All-optical processing technologies for next generation optical networks

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**NANYANG
TECHNOLOGICAL
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**ALL-OPTICAL PROCESSING TECHNOLOGIES FOR
NEXT GENERATION OPTICAL NETWORKS**

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2012

All-Optical Processing Technologies for Next Generation Optical Networks

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Summary

All-optical processing technologies are highly desirable for next generation optical networks because they can resolve the electrical bottleneck issues. All-optical processing technologies span many research areas, which include optical buffering, optical logic gates, optical wavelength conversion/multicasting, optical signal regeneration, ultra-fast optical switching, optical signal modulation format conversion, de-multiplexing of optical time division multiplexing (OTDM) signal, optical data exchange, and etc. This thesis focuses on two aspects of all-optical processing technologies; namely, optical buffering and wavelength multicasting.

First, we experimentally demonstrated an optically controlled loop buffer, which utilized a semiconductor optical amplifier (SOA)-based loop mirror as a fast switch to realize the writing and reading of optical data packets within this buffer and a circulator-based optical reflector to achieve internal re-circulations. According to the experimental results, the proposed loop buffer has better performance in terms of number of achievable re-circulations, compared to other similar loop buffer structures. In addition, the number of re-circulations can be significantly increased while maintaining acceptable performance degradation by using negative instead of positive control method.

Next, we devised and experimentally demonstrated an all-optical wavelength multicasting scheme based on four-wave mixing (FWM) effect in a highly nonlinear fiber (HNLF) Sagnac loop mirror. Normally when the number of pumps used increases

to three or more, there is a possibility that the pump-pump generated idlers will have the same wavelength as the multicast channels. By using a loop mirror in the proposed design, the multicast channels and signal will be filtered out from the pumps and pump-pump generated FWM idlers. Thus, even when the wavelength of a multicast channel overlaps with the pump-pump generated idler, clear eye diagram can be observed. In the experimental demonstration, six and ten multicast channels were successfully demonstrated by using two- and three-pump lasers, respectively. Both on-off keying (OOK) and differential phase-shift keying (DPSK) signals at 10-Gbit/s were demonstrated experimentally.

As FWM-based wavelength multicasting scheme has a drawback of polarization dependent operation, we proposed and experimentally demonstrated a practical optical wavelength multicasting scheme based on the FWM effect with reduced polarization sensitivity using either an HNLF or an SOA. The polarization sensitivity was significantly reduced from more than 20 dB to approximately 5 dB using the HNLF and 2.5 dB using the SOA in the experiments. Comprehensive comparisons of the performance differences between using the HNLF and SOA for this proposed multicasting scheme were carried out. By using three co-polarized probes, seven OOK and DPSK multicast signals at 10-Gbit/s were demonstrated.

Finally, by combining cross-gain modulation (XGM) and cascaded FWM effects in an SOA, seven 10-Gbit/s OOK multicast channels with 100 GHz spacing were demonstrated by using a single-pump laser source. It is highly desirable to obtain as many multicast channels as possible by using fewer pump lasers, which can reduce the implementation cost. To the best of the author's knowledge, the number of multicast

channels that were demonstrated is the highest reported so far for single-laser configuration with an SOA.

This thesis provides detailed description of the experimental setups, analyses of results, and how the work could be further extended.

List of Abbreviations

ASE	Amplified Spontaneous Noise
AWG	Arrayed Waveguide Grating
BER	Bit Error Rate
BTB	Back-to-Back
cw	Clockwise
ccw	Counter-clockwise
CE	Conversion Efficiency
CFBG	Chirped Fiber Bragg Grating
CPO	Coherent Population Oscillation
CROW	Coupled-Resonator Optical Waveguide
CW	Continuous Wave
DCF	Dispersion Compensating Fiber
DFB	Distributed Feedback
DFG	Difference-Frequency Generation
DLOB	Dual Loop Optical Buffer
DPSK	Differential Phase-Shift Keying
DSF	Dispersion Shift Fiber
DWDM	Dense Wavelength Division Multiplexing
EAM	Electro-Absorption Modulator
EDFA	Erbium Doped Fiber Amplifier
EIT	Electromagnetically Induced Transparency

FBG	Fiber Bragg Grating
FDL	Fiber Delay Line
FF	Fixed-wavelength Filter
FOPA	Fiber Optical Parametric Amplifier
FPLD	Fabry-Pérot Laser Diode
FWM	Four-Wave Mixing
HNLF	Highly Nonlinear Fiber
IM	Intensity Modulator
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
LD	Laser Diode
MZI	MachZehnder Interferometer
NF	Noise Figure
NFOEC	National Fiber Optics Engineers Conference
NOLM	Nonlinear Optical Loop Mirror
NPR	Nonlinear Polarization Rotation
NRZ	Non-Return-to-Zero
OC	Optical Coupler
OEO	Optical-Electrical-Optical
OFC	Optical Fiber Communication Conference
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-Off Keying
OPS	Optical Packet Switching
OSA	Optical Spectrum Analyzer

OSC	Oscilloscope
OSNR	Optical Signal-to-Noise Ratio
OTDM	Optical Time Division Multiplexing
PB	Polarization Bi-stable
PBS	Polarization Beam Splitter
PC	Polarization Controller
PCF	Photonic Crystal Fiber
PM	Phase Modulator
PM-WDM	Polarization Maintaining Wavelength Division Multiplexer
PPG	Pulse Pattern Generator
PPLN	Periodically Poled Lithium Niobate
PRBS	Pseudo-Random Bit Sequence
PSA	Phase Sensitivity Amplifier
QD	Quantum Dot
QPM	Quasi-Phase Matching
RZ	Return-to-Zero
SBS	Stimulated Brillouin Scattering
SFG	Sum-Frequency Generation
SLAOM	Semiconductor Laser Amplifier in a Loop Mirror
SMF	Single Mode Fiber
SOA	Semiconductor Optical Amplifier
SOP	State of Polarization
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering

SSB	Single-Side Band
TEC	Temperature Controller
TF	Tunable-wavelength Filter
TOAD	Terahertz Optical Asymmetric De-multiplexer
TWC	Tunable Wavelength Converter
VCSEL	Vertical-Cavity Surface-Emitting Laser
VOA	Variable Optical Attenuator
VSF	Vestigial Side-Band
WC	Wavelength Conversion
WDM	Wavelength Division Multiplexer
XAM	Cross-Absorption Modulation
XGM	Cross-Gain Modulation
XPM	Cross-Phase Modulation

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Chapter 1 Introduction

Dr. Charles Kuen Kao, sometimes referred to as the “father of fiber optical communications”, was awarded the Noble Prize for physics in 2009 for groundbreaking achievements concerning the transmission of light in fibers for optical communication. Many of the students, researchers, professors, and engineers who work in the field of optical communications and related disciplines were elated by this exciting news.

Since the invention of the laser in 1958 followed by the development of low loss optical fibers in the early 1970s, research and application of optical fiber communications have progressed by leaps and bounds. Dense wavelength division multiplexing (DWDM) and the availability of erbium doped fiber amplifier (EDFA), significantly introduce another multi-fold increase in the capacity of the optical fiber transmission system [1].

Today, optical fiber communications play a crucial role in our daily life as the foundation of the information superhighways that allow huge data traffic flows among cities both geographical near and far, which, in turn, enables everyone to be connected in cyberspace. The information-carrying capacity of optical fiber over long distances is unsurpassed by any other media. Such a capacity is possible, due to the following unique set of salient features that optical fiber offers: huge bandwidth, small size, low weight, low cost of fabrication, low signal loss, immunity to electrical interference, and high safety and security [1].

1.1 Background and motivations

Since the inception of the Internet, Internet users and traffic have grown exponentially [2]. More and more people all over the world can currently afford to buy a computer and access the Internet. Fig. 1.1 shows the growth of the number of Internet users from 1995 to 2010 [3]. The number of Internet users can be seen to have increased significantly from only 16 million in 1995 to about 1650 million in 2010. It is also worthwhile to note that terminal devices connected to the Internet are no longer only computers, as more smart personal devices, such as iPhones and Androids, have the ability to access the Internet. This trend further increases Internet usage.

In addition to existing applications, such as email and the World Wide Web, new applications, such as Facebook, YouTube, online gaming, e-health technology, e-commerce, high-definition TV and movie, and video conferencing, among others, are becoming more and more popular and essential in our daily life. These new applications contribute significantly to the explosive growth of Internet traffic.

Internet traffic doubled every 21 months from 1969 to 1982, and the doubling period shortened to 9 months between 1983 and 1997. From 1998 to 2008, Internet traffic doubled every 6 months [4]. It would not be a surprise if the doubling period were to shorten further in the future. Just imagine how large the Internet traffic will be if all YouTube videos were to become high definition!

Therefore, it is a matter of some urgency to scale up Internet capacity in order to handle such an explosive growth in traffic.

Fig. 1. 1. Internet users' growth in the world from year 1995 to year 2010. Source: Internet World Statistics [3].

Increasing the data rate per wavelength and exploiting the transmission bandwidths of the fibers can enhance the transmission capacity. Presently, 40-Gbit/s per wavelength optical fiber transmission system is commercially available, and 100-Gbit/s per wavelength fiber transmission system will be available in the near future [5]. At the same time, ultra-high data rate single-wavelength systems have been pushing toward 1-Tbit/s and beyond in the laboratories in recent years [6-10]. Advancing in parallel is the expansion of the wavelength spectrum of optical fibers to a wider range of 1260 nm to 1675 nm, which could provide over 50 THz of bandwidth for transmission [1].

By combining the technologies of DWDM, orthogonal frequency division multiplexing (OFDM), and coherent detections, the system transmission capacity can

be significantly enhanced. In the post-deadline session of the latest Optical Fiber Communication Conference/National Fiber Optics Engineers Conference (OFC/NFOEC) 2011, researchers set two records for the world's largest capacity transmission systems, which were 101.7-Tbit/s over a 165-km single mode fiber (SMF) and 109-Tbit/s over a 16.8-km homogeneous multi-core fiber, respectively [11, 12].

Many design issues need to be addressed as the data rate per wavelength increases to 40-Gbit/s and beyond [13]. One of the most important issues is the electrical bottleneck [14]. It is acceptable to use optical fibers to transmit such high speed and large capacity optical signals. However, some signal processing functions, such as signal regeneration, wavelength converting/multicasting, buffering, switching, and modulation format conversion, are currently all handled in the electrical domain. This means optical signal needs to be first converted to electrical signal and then converted back to optical signal for transmission after these processes. The optical-electrical-optical (OEO) conversion operation is expensive when the data rate reaches 40-Gbit/s and beyond. Moreover, OEO conversion consumes considerable energy and requires means to dissipate heat, which, in turn, increases the implementation cost.

