained by evaluating the change of the attenuation loss to ambient refractive index $d\beta_A/dn_{amb}$.

Figure 7.6: The relationship of the attenuation loss and the ambient refractive index.

When the LPG was immersed to refractive index oils orderly ($n_{amb}=1.35$, 1.37, 1.39, 1.41 and 1.43), the relationship of the attenuator's loss and the value of ambient refractive index is as illustrated as Figure 7.6. The ring-up time for each case was kept around same, with a small deviation of 0.2%.

By Figure 7.6, the attenuation loss decreases with the enhancement of the ambient refractive index. A maximum decay of -19.25dB at refractive index of 1.43 is observed. From refractive index 1.35 to 1.43, the decay displays approximately linear, with a slope of -90.50dB. If the sensitivity is converted to in term of ring-up time, $d\tau_U/dn_{amb}$ is equal to -529.77 μ s, with a ring-up time change of -42.38 μ s. That means

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when the ambient refractive index is 1.43, the ring-up time will be $44.84 + (-42.38) = 2.56\mu\text{s}$, a quite short ring-up time!

Figure 7.7: The comparison of the changes of the ring-up/down time.

The minimum detectable refractive index, alternatively, which can be obtained by Equation (7.20), was achieved by repeating the CRU process when the LPG kept to be immersed in the steady ambient surrounding. The comparison of the CRD and CRU scheme was done. The same LPG was adopted in both experiments. So the value of the term $d\beta_T/dn_{amb}$ was exactly same; when the absolute values of the net gain and net loss were adjusted identical, only the term time percent difference $d\tau_U/\tau_U$ of the ring-up time in CRU and $d\tau_D/\tau_D$ of the ring-down time for CRD should be compared. The results are as shown in Figure 7.7. For both schemes, the net gain or net loss was always kept approximately same, the corresponding ring-up time or ring-down time remained approximately same as well. For each process, the time percent difference had no distinguishable variance, with a typical deviation kept below 5.4%. However, the CRU process apparently outperforms CRD scheme due to the smaller time percent difference at the same conditions. For CRD, the mean time

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percent difference was 1.02%, while the CRU scheme could achieve as small as 0.37%, 3 times smaller than the former scheme. The minimum detectable ring-up time was smaller than the minimum detectable ring-down time, and thus the corresponding minimum detectable refractive index was 1.72×10^{-5} in CRU, while 4.73×10^{-5} in CRD, as seen from Table 7.1. From Table 7.1, the minimum detectable refractive indices of CRD and CRU at different ambient refractive indices are compared as well. It shows at different ambient refractive indices, the minimum detectable refractive indices of CRU are apparently smaller than that of CRD. Those values are definitely smaller than the typical minimum detectable refractive index by direct LPG refractive index sensor (the minimum detectable refractive index of 7.69×10^{-5} was obtained in Ref. [135]), which generates CRD and CRU promising spectroscopic techniques for bio-sensing.

Table 7.1: The minimum detectable refractive indices of CRD and CRU at different ambient refractive indices.

	n_{amb}	1.35	1.37	1.39	1.41	1.43
CRD	$\Delta n_{amb,CRD}$	5.04×10^{-5}	5.00×10^{-5}	4.96×10^{-5}	4.73×10^{-5}	4.99×10^{-5}
CRU	$\Delta n_{amb,CRU}$	1.91×10^{-5}	1.72×10^{-5}	1.86×10^{-5}	1.85×10^{-5}	1.81×10^{-5}

7.4 Conclusion

In this chapter, CRD and CRU spectroscopic techniques are applied for bio-sensing area. LPG CRD/CRU refractive index sensor in the fiber loop is set up. The ring-down/up time and the LPG transmission loss with the changes of refractive index of this sensing built-up are investigated. Comparing with our previous application of

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LPG to CRD-based strain sensing, the experimental challenge for this refractive index sensing scheme is that the LPG transmission loss decays greatly in higher ambient refractive index, and thus the corresponding ring-down/up time is shortened quickly and thus becomes difficult to be captured. So in our experiment, the ring-down/up time keeps invariable by adjusting the attenuation loss of the variable attenuator. The total loss is compensated and the net loss/gain remains constant. By detecting the various decays of the attenuation loss at different ambient refractive indices, the sensitivity of this sensor is evaluated. The experimental results indicate that LPG CRD/CRU sensors display good linear responses in the index region of 1.35-1.43. And by the analysis, the minimum detectable refractive index from the CRU is smaller than the CRD scheme, which presents a potential for the CRU fiber loop to the high-sensitive and highly demanded bio-sensing applications.