All-optical processing technologies, which process signals entirely in the optical domain without the OEO conversion, are highly desirable because they bypass the electrical bottleneck issue. All-optical processing technologies mainly include optical buffering, optical logic gates, optical wavelength conversion/multicasting, optical signal regeneration, ultra-fast optical switching, optical modulation format conversion, de-multiplexing of optical time division multiplexing (OTDM) signal, and optical data exchange [15-35].

All-optical processing technologies are implemented by applying certain nonlinear optics phenomena in some devices which have high nonlinearity [35]. These nonlinear optics phenomena include self-phase modulation (SPM), cross-gain modulation (XGM), cross-phase modulation (XPM), cross-absorption modulation (XAM), four-wave mixing (FWM), fiber optical parametric amplifier (FOPA), nonlinear polarization rotation (NPR), stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), and cascaded sum- and difference frequency generation (SFG/DFG) [35]. In contrast, the devices typically used for nonlinear processing are semiconductor optical amplifier (SOA), highly nonlinear fiber (HNLF), dispersion shifted fiber (DSF), photonic crystal fiber (PCF), periodically poled lithium niobate (PPLN) waveguide, silicon photonic nanowires, Chalcogenides, SOA-MachZehnder interferometer (SOA-MZI), carbon-nanotube, and electro-absorption modulator (EAM) [15-35].

In summary, there are many research topics on all-optical processing technologies. However, this thesis mainly focuses on the all-optical buffering and all-optical wavelength multicasting technologies.

1.2 Contributions of the thesis

The main contributions of this thesis are summarized as follows:

1. An optically controlled loop buffer was proposed and experimentally demonstrated. It utilized an SOA-based loop mirror as a fast switch to realize the writing and reading of optical data packets within this buffer and a circulator-based optical reflector to achieve internal re-circulations. By adding fibers with different lengths between the loop mirror and the circulator, a variable delay time for each

circulation can be obtained. The buffering performances of the 2.5-Gbit/s and 10-Gbit/s optical data packets were demonstrated. This loop buffer has the merit of improved performance on number of achievable re-circulations, compared to other similar loop buffer structures. The influence of the two different control signal formats (positive and negative control methods) on packet signal degradation during buffering was examined. According to the results obtained, the packet data signals, both at 2.5-Gbit/s and 10-Gbit/s, can still remain in good quality after 24 and 16 circulations, respectively, by using the positive control method. The number of circulations obtained can go as large as 36 for the 2.5-Gbit/s data packet when the negative control method is used (see Chapter 3).

2. An all-optical wavelength multicasting scheme using FWM in an HNLF Sagnac loop mirror was proposed. In the FWM-based multicasting scheme, the number of multicast channels that can be produced depends highly on the number of pump lasers used. As the number of pump laser increases, the idlers generated among pump-pump lasers will be the crosstalk to the multicast channels. Using the loop mirror has the advantage that even when the wavelength of a multicast channel overlaps with that of the pump-pump generated idler, a clear eye diagram can still be observed. Six and ten 10-Gbit/s multicast channels, which are compliant with the international telecommunication union (ITU) grid, were successfully demonstrated by using two- and three-pump lasers, respectively. Multicasting of the on-off keying (OOK) and differential phase-shift keying (DPSK) signals were both successfully demonstrated. The maximum power penalty of the multicast channels was less than 3.5 dB. Furthermore, compared with the non-loop configuration, a power penalty improvement of up to 1.2 dB can be achieved in this proposed Sagnac loop configuration (see

Chapter 4).

3. As FWM-based wavelength multicasting scheme has a drawback of polarization dependent operation, a practical all-optical wavelength multicasting scheme based on the FWM effect with reduced polarization sensitivity was demonstrated in both an HNLF and an SOA. Comprehensive comparisons of the performance differences between using the HNLF and SOA for this proposed multicasting scheme were carried out. Seven multicast channels were experimentally demonstrated by using three co-polarized probes and a modulated signal. The polarization sensitivity was significantly reduced from more than 20 dB to approximately 5 dB using the HNLF and to 2.5 dB using the SOA. The low polarization sensitivity led to a difference of less than 1 dB in the power penalty of the multicast channels at a bit error rate (BER) of 10^{-9} . In addition, we compared the multicasting performance of the OOK and DPSK signals using the proposed scheme and found that the power penalties of the DPSK multicast channels in the HNLF and the SOA were less than 1.25 dB and 1.1 dB, respectively, and the power penalties of the OOK multicast channels were less than 1.5 dB and 3.1 dB in the HNLF and the SOA, respectively (see Chapter 5).

4. Combining XGM with the cascaded FWM effects in an SOA, seven multicast channels with 100 GHz spacing of an ITU standard grid were demonstrated using only a single pump laser source. To the best of the author's knowledge, the number of multicast channels demonstrated is the highest reported to date when only one laser is used in an SOA. It is highly desirable to replicate as many multicast channels as possible by using fewer pump lasers, which can reduce the implementation cost. Error-free operations of the seven 10-Gbit/s OOK multicast channels were achieved with a power penalty of less than 3.3 dB (see Chapter 6).

1.3 Thesis outline

The thesis is organized in seven chapters.

Chapter 1 gives brief introductions, background and motivations, and the major contributions of this thesis.

Chapter 2 reviews the current states of the optical buffering and wavelength multicasting technologies. In addition, the advantages and disadvantages of using SOA and HNLF are compared in this chapter.

Chapter 3 presents the proposed optically controlled loop buffer with improved performance on the number of achievable re-circulations. The operation principle of this loop buffer and the experimental results are described.

Chapter 4 describes the optical wavelength multicasting scheme using FWM in an HNLF Sagnac loop mirror. The advantages of using the Sagnac loop mirror are addressed, and the experimental results of using two- and three-pump lasers for multicasting in loop and non-loop configurations are demonstrated. Moreover, OOK and DPSK signals are demonstrated for multicasting performance.

Chapter 5 describes original research work on polarization sensitivity reduced optical wavelength multicasting based on the FWM effect. The operation principle of this scheme is described in detail. Both OOK and DPSK signals' multicasting are also demonstrated. In addition, a performance comparison of HNLF and SOA for this multicasting scheme is included.

Chapter 6 presents another optical wavelength multicasting scheme, which can generate seven multicast channels in an SOA using only single pump laser. The operation principle and the experimental results are discussed there.

Chapter 7 concludes the thesis and proposes some interesting work for the future.

Chapter 2 Literature Survey

In this chapter, we present a brief literature survey of the optical buffering and optical wavelength multicasting technologies, including recent research advances. However, the implementation details and measurement results of these schemes are largely omitted, due to space limitations.

2.1 Optical buffering technologies

2.1.1 Introduction

Optical buffering has attracted considerable attention because it is one of the most important enabling technologies for next generation optical networks. Optical buffering, as well as wavelength conversion (WC) and space-deflection routing [36], can resolve the contention problem and be applied to slotted optical packet switching (OPS) network to synchronize the packets from different input ports [37].

Optical buffers can be categorized into a few different types. One possible approach is based on slow light [15], [38-48]. However, this technology still has a long way to go before it could be used in practice because of the limited delay-bandwidth product [15]. Recently some researchers proposed using dispersions in dispersion compensating fibers (DCF) or chirped fiber Bragg grating (CFBG) to delay the optical signal [49-52]. This scheme is not affected by the delay-bandwidth limitation, as is the case for slow light buffers; however, the dispersions could significantly degrade the quality of high

data rate signal. Another optical buffering technology is based on fiber delay line, which has the merits of low loss and cost effectiveness. Unfortunately, the large physical size of the fiber delay line makes it difficult to be integrated with other components [53-63].

2.1.2 Optical buffering based on slow light effect

Several methods are possible to realize the slow light effect, such as electromagnetically induced transparency (EIT) [38], the coherent population oscillation (CPO) [39], SRS [40], Raman-assisted parametric amplification [41], coupled-resonator optical waveguide (CROW) [42], polarization bi-stable vertical-cavity surface-emitting laser (PB-VCSEL) [43], and the SBS effect [44-48].

Among these schemes, the SBS slow light offers several advantages compared with the other methods [45]: low relative threshold pump power, room temperature environment, and compatibility with existing telecommunication technology.

However, the gain bandwidth of the SBS is only on the order of tens of MHz, which is too small for practical application. Thus, other approaches, such as phase or noise modulation of the pump [44-46] or using double Brillouin pumps [47], were proposed to increase the slow light bandwidth. However, the SBS gain is reduced at the expense of expanding the bandwidth. As a result, the delay time that can be achieved, which is proportion to the gain, is reduced. Due to the uneven gain bandwidth, the issue of pulse broadening after SBS slow light buffering also needs to be addressed [48].

In summary, slow light based optical buffers still have a long way to go before

becoming practical. One of the essential research issues is how to overcome the delay-bandwidth limitation.

2.1.3 Optical buffering based on dispersions in DCF or CFBG

Recently, some researchers proposed a novel optical buffer using the dispersions in DCF or CFBG [49-52]. Due to the large dispersion slopes in DCF and CFBG, optical signals at different wavelengths experience different delays. Thus, different delay times can be achieved by converting the signal into different wavelengths before undertaking the DCF or CFBG.

Fig. 2.1 illustrates the general concept of this buffer. At the input, a tunable wavelength converter (TWC) is required to convert the wavelength of the input optical signal into certain wavelength that can experience the desired delay in the dispersion mediums (DCF or CFBG). At the output, another TWC is used to convert the wavelength of the delayed optical signal back to its original. Compared to the slow light buffer, this buffer does not have the issue of limited delay-bandwidth product. However, the dispersions can degrade the signal quality when the data rate of the signal increases. Therefore, the phase conjugation method was proposed to reduce such degradation, which can also further increase the maximum delay time [50-52].

It was reported that more than one microsecond time delays were achieved with relatively fine delay time resolution [50].

Fig. 2. 1. General concept of optical buffer based on dispersion in DCF or CFBG.

2.1.4 Optical buffering based on fiber delay line

Fiber delay line based buffers have been regarded as the most feasible solution. For this buffer, the objective is to increase the propagation distance of light in the medium in order to attain the desired delay. Thus, the ability to reconfigure dynamically within a few nanoseconds, even when the signal is already being buffered, becomes a major research topic. In addition, because only a 5- μ s delay time is achievable by going through 1-km long fibers, which is quite bulky in size, the problem of bulky fiber needs to be addressed when implementing this buffer.

2.1.4.1 Multistage delay line

Fig. 2. 2. Logarithmic delay line.

As shown in Fig. 2.2, a simple conventional fiber based buffer is the logarithmic delay line [53]. The incoming optical signal enters a pipeline of cascaded 2×2 fast

optical switches. One of the outputs of the switch is connected to a delay line, while the other is connected straight through to the following switch, providing a choice of introducing a delay or not. By controlling these fast switches, variable delays can be attained.

Fig. 2. 3. Broadcast and select buffer Type 1.

Fig. 2. 4. Broadcast and select buffer Type 2.

Another form of the multistage delay line is based on the broadcast and select structure [54] (see Fig. 2.3 and Fig. 2.4). In this structure, the delay time is tuned by controlling the SOA on-off gates.

Increasing the number of stages in the above buffer structures can enhance the maximum time delay capacity. However, the insertion loss and crosstalk also increase with the increasing number of stages in the logarithmic delay line. Large coupling loss and accumulated amplified spontaneous emission (ASE) noise from the SOA degrades the signal quality in each broadcast and select stage. Therefore, multistage delay line based buffer is not scalable.

2.1.4.2 Folded-path delay line

Fig. 2. 5. Dynamically reconfigurable folded-path delay line based on SOA on-off gates [55].

Fig. 2.5 and Fig. 2.6 show two different forms of dynamically reconfigurable folded-path buffer [55, 56]. In this buffer, the optical signal goes through the fiber delay line twice, which can reduce the length of the fiber by half. In addition, dynamical reconfiguration can be achieved by controlling the SOA on-off gates in Fig. 2.5. In contrast, the reconfiguration in Fig. 2.6 is adjusted by modifying the TWC to

match the reflect wavelength of the fiber Bragg grating (FBG).

Compared to the multistage delay line based buffer, this folded-path buffer has the advantages of being more scalable and compact.

Fig. 2. 6. Dynamically reconfigurable folded-path delay line based on TWC and FBG reflector [56].

However, because the fiber delay line can be used only twice, more sections will be required in Fig. 2.5. The TWC with a large wavelength tuning range is necessary in Fig. 2.6 when constructing a large capacity buffer.

2.1.4.3 Re-circulating delay line

The re-circulating buffer was first proposed in 1996 [57]. As depicted in Fig. 2.7, an optical packet signal traverses a delay line loop repeatedly until it is ready to be read out from the buffer. The variable delay time is obtained by electronically controlling the two SOA on-off gates. The SOA gate in the loop can amplify the signal to compensate for the insertion loss during each circulation. Though a large delay time can be achieved by increasing the number of circulations, this buffer structure still

suffers from a large insertion loss as the number of circulation increases. Moreover, the accumulated ASE noise from the SOA is detrimental to the signal.

Fig. 2. 7. Re-circulating buffer.

In [58], a novel dual loop optical buffer (DLOB) based on a 3×3 collinear fiber coupler was proposed and designed. In this structure, a semiconductor laser amplifier in a loop mirror (SLALOM) provides the function of reading and writing [59], and a fiber loop mirror works as a reflector. As illustrated in Fig. 2.8, a signal, launched from the circulator to the 3×3 collinear fiber coupler, is split into clockwise (cw) and counter-clockwise (ccw) traveling signals in loop 1. When cw and ccw signals meet again at the coupler, the signal is reflected to port 2 of the coupler and leaves from this DLOB. If an optical control signal is coupled into the SOA through the wavelength division multiplexer (WDM) coupler, a phase difference of π between the cw and ccw signals is introduced by means of the XPM effect in SOA, the signal will be split into loop 2 and no signal will appear at port 2 of the coupler. This means that the signal has been written into the DLOB. The signal circulates between loop 1 and loop 2 until the desired delay time reaches. Next, another optical control signal is injected into the SOA,

leading to a phase difference of π between the two cw and ccw traveling signals. The buffered optical signal will leave the DLOB through port 2 of the coupler, which means the optical signal is being read out from the buffer.

Fig. 2. 8. DLOB based on a 3×3 collinear fiber coupler (courtesy of [58]).

Compared to the re-circulating buffer mentioned above, this DLOB is optically controlled, and no large insertion loss exists as the number of circulation increases. However, optimizing the two polarization controllers (PC) in these two loops makes this buffer more complicated. In addition, the 3×3 collinear fiber coupler might not be easy to fabricate.

There are some other optical loop buffers that are optically controlled. For example, in [60], a Sagnac interferometer and phase sensitive amplifier (PSA) were employed to read optical data packets through the XPM effect, and a nonlinear optical loop mirror (NOLM) was employed to write the stored packet. In addition, the PSA has the inherent characteristic of stabilizing the “one” and “zero” of the buffered signal,

thereby eliminating the ASE noise.

Furthermore, by using a terahertz optical asymmetric de-multiplexer (TOAD) as an optical 2R regenerator in the fiber loop, the accumulated ASE noise in the optical packet can be eliminated in every round trip [61]; thus, the number of circulations can be increased further. However, the implementation cost will be greatly increased if a PSA or 2R regenerator is incorporated in the buffer structure.

Fig. 2. 9. Electrically tunable delay line using an optical single-side-band modulator [64].

In addition to using SOA as the medium for the XPM induced nonlinear phase shift, DSF and PCF can also be employed as the nonlinear medium for the XPM effect [62, 63].

To date, the above proposed loop buffer structures have a common drawback in that the length of buffered optical packet is limited by the loop length. In other words, the length of the buffered packet should be less than the loop length. In [64], a novel loop buffer using an optical single-side-band (SSB) modulator was proposed to buffer the packets of arbitrary length (shown by Fig. 2.9). The number of circulations in the loop is determined by the SSB tuning frequency. Though variable length can be buffered in this structure, the high insertion loss due to the SSB modulator limits the number of re-circulation to just a few.

In addition to using the SSB modulator for frequency detuning, a parametric wavelength converter, working as a wavelength shift, can also be employed to detune the wavelength of the buffered signal [65]. The insertion loss inside this loop is much lower because the parametric wavelength converter has high conversion efficiency (CE) [65].

2.1.5 Summary

Table 2.1 compares the performances of different optical buffers in terms of delay time range, tuning resolution of delay time, transparency to data rate and modulation format, etc.

Optical buffering is still a hot research topic as there is no effective way to design an optical buffer that demonstrates the same functions as those of an electrical buffer. There is a long way to go before the optical signal can be arbitrary written into and read from an optical buffer without or with little signal degradation.

Table 2. 1. Performance evaluation of different optical buffers.

Type of buffer	Delay time range	Tuning resolution	Transparency to data rate and modulation format	Disadvantages
Slow light (SBS) [45]	Several signal pulses (small)	Continuous (good)	Yes	Requires high power pumps and nonlinear devices for SBS effect; Delay-bandwidth product limitation
Dispersion in DCF/CFBG [49-52]	Microseconds in DCF (medium)/ Several hundreds of picoseconds in CFBG (small)	Continuous (good)	Yes	Two TWCs are required, each consists of pumps, tunable filters and amplifiers; Dispersion degrades high speed data signal
Multistage fiber delay line [53, 54]	Seconds (large)	Discrete (medium)	Yes	Fast tuning 2×2 optical switches or on-off SOA gates are required; Insertion loss; Crosstalk and ASE noise from SOA; Bulky
Folded-path delay line [55, 56]	Seconds (large)	Discrete (medium)	Yes	On-off SOA gates or two TWCs are required; ASE noise from SOA; Bulky (although it is reduced by half due to using the fiber twice)
Re-circulating delay line (DLOB) [58]	Around ten re-circulations, from microseconds to seconds (large)	Discrete (poor)	Transparent to the modulation format, the data rate is limited by the carrier recovery time of the SOA	Nonlinear medium, such as SOA, is required to realize fast switching; ASE noise from SOA; The buffered optical signal should be smaller than the loop length

2.2 Optical wavelength multicasting technologies

2.2.1 Introduction

Optical wavelength multicasting, whereby an input signal is simultaneously replicated onto multiple selected destinations, is another key technique for implementing a multicast-capable optical network. The efficiency and throughput of DWDM optical networks can be improved significantly in the presence of multicast traffic [66]. Multicasting can be implemented in the network [67-72] or physical layers [18, 19], [27], [73-103]. In this thesis, we only focus on physical layer multicasting.

Substantial effort has been made to realize all-optical wavelength multicasting [18,

19], [27], [73-103]. Based on the working principle, these techniques can be classified into broadcast and select structure [73], SPM in PCF or HNLF [74, 75], XGM in SOA or in FOPA [76-80], XPM in HNLF Sagnac loop mirror or SOA-MZI [81-84], NPR in SOA [85], single-pump modulated FOPA or two pumps self-seeded FOPA [18], [86-88], XAM in EAM [19], [89, 90], cascaded SFG/DFG in PPLN waveguide [91], injection locking in Fabry-Pérot laser diode (FP-LD) [92], and FWM in PCF, HNLF, Bismuth-oxide HNLF, DSF, SOA, silicon photonic nanowires, and lead silicate fiber [27], [93-100].

2.2.2 Multicasting based on broadcast and select structure

Fig. 2. 10. Broadcast and select structure based multicasting scheme.

Fig. 2.10 shows the broadcast and select multicasting structure. The input signal is first split to all branches, and the SOA on-off gates select the desired multicasting ports [73]. This scheme has the merits of data rate and modulation format transparency. However, it is not scalable, due to the high split loss when the number of multicast

channels increases. Moreover, all the multicast channels generated have the same wavelength, which may not be practical in certain circumstances where the multicast channels should be on different wavelengths [18].

2.2.3 Multicasting based on the SPM effect

It is well known that the SPM effect can lead to spectral broadening of optical pulses [35]. By splicing the broadened spectrum of the optical pulse, several multicast channels can be generated [74, 75]. Fig. 2.11 describes the general idea behind this multicasting scheme. The return-to-zero (RZ) optical signal is firstly amplified to a high-power level before being coupled into the nonlinear medium (PCF or HNLF) [74, 75]. Next, the spectrum of the optical signal is broadened in the nonlinear medium, and an arrayed waveguide grating (AWG) is used to splice the multicast channels.

Fig. 2. 11. The concept of splicing SPM broaden spectrum for multicasting.

This multicasting scheme demonstrates the merits of a polarization-insensitive operation and of not using an external pump laser source. Unfortunately, it can be only applied to the OOK signal for multicasting. Moreover, the pulse of the signal should be narrow, and a high input power is required in order to significantly broaden the signal

spectrum.

2.2.4 Multicasting based on the XGM effect

XGM has been widely used in SOA because of its simplicity, compactness, stability, and polarization independence. Fig. 2.12 demonstrates the operation principles of this wavelength multicasting scheme in an SOA [76]. Several low-power continuous wavelength (CW) probes and a high-power OOK modulated signal are coupled in the SOA. When the signal is at a high level, '1', the gain of the SOA is saturated, and the probes do not have any gain in the SOA. However, when the signal is at a low level, '0', the gain of the SOA is not saturated and the probes are all amplified. As a result, the low-power probes are modulated by the high-power OOK signal.

Fig. 2. 12. XGM based wavelength multicasting in an SOA.