Chapter 8

Conclusion

8.1 Conclusions

This thesis mainly reports optical fiber cavity ring-down (CRD) and cavity ring-up (CRU) based-sensors for chemical sensing and other applications. Direct absorption spectroscopy, which is the most commonly used spectroscopic technique, is first investigated. The noises in the direct absorption spectroscopy-based fiber chemical sensor are analyzed. A practical optical fiber sensing system based on direct absorption spectroscopy is conducted. The hydrogen cyanide (HCN) gas is detected by using this optical fiber sensing system. The main noise, from the analysis, is found to be the intensity noise from the laser source. Aiming at reducing the effect of this kind of noise, a digital finite impulse response (FIR) filter is designed to improve this chemical sensor's sensitivity. Both simulation and experimental results have shown that by using the well designed digital FIR filter, the highest detection accuracy is achieved at the HCN strongest absorption line R(7) at 1537.299nm. At this absorption wavelength, the filtered detection accuracy can reach 0.1ppm, 13dB enhancement than the unfiltered result. Furthermore, the weakest HCN absorption line P(35) at 1572.387nm can also be detected by using this digital signal processing (DSP) technique while they cannot be detected by using other methods. The linear relationship of the unfiltered and filtered SNR of P(35) absorption line with the input power of the light source are also investigated, which indicates the input power will not affect the capability of the designed filter. This work shows a promising potential

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to apply DSP technique to optical fiber sensor system for enhancing the chemical measurement accuracy.

The success of introducing DSP technique motivates us to solve the challenge of identification of the unknown gas mixture detected by an optical fiber chemical sensor using pattern recognition technique. An automatic gas mixture recognition system by using support vector regression (SVR) technique is proposed. After the recognition model, the gas components and the corresponding concentration are obtained. By this SVR model, up to 3 components of the gas mixture could be identified automatically as $C^{12}O$, $C^{13}O$ and HCN with the concentrations of 19.5%, 18.9% and 1.40% respectively, identical with the data the product supplier provides. The RMS detection error is scaled in term of concentration of 0.01% is obtained. Single gas component could be also distinguished by this SVR recognition system. In our investigation, the target gas of $C^{12}O$ with the concentration of 92.8% is detected successfully, with a high measurement accuracy of 0.03%.

Successively, CRD spectroscopy in fiber optics is studied. Passive CRD spectroscopy for optical fiber sensors, which is without the gain compensation, and active CRD with a gain provided are exploited respectively. The passive CRD spectroscopy, may not be suitable for application in trace gas detection, but an application of passive CRD in strain sensing is proposed by us. A long period grating (LPG) CRD strain sensor in a fiber loop is set up. The decay time, the sensitivity and minimum detectable strain of this sensing built-up are investigated. The experimental results indicate that the LPG CRD sensor displays a good linear response in a wide strain region from 0 to 3000 $\mu\epsilon$ at the wavelength of 1600nm. Meanwhile, by using this sensing scheme, a high sensitivity of 1.261ns/ $\mu\epsilon$ and a small minimum detectable

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strain of $9\mu\epsilon$ are obtained, comparing with the conventional direct LPG strain sensor, which shows a new generation of fiber sensors for strain measurement.

After that, the active CRD fiber loop is investigated comprehensively for trace gas detection. The mathematical model of the CRD fiber loop is initially developed. From this model, it is found that the amplified spontaneous emission (ASE) noise, induced by an erbium doped fiber amplifier (EDFA), is always a key problem for the measurement accuracy in a CRD fiber amplified loop chemical sensing system. A digital least mean square (LMS) adaptive filter is proposed to reduce the ASE noise. The simulation results show by a well designed LMS adaptive filter, the RMS detection error of 16ppm after filtering is achieved when the net loop loss is $-0.10\pm0.01\text{dB}$, and the error is reduced by 14dB than that without filtering. Then, the experimental setup of the CRD fiber loop is used for trace acetylene (C_2H_2) detection. In the experiment, the filtered RMS minimum measurement concentration could reach 14.78ppm with an approximate net loss of -0.22dB . The experimental results before and after filtering at different net losses are compared and the minimum measurement concentrations of the filtered results are apparently decreased compared with the unfiltered results. Simulation based on the CRD model is also executed and similar filtered results are obtained, which further proves that this designed filter could be applied to improve the accuracy of the CRD contaminated signals. Therefore, this digital signal processing technique shows a promising feasibility combining with the CRD sensing system for measurement accuracy enhancement.

Following the fully investigation of CRD spectroscopy, a novel concept of CRU spectroscopy is proposed for trace gas detection in a fiber chemical sensing system. A comprehensive theoretical model of CRU spectroscopy for trace gas

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detection with dynamic gain of EDFA taken into account has been presented. The effects of the EDFA pump power, the EDF length, the input signal parameters and the intra-cavity loss to the features of CRU output signals are numerically simulated and discussed. The simulation results indicate that minimization of the net gain is extremely important for achieving high measurement sensitivity in a fiber CRU scheme. Therefore, adjusting the net gain by changing the cavity loss and even the input signal are fully analyzed. Meanwhile, optimization of the active fiber length enables to degrade the power fluctuation and to keep the CRU in the best performance.