As the data format of the multicast channels is inverted compared to the original format due to the XGM effect, double stages of XGM were proposed in two successive SOAs to convert the multicast channels' format back to the original format [78, 79]. Moreover, the ASE noise in an SOA can also be modulated through the XGM effect, and four 622-Mbit/s multicast channels can be obtained by spectrum splicing the

modulated ASE noise [80].

The XGM-based multicasting scheme is modulation format dependent, which can only be applied on OOK signal. In addition, the data rate of the multicast signal is limited by the carrier recovery time of the SOA.

2.2.5 Multicasting based on the XPM effect

XPM-based multicasting is commonly applied in interferometric schemes, as in the Sagnac loop mirror or in SOA-MZI [81-84]. The operation principle of SOA-MZI is illustrated in Fig. 2.13. Several low-power CW probes are divided equally into the two arms of SOA-MZI, and they experience identical phase shifts in each arm. These probes are transmitted through constructive interference. If a high-power OOK signal at a different wavelength is injected into the arm of SOA 1 and the signal is also at '1', then the phase of all the probes in that arm will be changed due to the XPM effect in SOA 1. These probes will be transmitted through destructive interference if the phase shift of the probes is close to π . However, the probes will still be transmitted through constructive interference when the signal is at '0'. Thus, the data information of the signal is multicast to all the probes. The data format of the probes at the constructive interference port is inverted with respect to the input signal, whereas it is not inverted at the destructive interference port. The operation principle of a Sagnac loop mirror interferometer is quite similar to that of SOA-MZI [81]. Therefore, we will not discuss the XPM-based multicasting scheme implemented with the Sagnac loop mirror.

The primary shortcoming of using an XPM-based multicasting scheme is that it can only be applied on OOK signal. In addition, the data rate is constrained by the carrier

recovery time of the SOA.

Fig. 2. 13. XPM based wavelength multicasting in SOA-MZI.

2.2.6 Multicasting based on the NPR effect

Fig. 2.14 describes the general idea behind the NPR-based multicasting scheme [85]. The high-power OOK signal and several low-power CW probes are coupled into an SOA. By carefully controlling the polarization states of the input probes and the PC at the output of the SOA, the probes will go through Output 2 of the polarization beam splitter (PBS) if the signal is at '0'. However, when the signal is at '1', the polarization states of all the probes will be rotated, due to the NPR effect in the SOA. If the polarization rotation angle is 90 degree, the probes will go through Output 1 of the PBS [85]. Thus, the signal is multicast to the probes either at Output 1 or Output 2. The data format of the multicast channels at Output 2 is inverted to the original signal, whereas it is not inverted at Output 1.

Fig. 2. 14. NPR based multicasting in an SOA.

2.2.7 Multicasting based on the FOPA effect

One of the most effective FOPA-based multicasting schemes is single-pump modulated FOPA [18],[86]. As shown in Fig. 2.15, the signal is OOK modulated at the wavelength of the parametric pump. When the pump is at '1', the CW probes are amplified and the corresponding idlers are generated at the other side of the parametric pump. However, when the pump is at '0', which means that the pump power is notably low, the probes are not amplified, and the idlers cannot be generated as well. As a result, the signal information of the pump is multicast to the probes and to the idlers. By using 20 CW probes, a total of 40 multicast channels can be achieved. This number represents the largest number of multicast channels ever reported in the literature [18].

In spite of such a large number of multicast channels that can be generated in a single-pump modulated FOPA, only OOK signals can be used for multicasting, and the polarization-dependent operation of FOPA also needs to be addressed.

Fig. 2. 15. Operation principle of single-pump modulated FOPA based multicasting.

In addition to the single-pump modulated scheme, FOPA can be used as a FWM-based multicasting scheme [87, 88], the operation principle of which will be described in Section 2.2.10.

One interesting finding that needs to be addressed is the use of two parametric pumps by self-seeded FOPA [88]. In this scheme, two FWM idlers of high power are generated by the pump-pump non-degenerate FWM effect. Next, these two high-power idlers, serving as new pump sources, interact with the signal to generate new multicast channels via the FWM effect. However, the parametric pumps need to be phase modulated in order to suppress the SBS effect, which leads to crosstalk to the phase modulated multicast signal [87, 88].

2.2.8 Multicasting based on the XAM effect

The operation principle of this multicasting scheme, which is illustrated in Fig. 2.16, is quite straightforward. A high-power OOK signal and several CW probes are counter launched into the EAM. Nonlinear optical transmission is realized by applying

a high input signal to the EAM. When the signal is at '1', a transmission window is created and all the probes can be transmitted through the EAM. However, when the signal is at '0', the transmission window is closed and all the probes are blocked. Thus, the data information of the input signal can be multicast to all the probes [19], [89, 90]. The advantage of this scheme is that it is polarization insensitive. The disadvantages of this scheme are that it can only be used with OOK signal and the data rate of the signal is limited by the data rate of the EAM [19].

Fig. 2. 16. The general idea of XAM based multicasting.

2.2.9 Multicasting based on the cascaded SFG/DFG effect in PPLN

The operation principle of this multicasting scheme can be explained by means of Fig. 2.17. One pump laser and one signal are located symmetrically at both sides of the quasi-phase matching (QPM) wavelength of the PPLN. A sum signal is subsequently generated by the SFG process between the pump and signal. Next, through the DFG process between the sum signal and these CW probes, several multicast channels are

generated at the output of the PPLN [91]. This scheme is transparent to the modulation format and data rate of the signal. However, the power of the multicast channels is not high due to the low CE.

Fig. 2. 17. Multicasting based on SFG/DFG effect in PPLN.

2.2.10 Multicasting based on injection locking in FP-LD

The wavelength multicasting scheme based on injection locking in FP-LD is described in Fig. 2.18. A high-power OOK modulated signal and several low-power CW probes are coupled into the FP-LD. The wavelengths of the signal and all the probes need to be set at the longitudinal modes of the FP-LD; otherwise, no injection locking will be achieved. When the signal is at '0', no injection locking occurs, due to the low input power of the probes, all of the probes will be reflected back from the FP-LD. However, when the signal is at '1', the FP-LD will be injection-locked at the signal wavelength because the signal has higher power than do the probes, and the power of the probes will be suppressed from the FP-LD [92]. As such, the signal information is multicast to the probes. Similar to the XGM-based multicasting scheme, the data

format of the multicast channels is inverted with respect to the input signal. And it can only be applied on OOK signal for multicasting. In addition, the operation data rate is limited by the FP-LD itself [92].

Fig. 2. 18. Multicasting based on injection locking in FP-LD.

2.2.11 Multicasting based on the FWM effect

The origin of FWM lies in the nonlinear response of bound electrons of a substance to an electromagnetic field [35]. The FWM phenomenon is a third-order process that involves nonlinear interaction among four optical waves [35].

The general coupling equation for the FWM process in the fibers, which takes into account the SPM and XPM effects and pump depletion, can be expressed by [35]:

$$\frac{d\vec{A}_1}{dz} = -\frac{\alpha}{2}\vec{A}_1 + i\gamma[(|\vec{A}_1|^2 + 2\sum_{k \neq 1} |\vec{A}_k|^2)\vec{A}_1 + 2\vec{A}_2^* \vec{A}_3 \vec{A}_4 e^{i\Delta k z}], \quad (2.1)$$

$$\frac{d\vec{A}_2}{dz} = -\frac{\alpha}{2}\vec{A}_2 + i\gamma[(|\vec{A}_2|^2 + 2\sum_{k \neq 2} |\vec{A}_k|^2)\vec{A}_2 + 2\vec{A}_1^* \vec{A}_3 \vec{A}_4 e^{i\Delta k z}], \quad (2.2)$$

$$\frac{d\vec{A}_3}{dz} = -\frac{\alpha}{2}\vec{A}_3 + i\gamma[(|\vec{A}_3|^2 + 2\sum_{k \neq 3} |\vec{A}_k|^2)\vec{A}_3 + 2\vec{A}_1\vec{A}_2\vec{A}_4^*e^{-i\Delta k z}], \quad (2.3)$$

$$\frac{d\vec{A}_4}{dz} = -\frac{\alpha}{2}\vec{A}_4 + i\gamma[(|\vec{A}_4|^2 + 2\sum_{k \neq 4} |\vec{A}_k|^2)\vec{A}_4 + 2\vec{A}_1\vec{A}_2\vec{A}_3^*e^{-i\Delta k z}], \quad (2.4)$$

where $\vec{A}_j (j=1,2,3,4)$ is the slowly varying envelope of the optical field with a frequency at ω_j with a corresponding power that is given by $P_j = |\vec{A}_j|^2$. The fiber loss coefficient is denoted as α , and γ is the fiber nonlinear coefficient. Δk is the propagation constant mismatch, defined as:

$$\Delta k = \beta_3 + \beta_4 - \beta_1 - \beta_2, \quad (2.5)$$

where $\beta_j = \beta(\omega_j)$ ($j=1,2,3,4$) is the propagation constant in the fiber. Strong FWM occurs only if the phase mismatch nearly vanishes. Thus, the fibers and waveguides with zero dispersion and zero dispersion slopes are highly desirable for the FWM [35] [93, 94]. The phase matching condition in SOA, however, is immune [96].

A considerable amount of work on FWM-based multicasting scheme has been reported. Fig. 2.19 illustrates the general concept of this scheme. A signal at frequency ω_s ($\vec{E}_s$) and two high-power pumps at frequencies ω_{p1} and ω_{p2} ($\vec{E}_{p1}$ and $\vec{E}_{p2}$) are coupled to the FWM medium. The FWM medium can be HNLF, PCF, Bi-HNLF, SOA, silicon photonic nanowires, or lead silicate fiber [27], [87, 88], [93-100]. If the polarization states of the signal and pumps are co-polarized, several FWM idlers will be generated at the output, as can be seen in Fig. 2. 19.

Fig. 2. 19. Operation principle of FWM-based wavelength multicasting.

Taking the FWM wave ω_{p1P1S} as an example, the complex amplitude of this FWM idler can be expressed as [94]:

$$\vec{E}_f = \eta^{1/2} \vec{E}_{p1}^2 \vec{E}_s^* \exp[j(\omega_f t + \phi_f)], \quad (2.6)$$

where η denotes the CE of the FWM process, and ω_f and ϕ_f denote the frequency and phase of the FWM wave, respectively.

And

$$\omega_f = 2\omega_{p1} - \omega_s, \quad (2.7)$$

$$\phi_f = 2\phi_{p1} - \phi_s, \quad (2.8)$$

The power of this FWM wave is

$$P_f = \vec{E}_f \cdot \vec{E}_f^* = \eta P_{p1}^2 P_s, \quad (2.9)$$

Table 2.2 summarizes the frequency, phase, differential phase, and power information of all the FWM waves. The phase and amplitude of the pumps are constant.

Table 2. 2. Frequency, (differential) phase, power information of all the FWM waves.

FWM wave	Frequency (ω_f)	Phase (ϕ_f)	Differential Phase	Power
$\omega_{P_2P_2S}$	$2\omega_{P_2} - \omega_S$	$2\phi_{P_2} - \phi_S$	$-\phi_S$	$\eta P_{P_2}^2 P_S$
$\omega_{P_2P_2P_1}$	$2\omega_{P_2} - \omega_{P_1}$	$2\phi_{P_2} - \phi_{P_1}$	0	$\eta P_{P_2}^2 P_{P_1}$
$\omega_{P_1P_2S}$	$\omega_{P_1} + \omega_{P_2} - \omega_S$	$\phi_{P_1} + \phi_{P_2} - \phi_S$	$-\phi_S$	$\eta P_{P_1} P_{P_2} P_S$
$\omega_{P_2SP_1}$	$\omega_{P_2} + \omega_S - \omega_{P_1}$	$\phi_{P_2} + \phi_S - \phi_{P_1}$	ϕ_S	$\eta P_{P_2} P_S P_{P_1}$
$\omega_{P_1P_1S}$	$2\omega_{P_1} - \omega_S$	$2\phi_{P_1} - \phi_S$	$-\phi_S$	$\eta P_{P_1}^2 P_S$
ω_{SSP_1}	$2\omega_S - \omega_{P_1}$	$2\phi_S - \phi_{P_1}$	0	$\eta P_S^2 P_{P_1}$
$\omega_{P_1P_1P_2}$	$2\omega_{P_1} - \omega_{P_2}$	$2\phi_{P_1} - \phi_{P_2}$	0	$\eta P_{P_1}^2 P_{P_2}$
$\omega_{P_1SP_2}$	$\omega_{P_1} + \omega_S - \omega_{P_2}$	$\phi_{P_1} + \phi_S - \phi_{P_2}$	ϕ_S	$\eta P_{P_1} P_S P_{P_2}$
ω_{SSP_2}	$2\omega_S - \omega_{P_2}$	$2\phi_S - \phi_{P_2}$	0	$\eta P_S^2 P_{P_2}$

From Table 2.2, we can see that the FWM idlers at frequencies of $\omega_{P_2P_2S}$, $\omega_{P_1P_2S}$, $\omega_{P_2SP_1}$, $\omega_{P_1P_1S}$, and $\omega_{P_1SP_2}$ are the multicast channels because these idlers preserve the amplitude and phase information of the signal, whereas the rest are not.

Like broadcast and select and cascaded SFG/DFG-based multicasting schemes, the FWM-based multicasting scheme has the advantage of modulation format and data rate transparency. However, the CE of the multicasting channels is not high [94].

2.2.12 Summary

In summary, much research on all-optical wavelength multicasting has been reported. Table 2.3 compares the performances of different optical multicasting schemes in terms of transparency to data rate and modulation format, CE of the multicast channels, number of used probes, pumps and the number of multicast channels achievable, etc.

Table 2. 3. Performance comparison of different optical multicasting schemes.

Type of multicasting schemes	Transparency to data rate and modulation format	CE of the multicast channels	Comments	Number of		
				CW probes	Pumps	Multicast channels achievable
Broadcast and selected [73]	Yes	Poor when the number of multicast channels increases	Polarization insensitive; Not scalable; All the multicast channels have the same wavelength	0	0	Not reported
SPM in PCF/HNLF [74, 75]	Only OOK can be used	Good	Polarization insensitive; Require narrow signal pulse	0	0	6/14
XGM in SOA/FOPA [76-79]	Only OOK can be used and the data rate is limited by the carrier recovery time of SOA if using SOA	Good	Data format inverted to input signal; Polarization insensitive in SOA/Polarization dependent in FOPA	8/3	0/2	8/3
XPM in SOA-MZI/Sagnac loop mirror [81-84]	Only OOK can be used and the data rate is limited by the carrier recovery time of SOA if using SOA-MZI	Good	Polarization insensitive in SOA/Polarization dependent in Sagnac loop mirror	8/8	0	8/8
NPR in SOA [85]	Only OOK can be used	Good	Polarization dependent	4	0	4
Single pump modulated FOPA [86]	Only OOK can be used	Good	Polarization dependent	20	0	40
Self-seeded FOPA [88]	Yes	Good	Polarization dependent	0	2	8
XAM in EAM [89, 90]	Only OOK can be used and data rate is limited by the operation bandwidth of EAM	Good	Polarization insensitive	7	0	7
Cascaded SFG and DFG in PPLN [91]	Yes	Poor	Polarization dependent	7	1	7
Injection locking in FP-LD [92]	Only OOK can be used, data rate is limited	Good	Data format inverted to input signal; Polarization dependent	8	0	8
FWM [94]	Yes	Poor	Polarization dependent	0	3	9

It can be seen from Table 2.3 that there is no report on the number of multicast channels that can be achieved with the broadcast and select structure, which may be due to the very simple operation. We believe it is not difficult to generate 256 multicast channels in a simple stage using the broadcast and select structure. In such case, the power of each multicast channel shall be

$$P = \text{Input power of signal} - \text{Insertion loss of the splitter} - 24\text{dB}, (2.10)$$

The insertion loss can be easily compensated by the gain of the SOA; however, 256 SOA on-off gates are required, which is very costly. Another disadvantage of the broadcast and select structure is that all the multicast channels generated will have the same wavelength, which renders the scheme useless for many practical application scenarios [86].

Most of the multicasting schemes proposed in the literature can only be applied on OOK modulated signals. Only the broadcast and select, cascaded SFG/DFG in PPLN, and FWM based multicast schemes are transparent to the modulation format and data rate.

In addition, with the exception of the single-pump modulated FOPA, for which 40 multicast channels have been demonstrated, the number of multicast channels that can be achieved with all the other multicasting schemes is merely a few, due to the system performance degradation when the number of multicast channels is increased.

It is noted that, by combining the injection locking and FWM effects [101] or by combining XGM, XPM, and FWM effects [102, 103], the number of multicast channels that can be generated can be further increased to eleven and beyond.

2.3 Introduction to SOA and HNLF

As described in Sections 2.1 and 2.2, SOA and HNLF are widely used in optical buffering and wavelength multicasting technologies. We will give a brief description of the nonlinear properties of SOA and HNLF and then compare the advantages and

disadvantages of using them in optical buffering and wavelength multicasting applications.

The nonlinear properties of SOA that are widely exploited are XGM, XPM, NPR, and FWM effects, while SPM, XPM, NPR, FWM, and optical parametric process of HNLF are used extensively. Since safe optical power input to the SOA is usually limited to less than 20-dBm, the SPM and optical parametric process, which normally require the pump power to be at least 25-dBm, are difficult to be achieved using SOA. The optical power input to the HNLF can be much higher, says 30-dBm or higher; hence, SPM and optical parametric process can be more easily demonstrated using HNLF.

On the other hand, it is quite easy to achieve XGM effect in the SOA due to its nonlinear gain property and that the required pump power to the SOA needs not be very high, usually in the realm of several dBm. FOPA based XGM effect can be demonstrated in HNLF [77]. Since FOPA requires rather high input pump power [77], the implementation cost is higher than that of using SOA. As a result, XGM is normally achieved with SOA and not HNLF.

Table 2. 4. Advantages and disadvantages of using HNLF and SOA for nonlinear optical applications.

	Advantages	Disadvantages
SOA	(a). Ease of photonics integration (b). Compact in size (c). High CE (d). Low pump power	(a). Limited carrier recovery time (b). Large ASE noise figure (c). Active device (power consumption)
HNLF	(a). Ultrafast response time (b). Low noise figure (c). Passive device (no power consumption) (d). Wide and flat band wavelength conversion bandwidth	(a). Low CE (b). Difficult for photonics integration (c). Bulky (d). High pump power

The advantages and disadvantages of employing SOA and HNLF for nonlinear optical applications are summarized in Table 2.4.

The carrier recovery time of the SOA limits the data rate of the signal. Recently, quantum dot (QD) SOA has been fabricated and demonstrated, the gain bandwidth is much larger than that of the quantum well/wire SOA, and more importantly, the carrier recovery time of QD SOA can be reduced to several picoseconds [76]. In addition, SOA used with offset filtering and turbo-switch SOA can further increase the data rate of the signal [104, 105].

The nonlinear coefficient of HNLF varies from 10 to 30 $\text{W}^{-1}\text{Km}^{-1}$. Recently some novel nonlinear fibers with ultra-high nonlinear co-efficient have been produced. The nonlinear co-efficient of a Bi-HNLF that has been produced recently is around 1100 $\text{W}^{-1}\text{Km}^{-1}$ [94]. Only a few meters of these nonlinear fibers can be used to generate the required nonlinear effects.

When the technology becomes mature, the disadvantages of using SOA and HNLF will be overcome; and both will play important roles in future all-optical processing systems.

2.4 Conclusions

In this chapter, we give a brief review of two enabling technologies for realizing an all-optical processing optical network; namely, optical buffering and wavelength multicasting technologies. In addition, the basic nonlinear properties of SOA and HNLF are briefly introduced and the advantages and disadvantages of using SOA and

HNLF are compared.

For all-optical buffering technology, slow light based optical buffer was once regarded as a promising solution. However, it was found to be not suitable for practical use subsequently due to its low delay-bandwidth product. Buffer based on dispersions in DCF or CFB does not have the delay-bandwidth constraint, however, the dispersions could degrade system performance and, hence, not suitable for high data rate systems. Fiber based buffer seems to be most practical if the bulkiness problem can be resolved, which could be achieved via the use of fiber loop buffer.

In conclusion, fiber loop based optical buffer has the most potential to be used in practice. There is still a long way to go before an optical buffer can arbitrary delay any modulation format and data rate signal without significant degradation.

Substantial research work on all-optical wavelength multicasting technology has been carried out and reported over the last few years. However, more research efforts are required to design an optical wavelength multicasting scheme that: 1) is transparent to the data modulation format and data rate; 2) can generate as many multicast channels as possible using fewer pumps or probes; and 3) can arbitrarily select the multicast channels at different wavelengths.

In the following chapters, we will describe how our proposed optical buffering and wavelength multicasting technologies operate and perform; and how they could help to resolve some of the aforementioned issues.

Chapter 3 Optically Controlled Loop Buffer with Improved Performance

3.1 Introduction

As discussed in Chapter 2, the fiber loop buffer is one of the promising schemes for implementing optical buffers owing to its compactness. There are two key design challenges for fiber loop buffer. First, to increase the number of re-circulations such that optical packet could be buffered for a long period of time; second, to design the buffer such that it can cater for optical packets with different lengths or variable lengths [57, 58], [60-65].