With the guidance of the simulation, CRU fiber chemical sensing system is experimentally conducted. In this study, the characteristics of the CRU output power is investigated as a function of the EDFA pump current, input signal and the total intracavity loss. The experiments verify the simulation results that the EDFA, the input signal and the cavity parameter will all affect the CRU performance. The experiments also have indicated that minimization of the net gain is extremely important for achieving high measurement sensitivity in a fiber CRU scheme. The minimum detectable concentration of 300ppm is achieved at the net gain of 0.42dB, 4 times smaller than that from CRD experimental result, which proofs the superiority of the CRU scheme and shows a promising potential for CRU fiber loop in the application of chemical sensing systems.

In our final part of work, CRD and CRU spectroscopic techniques are applied for bio-sensing area. LPG CRD/CRU refractive index sensors in the fiber loop are set up. The ring-down/up times and the LPG transmission loss with the changes of refractive index of the measurement materials are investigated. By detecting the

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various decays of the attenuation losses at different ambient refractive indices, the sensitivities of the sensors are evaluated. The experimental results indicate that the LPG CRD/CRU sensors display good linear responses in the index region of 1.35-1.43, with slopes of approximately -90dB. The sensitivities could achieve around -530 μ s, with ring-up/down time changes of -43 μ s. And by the analysis, the minimum detectable refractive index from the CRU is smaller than the CRD scheme, 1.72×10^{-5} comparing of 4.73×10^{-5} in CRD, which presents a potential for the CRU fiber loop to the high-sensitive and highly demanded bio-sensing applications.

8.2 Future Work Recommendations

For future work recommendations, sensitivity is the main limitation to realize commercialization or expand the range of applications of the optical fiber chemical sensors. Therefore, sensitivity improvement and the search for suitable applications of the developed spectroscopic techniques are our two main recommended directions. Looking into the future, we would like to recommend the following areas:

- Passive and active fiber cavity ring-down (CRD) spectroscopy for other sensing applications. In our work, due to the limitation of the laboratory condition, the passive fiber CRD spectroscopy is merely applied for strain sensing area. However, due to its high sensitivity, it could be applied to temperature, bending, pressure and other sensing sectors compatible with other sorts of sensors such as long period grating (LPG) and micro-groove.
- Multiple-gas detection. In our experiment, only the single gas was detected by the built-up CRD and CRU fiber loop. Multiple-gas detection, however, is a more practical requirement for the real industry setting. Multiple-gas detection, due to

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its large absorption region, however, may require a super-broadband light source, a highly tunable bandpass filter and photodetector with flat response and broad bandwidth. With the rapid development of the optical equipment, we suppose the practical prototypes could be realized in the near future.

- Further development of high-sensitivity spectroscopic technique. Although in this thesis, CRD and CRU spectroscopic based sensors both demonstrate good sensitivity comparing with those fiber sensing systems by other modulation techniques, the sensitivity, however, still cannot compete with the bulky counterparts. The main reason is due to the lower sensitivity of the fiber devices. However, optical fiber sensors really show great superiority due to attractive features of the fibers. Therefore, the development of the highly sensitive optical devices, may further to perfect the CRD and CRU sensing systems. For example, with a photodetector with smaller minimum detectable power, more output pulses from the CRD fiber loop could be detected, and thus the signal acquisition and exponential fit of the ring-down time will be enhanced, which will improve the sensitivity of the CRD sensing system. Furthermore, to improve the stabilities of the optical devices, e.g. the EDFA and variable attenuator, the net loss in the CRD fiber loop or the net gain in the CRU fiber loop will be more stable and easier to be kept at a small value. As the analysis from Chapters 5 and 6, those stable and small net loss/ net gain will guarantee high sensitivities for the CRD/CRU fiber loops.
- Last but not the least, LPG CRD and CRU fiber loops are proposed for bio-sensing. These schemes may also be applied to medical or biomedical applications, such as cancer cells detection. The refractive index of the normal

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cell is different from that of the cancer cell, so by reading this refractive index change, the abnormal cell could be detected. It may also detect the obstruction in the endotracheal tube which is used to help patients to breathe as well. When there is blockage by the secretion (such as saliva and substances e.g., mucus or phlegm, from the respiratory tract) located in the sensing region of LPG, the resonant peak of LPG and the peak amplitude will shift. By this means, the presence and the location of the secretion will be detected instantly and according methods to clear up this obstruction could be applied. Therefore, there will exist broad applications and potentials for this LPG CRD/CRU sensing system.

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