In this chapter, we present a simpler loop buffer that is based on the same operation principle as the DLOB for writing and reading of packets, but to do so without a 3×3 collinear coupler [58]. Here we only make use of an SOA-based loop mirror as a fast switch [59] and a circulator-based optical reflector to achieve a cost effective optical loop buffer with improved number of achievable re-circulations. Furthermore, the buffering performances under both positive and negative control methods are demonstrated [104].

3.2 SOA-based loop mirror as a fast switch

Fig. 3. 1. Configuration of the SOA based loop mirror as a fast switch.

The use of an SOA-based loop mirror as a fast switch is illustrated in Fig. 3.1. The fast switch is based on the XPM effect in SOA. The switch consists of a 50:50 coupler, a PC, a fiber of a certain length, and an SOA. The SOA is asymmetrically located in the loop [59]. A signal with an electrical field $\vec{E}_{in}(t)$ (optical power $P_{in}(t)$), is split in the coupler and travels in cw and ccw directions through the fiber. Assume t_1 and t_2 are the traveling times for the cw and ccw signals from the coupler to the SOA, and that t_1 is smaller than t_2 . The cw signal will be amplified by the SOA with the complex gain as follows [59]:

$$\vec{g}_{cw}(t) = g_{cw}(t) \cdot \exp[-j\phi_{cw}(t)], (3.1)$$

$$\text{with } g_{cw}(t) = g(t + t_1), (3.2)$$

$$\varphi_{cw}(t) = \varphi(t + t_1), (3.3)$$

The ccw signal, which arrives at the SOA by time $t_2 - t_1$ later, will be amplified with the gain of:

$$\vec{g}_{ccw}(t) = g_{ccw}(t) \cdot \exp[-j\varphi_{ccw}(t)], (3.4)$$

$$\text{with } g_{ccw}(t) = g(t + t_2), (3.5)$$

$$\varphi_{ccw}(t) = \varphi(t + t_2), (3.6)$$

After traveling through the loop, these two (cw and ccw) signals will interfere at the coupler if the PC inside the loop is properly adjusted. Let d and k stand for the through and cross coupling ratios of the coupler, and the electrical fields at Output 1 and Output 2 can be expressed as follows [59]:

$$\vec{E}_{out1}(t) = jdk\vec{E}_{in}(t - t_d) \cdot e^{-j\omega t_d} \cdot [\vec{g}_{cw}(t - t_d) + \vec{g}_{ccw}(t - t_d)], (3.7)$$

$$\vec{E}_{out2}(t) = \vec{E}_{in}(t - t_d) \cdot e^{-j\omega t_d} \cdot [d^2 \cdot \vec{g}_{cw}(t - t_d) - k^2 \cdot \vec{g}_{ccw}(t - t_d)], (3.8)$$

Consider the ideal 50:50 coupler with $d^2 = k^2 = 0.5$ and suppose $t_d = t_1 + t_2$ is the round trip time of the signal traveling in this loop, the powers at Output 1 and Output 2 can be expressed respectively as:

$$\begin{aligned}
 P_{out1}(t) &= \frac{1}{2} \vec{E}_{out1}(t) \cdot \vec{E}_{out1}^*(t) \\
 &= \frac{1}{4} P_{in}(t-t_d) [G_{cw}(t-t_d) + G_{ccw}(t-t_d) \\
 &\quad + 2g_{cw}(t-t_d) \cdot g_{ccw}(t-t_d) \cdot \cos(\varphi_{cw}(t) - \varphi_{ccw}(t))], (3.9)
 \end{aligned}$$

$$\begin{aligned}
 P_{out2}(t) &= \frac{1}{2} \vec{E}_{out2}(t) \cdot \vec{E}_{out2}^*(t) \\
 &= \frac{1}{4} P_{in}(t-t_d) [G_{cw}(t-t_d) + G_{ccw}(t-t_d) \\
 &\quad - 2g_{cw}(t-t_d) \cdot g_{ccw}(t-t_d) \cdot \cos(\varphi_{cw}(t) - \varphi_{ccw}(t))], (3.10)
 \end{aligned}$$

$$\text{where } G_{cw}(t-t_d) = |\vec{g}_{cw}(t-t_d)|^2, (3.11)$$

$$G_{ccw}(t-t_d) = |\vec{g}_{ccw}(t-t_d)|^2, (3.12)$$

From (3.9) and (3.10), it can be seen that if the gain and phase of the cw and ccw signals are the same, the injected signal will be entirely reflected back to Output 1, and no power will be emitted at Output 2.

When the cw signal arrives at the SOA, a control signal is injected into the SOA at the same time, and this control signal leaves the SOA before the ccw signal arrives at the SOA. Next, the gain and phase between the cw and ccw signals are varied. The control signal is coupled into the SOA via WDM 1 and leaves from WDM 2 (see Fig. 3.1).

The amplitude and phase change of an optical field after going through an SOA with the length of active region L can be described as [59]:

$$\begin{aligned}
 \frac{\vec{E}_{out}}{\vec{E}_{in}} &= \exp(-j \frac{2\pi \vec{n} L}{\lambda}) \\
 &= \exp(-j \frac{2\pi n' L}{\lambda}) \cdot \exp(-\frac{2\pi n'' L}{\lambda}) \\
 &= \exp(-j\varphi_s) \cdot \sqrt{G}, (3.13)
 \end{aligned}$$

The complex refractive index equation can be written as follows:

$$\vec{n} = n' - jn'', (3.14)$$

The real part of the refractive index indicates the phase delay, whereas the imaginary part denotes the gain or attenuation of the signal.

Also, assume the relation [59]:

$$\frac{dn'}{dN} = \alpha \cdot \frac{dn''}{dN}, (3.15)$$

where α is the line-width enhancement factor of the SOA and N is the carrier density in the conduction band of the SOA.

Next, from (3.13) to (3.15), the relation between the phase differences and gain ratios for the signals having two different states in the SOA can be derived as follows:

$$\varphi_1 - \varphi_2 = -\frac{\alpha}{2} \ln \frac{G_1}{G_2}, (3.16)$$

Thus, the phase difference ($\Delta\Phi$) and gain ratios (G_{cw} and G_{ccw}) for the cw and ccw traveling signals induced by the SOA can be expressed by:

$$\Delta\Phi = \varphi_{cw}(t) - \varphi_{ccw}(t) = -\frac{\alpha}{2} \ln \frac{G_{cw}}{G_{ccw}}, (3.17)$$

Therefore, (3.9) and (3.10) can be written as:

$$P_{out1}(t) = \frac{1}{4} P_{in}(t-t_d) G_{ccw}(t-t_d) \cdot [1 + e^{\frac{2\Delta\Phi}{\alpha}} + 2e^{\frac{\Delta\Phi}{\alpha}} \cos \Delta\Phi], (3.18)$$

$$P_{out2}(t) = \frac{1}{4} P_{in}(t-t_d) G_{ccw}(t-t_d) \cdot [1 + e^{\frac{2\Delta\Phi}{\alpha}} - 2e^{\frac{\Delta\Phi}{\alpha}} \cos \Delta\Phi], (3.19)$$

The nonlinear phase shift ($\Delta\Phi$) in the cw traveling signal is introduced as a result of the XPM effect in the SOA by the control signal.

From (3.18) and (3.19), it can be seen that the signal will be reflected back to Output 1 (see Fig. 3.1) when $\Delta\Phi = 0$, and no power will be reflected at Output 2. If $\Delta\Phi = \pi$, the signal will be switched to Output 2. However, there will be some residual signal at Output 1 as can be seen from (3.18). Fig. 3.2 shows the normalized residual signal power against the value of α . It can be seen that as the value of α increases, the residual power decreases dramatically and it reduces to zero when the value of α approaches infinity. The typical value of α is in the range of 5 to 9 [106].

In order to make sure that the cw and ccw packet signals arrive at the SOA at different time, t_2 must be larger than t_1 . Also, the duration of the packet length should be less than $t_2 - t_1$. As a result, the delay time per circulation in this buffer must be larger than the duration of a packet length.

Fig. 3. 2. Normalized residual signal power at Output 1 against line-width enhancement factor.

3.3 Positive and negative control methods

Fig. 3. 3. Illustration of positive and negative control pulses.

Fig. 3.3 shows the positive and negative control pulses required to achieve the read and write functions of the loop buffer. The control pulse should be slightly wider than the length of the packet in order to ensure that the entire packet has a nonlinear π phase shift. As the control pulse narrows, the synchronization becomes more precise between the control pulses and packet data.

In the positive control method, the control signal enters the SOA with the cw traveling signal and introduces a nonlinear π phase shift to the cw signal. However, in the negative control method, the nonlinear π phase shift is introduced to the ccw traveling signal. The value of the phase difference $\Delta\Phi$ is π in the positive control method and $-\pi$ in the negative control method [107].

In [107], the researchers demonstrated theoretically that the negative control method had an improved power transfer ratio over the positive control method. It can be explained as follows.

The output power of the signal after n re-circulations can be expressed as [107]:

$$P_{stored} = \frac{1}{16} P_{in} (t - nt_d) G_{ccw}^{n+1} L_1^{n+1} L_2^n \cdot [1 + e^{-\frac{2\Delta\Phi}{\alpha}} - 2e^{-\frac{\Delta\Phi}{\alpha}} \cos \Delta\Phi]^2, \quad (3.20)$$

where G_{ccw} is the gain of the ccw signal, L_1 and L_2 are the loss of the SOA-based loop mirror and circulator-based reflector (see Fig. 3.5).

Assume the gain and loss are equal (the gain and loss normally are not equal in practice), $G_{ccw}^{n+1} L_1^{n+1} L_2^n = 1$, then the power transfer ratio of the buffer can be expressed as:

$$\Gamma = \frac{P_{stored}}{P_{in}} = \frac{1}{16} [1 + e^{-\frac{2\Delta\Phi}{\alpha}} - 2e^{-\frac{\Delta\Phi}{\alpha}} \cos \Delta\Phi]^2, \quad (3.21)$$

Since the value of the phase difference $\Delta\Phi$ is π in the positive control method and $-\pi$ in the negative control method, we can calculate the power transfer ratio of using positive and negative control method with respect to the value of α according to (3.21).

Fig. 3.4 demonstrates the power transfer ratio Γ against the value of α using positive

and negative control methods, respectively. The negative control method has better power transfer ratio than the positive control method when the value of α is not large. When the value of α increases, their power transfer ratio differences become small and close to 1.

Fig. 3. 4. Calculated power transfer ratio of using positive and negative control methods against the value of α .

In addition, there is another factor that leads to the improved performance of the negative control method. The SOA will be saturated most of the time in the negative control scheme as opposed to the case of positive control (see Fig. 3.3). Because the output ASE noise power from a saturated SOA is lower [80], the ASE noise has a smaller influence on the buffered signal degradation when the negative control scheme is used.

The improved power transfer ratio and reduced ASE noise in negative control method result in 1.8-dB BER power penalty improvement in [107]. This improved performance was confirmed in our experimental results [108].

3.4 Experiment demonstration of the proposed loop buffer

3.4.1 Experimental setup

The experimental setup is shown in Fig. 3.5. Distributed feedback (DFB) laser 1 emitting at a wavelength (λ) of 1540.56 nm is used as the optical carrier for the packet signal. The packet data is in the form of non-return-to-zero (NRZ) OOK signal modulated with the pattern “1010011000101111” by the intensity modulator (IM) and pulse-pattern generator (PPG) 1. Packet data rates at 2.5-Gbit/s and 10-Gbit/s are chosen to test the loop buffer performance. Each packet is separated by 31,984 zero bits as guard time. The reason why such a short packet length and long guard time are employed is to ensure that the delayed packet will not overlap with the next incoming packet after a large number of circulations.

In order to ensure that the cw and ccw direction signals arrive at the SOA asynchronously, an extra fiber needs to be inserted into the SOA loop mirror. In our experiment setup, a 5-m long additional fiber was inserted between PC and WDM 2 (see Fig. 3.5). The total delay time per circulation in this buffer is around 175 ns, which is determined by the total fiber length including the SOA loop mirror and the circulator-based reflector. By adjusting the fiber length between points A and B in Fig. 3.5, a variable time delay can be induced in each circulation. In the experimental setup, we did not insert extra fiber between points A and B.

The control signal, emitting from DFB 2 at the wavelength of 1550.12 nm, is also

NRZ-OOK modulated by PPG 2. Fig. 3.6 shows two control signal formats (positive and negative) for controlling the 2.5-Gbit/s data. According to Fig. 3.6, both the positive and negative control pulses are around 70 ns wide in order to overlap with the length of a 6.4 ns (16 bits) 2.5-Gbit/s data packet. As mentioned above, using relatively wider control pulses is an easy way to achieve the overlap between the control pulses and the packets. These two traces in Fig. 3.6 show approximately 700 ns of storage time, which equates to four circulations in this buffer.

For the 10-Gbit/s data, the duration is 1.6 ns, and a narrower control pulse, approximately 20 ns, is used as the control signal.

Fig. 3. 5. The experimental setup of the proposed loop buffer.

Due to the limitations in measuring the burst-mode BER performance in our experimental setup, we were unable to give the detailed power penalty performance of the buffered signals under different delay times. As a result, the optical waveform was

used to describe the quality of the buffered signal. The optical waveform of the buffered signal is measured by using the oscilloscope (OSC).

Fig. 3. 6. Two control signal formats (positive (a) and negative (b)) for controlling the 2.5-Gbit/s data.

Each packet arriving at the coupler via circulator 1 will be split into two parts, cw and ccw traveling signals. This packet will be written into the buffer when a phase difference of π occurs between the cw and ccw traveling signals. Therefore, this packet continues to circulate between the loop mirror and circulator-based reflector until another phase difference of π occurs again between the cw and ccw signals to read this packet. The detailed operation principle has been described in Section 3.2.

The coupler used in our experiment has the coupling ratio of 49:51. The bias current of the SOA is 300-mA with a small signal gain of 13.6 dB. The saturation output power of the SOA is 11.4-dBm. The carrier recovery time of this SOA is around 100-ps. A variable optical attenuator (VOA) is inserted into the loop to avoid ring laser effects.

In addition to the XPM effect between the control and data signals in the SOA, there are other nonlinear effects, such as FWM, XGM and NPR. Since the FWM idlers can be filtered out by WDM 1 and WDM 2 in the loop mirror; so it does not affect the performance of the buffer. For the XGM effect, the control signal remains constant during the switching period, the buffered signal will not be affected either. The NPR, indeed, introduces some polarization rotations to the data signal; however, this can be compensated by the PC inside the loop.

3.4.2 Experimental buffering performance of the 2.5-Gbit/s and 10-Gbit/s packets

Fig. 3.7 gives the buffering performance of the 2.5-Gbit/s data packet. Fig.3.7 (a) is the back-to-back (BTB) input data packet “1010011000101111”. Fig. 3.7 (b) to (f) are the buffered packets after 1, 6, 12, 18, and 24 circulations under the positive control method, whereas Fig. 3.7 (g) to (l) are the buffered packets after 1, 6, 12, 18, 24, and 36 circulations under the negative control method.

According to Fig. 3.7, it is not surprising to find that the negative control scheme performs much better than the positive one. The 2.5-Gbit/s data signal is still of relatively good quality after 36 circulations under the negative control scheme (see Fig. 3.7 (l)). However, the signal quality degrades severely after 18 circulations under the positive control scheme (see Fig. 3.7 (f)).

Fig. 3. 7. Buffer performances of the 2.5-Gbit/s data packet.

The buffering performance of the 10-Gbit/s data packet is shown in Fig. 3.8. Fig. 3.8 (a) is the BTB input data signal “1010011000101111”. Fig. 3.8 (b) to (f) are the data packets after 1, 4, 8, 12, and 16 circulations by positive control, and Fig. 3.8 (g) to (l) show the data packets after 1, 4, 8, 12, 16, and 18 circulations by negative control.

For the 10-Gbit/s data signal, however, the negative control method seems to only have a rather limited improvement. This finding is perhaps due to the limited carrier recovery time of the SOA, which results in data pattern degradation for the 10-Gbit/s signal [109].

Fig. 3. 8. Buffer performances of 10-Gbit/s data packet.

Although the ASE noise may still be reduced by employing negative control methods, the pattern degradation due to the limited carrier recovery time of the SOA is more significant compared to the ASE noise induced signal degradation. Nevertheless, we are confident that this buffer structure can work at 40-Gbit/s or at an even higher data rates if we employ a suitable SOA with a much shorter carrier recovery time [110].

It can be seen from Fig. 3.7 and Fig. 3.8 that the power of the buffered packet in the negative control method is higher than that in the positive control method, given the

same amount of delay time.

Nevertheless, there is a tradeoff because the negative control method requires more power than the positive one.

Fig. 3.9 shows the amplitude of the 2.5-Gbit/s and 10-Gbit/s buffered signals against the number of re-circulations for both the positive and negative control methods. According to Fig. 3.9, the amplitude of the buffered signal is larger than that of the BTB input data when the number of re-circulations is small. As the number of re-circulations increases, the amplitude decreases. This is because the total gain $G_{ccw}^{n+1} L_1^{n+1} L_2^n > 1$ when n is smaller, and $G_{ccw}^{n+1} L_1^{n+1} L_2^n < 1$ when n increases.

Fig. 3. 9. Buffered signal amplitude against the number of re-circulations using positive and negative control methods (a) 2.5-Gbit/s (b) 10-Gbit/s data packet.

3.4.3 Discussion

The DLOB requires the use of a 3×3 collinear coupler, and it is difficult to fabricate such coupler with ideal coupling ratios of 50:0:50 and 25:50:25 [58]. Meanwhile, the buffered packet needs to go through the 3×3 collinear coupler twice

for each circulation, and the power leakage of buffered packet is unavoidable. However, in our structure, the coupler with a 50:50 coupling ratio is much easier to obtain, and the data packet experiences only one interference transmission through the SOA-based loop mirror for each circulation. Therefore, the packet in the DLOB configuration cannot be stored for a long time due to the non-ideal coupling ratio of the 3×3 collinear coupler. This is the reason why our configuration allows an increased number of circulations in comparison to the results reported in [58].

So far only OOK signal is demonstrated for buffering performance in this loop buffer structure. From (3.7) and (3.8), we can see that the phase information of the buffered signal at Output 1 and Output 2 is the same as that of the input signal. Moreover, in Reference [111], the authors reported successful application of such NOLM to de-multiplex the OTDM DPSK signal. Hence, we believe this buffer can be used for other advanced modulation formats.

A short packet sequence with a large guard time was used in the experiments in order to observe the distortion of packet after being buffered for a long time. For instance, for a 16-bit packet at 10-Gbit/s, the packet duration is 1.6 ns. For a guard time of about 3200 ns and time delay per circulation of about 175 ns. The 16-bit packet can be allowed a maximum of 18 circulations (approximately 3150 ns delay) in this buffer without worrying about the arrival of the next packet to this buffer. For a data rate of 2.5-Gbit/s, the 31984 zero bits are equivalent to a guard time of about 12800 ns. As a result, it is possible to have a maximum of 70 circulations (around 12250 ns delay) in this buffer.

As indicated in Section 3.2, the duration of a packet length must be less than $t_2 - t_1$,

and the delay time per circulation must be larger than the duration of a packet length.

Nevertheless, we can choose the packet length to be of a larger value as long as a longer length fiber is inserted between the PC and WDM 2 (see Fig. 3.1), making sure the cw and ccw signals arrive at the SOA asynchronously.

In our experimental setup, only one data signal was demonstrated for buffering; however, it is possible to demonstrate two or even more data signals at different wavelengths [112]. Note that the wavelengths of the control and data signals should be within the gain bandwidth of the SOA; otherwise, the XPM effect will become weak and the performance of the buffer will be degraded.

Due to non-perfect switching in the loop, part of the signal power will leak to the data output port during each switching. Fig. 3.10 (a) and (b) show the 10-Gbit/s output data after two circulations in this buffer under positive and negative control, respectively. According to Fig. 3.10, the signal power leakage only occurs at the writing process, which results from the limited line-width enhancement factor of the SOA [106], [113]. Although the coupling ratio of the coupler is not the ideal 50:50 and the SOA has a small gain difference between the cw and ccw signals, there is no obvious power leakage to the data output when the packet is stored in this buffer. Furthermore, the leak power under the negative control method can be seen to be smaller than that under the positive control method.

However, as can be seen from Fig. 3.8 and Fig. 3.10, the leakage power is nearly comparable to the packet data power after 12 and 18 circulations for the positive and negative controls, respectively. One method to overcome this obstacle is to add an extra

SOA as a gate at the buffer data output. This extra SOA is switched off when the signal is re-circulating inside the loop buffer, thus the leak power is gated out. And when the signal is being read out of the buffer, this SOA is switched on to amplify the buffered signal.

Another issue that needs to be addressed is that part of the signal power will remain in the buffer when the packet is switched to the output. This residue signal can lead to crosstalk on the next buffered packet. The best way to solve this problem is to switch off the bias current of the SOA, thereby gating out this crosstalk. The on-off speed of an SOA is about several nanoseconds [55]; since the delay per circulation is about 175 ns, the on-off speed of the SOA is fast enough to do this task.

Fig. 3. 10. The 10-Gbit/s output data after two circulations in the loop under positive (a) and negative control format (b).

3.5 Conclusions

A loop buffer that has better performance in terms of the number of achievable recirculations compared other similar structures was reported in this chapter. According to experiment results, by employing the negative control format, the 2.5-Gbit/s and 10-Gbit/s data packets, still can be maintained in good condition after 36 and 18 circulations, respectively. Further improvements can be achieved by adding an extra SOA as a gate amplifier; this will enable the number of circulations to be increased, and also solve the problem of power leakage to the data output. The proposed buffer is scalable in that it will allow to work 40-Gbit/s or higher data rate if an SOA with a shorter carrier recovery time is used.

Chapter 4 Optical Wavelength Multicasting Based on FWM in an HNLF Sagnac Loop Mirror

In Chapter 3, we demonstrated an optically controlled loop buffer with improved performance compared to other similar structures. In the following three chapters, we will introduce three new all-optical wavelength multicasting schemes.

4.1 Introduction

As reviewed in Chapter 2, considerable research on all-optical wavelength multicasting has been reported in the literature. Among the multicasting schemes proposed, only the broadcast and select, cascaded SFG/DFG, and FWM based multicasting schemes are modulation format and data rate transparent. For other multicasting schemes, only OOK modulated signal can be used for wavelength multicasting.

Since modern optical communications systems should have the flexibility to allow the use of different modulation formats and because the data rate of optical communications systems has been significantly increased [114-116], a multicasting technique that is transparent to the modulation format and data rate of the signal is

highly desirable.

Unfortunately, the broadcast and select multicasting scheme has the drawback of not being scalable. For multicasting scheme based on the cascaded SFG/DFG effect in PPLN waveguide, K CW probes and one pump laser are required in order to produce K multicast channels. However, in FWM-based multicast schemes, six and nine multicast channels can be obtained by using only two- and three-pump laser sources, respectively [94]. Compared with the cascaded SFG/DFG-based multicasting scheme, the FWM-based multicasting scheme has the advantage of being more efficient.

Nevertheless, the number of multicast channels that can be generated in FWM-based multicasting scheme still depends on the number of pumps used. However, when a larger number of pump lasers is used, more pump-pump generated idlers are produced. Some of the idlers may have the same wavelengths as the multicast channels and thus induce significant crosstalk. This issue complicates the design and operation, as careful selection of pump wavelengths is critical in order to reduce the level of crosstalk [94].

In this chapter, we make use of an HNLF Sagnac loop mirror to realize optical wavelength multicasting based on the multi-pump FWM approach. As the Sagnac loop mirror can inherently separate the FWM idlers from the input pump and signal and also suppress the background ASE noise without optical filtering [30], [117-120], the problem of pump-pump generated idlers overlapping with the multicast channels can be overcome by using this HNLF Sagnac loop mirror.

In our proposed FWM-based multicasting scheme, the pumps, pump-pump

generated idlers, and pump ASE noise can be greatly suppressed at the output of the multicast channels. Consequently, clear eye diagrams can be observed even when the wavelength of a multicast channel has the same wavelength as the pump-pump generated idler does.

The generation of six and ten 10-Gbit/s OOK/DPSK multicast channels was experimentally demonstrated by using two- and three-pump lasers, respectively. The multicasting performance in a non-loop mirror configuration was also demonstrated for comparison.

4.2 FWM in HNLF-based Sagnac loop mirror

Fig. 4.1 (a) illustrates the operation principle of our proposed wavelength multicasting using Sagnac loop configuration. Beams from two pump lasers together with the pump amplifier's ASE noise ($\vec{E}_{P1}$, $\vec{E}_{P2}$, and $\vec{E}_{ASE}$) are coupled into the Sagnac loop via Input 1, whereas the signal ($\vec{E}_S$) is injected into the loop via Input 2. Via the FWM effect in HNLF, the cw and ccw beams return to the 3-dB OC. By adjusting PC in the symmetric loop mirror, the pump beams and the ASE noise ($\vec{E}_{P1}$, $\vec{E}_{P2}$, and $\vec{E}_{ASE}$) exit from Output 1, whereas the signal ($\vec{E}_S$) leaves through Output 2. However, the FWM waves ($\vec{E}_f$) will leave through either Output 1 or Output 2, depending on their phase conjugation.

The complex amplitudes of the pumps at port 3 of the coupler are $0.5 \cdot \vec{E}_{P1} \exp[j(\omega_{P1}t + \phi_{P1})]$, and $0.5 \cdot \vec{E}_{P2} \exp[j(\omega_{P2}t + \phi_{P2})]$ respectively. And the

The complex amplitude of the signal at port 3 and 4 of the coupler can be expressed

Fig. 4. 1. Operation principle of the proposed wavelength multicasting technique using Sagnac loop configuration.

Taking the FWM wave ω_{p1p1s} as an example first (see Fig. 4.1 (b)), the complex amplitudes of the FWM wave $\bar{E}_{f3}$ and $\bar{E}_{f4}$ at ports 3 and 4 after propagating through the loop can be expressed as [117]:

$$\vec{E}_{f3} = -(\eta/8)^{1/2} \vec{E}_{p1} \vec{E}_S^* \exp[j(\omega_f t + \phi_f)], (4.1)$$

$$\vec{E}_{f4} = j(\eta/8)^{1/2} \vec{E}_{P1}^2 \vec{E}_S^* \exp[j(\omega_f t + \phi_f)], (4.2)$$

where η denotes the CE of the FWM process, and ω_f and ϕ_f denote the frequency and phase of the FWM wave, respectively.

When $\vec{E}_{f3}$ and $\vec{E}_{f4}$ interfere at ports 1 and 2, the FWM output powers P_1 (at Output 1) and P_2 (at Output 2) can be expressed as:

$$P_1 = \frac{|\vec{E}_{f3} - j\vec{E}_{f4}|^2}{2} = 0, (4.3)$$

$$P_2 = \frac{|-j\vec{E}_{f3} + \vec{E}_{f4}|^2}{2} = P_{FWM}, (4.4)$$

where $P_{FWM} = |\vec{E}_{f3}|^2 + |\vec{E}_{f4}|^2$ is the total power of the generated FWM waves. As a result, the FWM wave ω_{P1P1S} will leave through Output 2, and no light component will appear at Output 1.

Next, let us take the FWM wave ω_{P2P2P1} as another example. The complex amplitudes of the FWM wave $\vec{E}_{f3}$ and $\vec{E}_{f4}$ at ports 3 and 4 after propagating through the loop can be expressed as:

$$\vec{E}_{f3} = -j(\eta/8)^{1/2} \vec{E}_{P2}^2 \vec{E}_{P1}^* \exp[j(\omega_f t + \phi_f)], (4.5)$$

$$\vec{E}_{f4} = (\eta/8)^{1/2} \vec{E}_{P2}^2 \vec{E}_{P1}^* \exp[j(\omega_f t + \phi_f)], (4.6)$$

When $\vec{E}_{f3}$ and $\vec{E}_{f4}$ interfere at ports 1 and 2, the FWM output powers P_1 (at Output 1) and P_2 (at Output 2) can be expressed as:

$$P_1 = \frac{|\vec{E}_{f3} - j\vec{E}_{f4}|^2}{2} = P_{FWM}, (4.7)$$

$$P_2 = \frac{|-j\vec{E}_{f3} + \vec{E}_{f4}|^2}{2} = 0, (4.8)$$

As a result, the FWM wave ω_{P2P2P1} will leave through Output 1.

Table 4. 1. Phase relationship of all the FWM waves and their corresponding output port.

FWM wave	Frequency (ω_f)	Phase (ϕ_f)	Differential Phase	E_{f3} and E_{f4}	P_{out1}	P_{out2}
ω_{P2P2S}	$2\omega_{P2} - \omega_S$	$2\phi_{P2} - \phi_S$	$-\phi_S$	$E_{f3} = -(\eta/8)^{1/2} E_{P2}^2 E_S^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = j(\eta/8)^{1/2} E_{P2}^2 E_S^* \exp[j(\omega_f t + \phi_f)]$	0	Yes
ω_{P2P2P1}	$2\omega_{P2} - \omega_{P1}$	$2\phi_{P2} - \phi_{P1}$	0	$E_{f3} = -j(\eta/8)^{1/2} E_{P2}^2 E_{P1}^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = (\eta/8)^{1/2} E_{P2}^2 E_{P1}^* \exp[j(\omega_f t + \phi_f)]$	Yes	0
ω_{P1P2S}	$\omega_{P1} + \omega_{P2}$ $-\omega_S$	$\phi_{P1} + \phi_{P2}$ $-\phi_S$	$-\phi_S$	$E_{f3} = -(\eta/8)^{1/2} E_{P1} E_{P2} E_S^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = j(\eta/8)^{1/2} E_{P1} E_{P2} E_S^* \exp[j(\omega_f t + \phi_f)]$	0	Yes
ω_{P2SP1}	$\omega_{P2} + \omega_S$ $-\omega_{P1}$	$\phi_{P2} + \phi_S$ $-\phi_{P1}$	ϕ_S	$E_{f3} = -(\eta/8)^{1/2} E_{P2} E_S E_{P1}^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = j(\eta/8)^{1/2} E_{P2} E_S E_{P1}^* \exp[j(\omega_f t + \phi_f)]$	0	Yes
ω_{P1P1S}	$2\omega_{P1} - \omega_S$	$2\phi_{P1} - \phi_S$	$-\phi_S$	$E_{f3} = -(\eta/8)^{1/2} E_{P1}^2 E_S^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = j(\eta/8)^{1/2} E_{P1}^2 E_S^* \exp[j(\omega_f t + \phi_f)]$	0	Yes
ω_{SSP1}	$2\omega_S - \omega_{P1}$	$2\phi_S - \phi_{P1}$	0	$E_{f3} = j(\eta/8)^{1/2} E_S^2 E_{P1}^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = -(\eta/8)^{1/2} E_S^2 E_{P1}^* \exp[j(\omega_f t + \phi_f)]$	Yes	0
ω_{P1P1P2}	$2\omega_{P1} - \omega_{P2}$	$2\phi_{P1} - \phi_{P2}$	0	$E_{f3} = -j(\eta/8)^{1/2} E_{P1}^2 E_{P2}^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = (\eta/8)^{1/2} E_{P1}^2 E_{P2}^* \exp[j(\omega_f t + \phi_f)]$	Yes	0
ω_{P1SP2}	$\omega_{P1} + \omega_S$ $-\omega_{P2}$	$\phi_{P1} + \phi_S$ $-\phi_{P2}$	ϕ_S	$E_{f3} = -(\eta/8)^{1/2} E_{P1} E_S E_{P2}^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = j(\eta/8)^{1/2} E_{P1} E_S E_{P2}^* \exp[j(\omega_f t + \phi_f)]$	0	Yes
ω_{SSP2}	$2\omega_S - \omega_{P2}$	$2\phi_S - \phi_{P2}$	0	$E_{f3} = j(\eta/8)^{1/2} E_S^2 E_{P2}^* \exp[j(\omega_f t + \phi_f)]$ $E_{f4} = -(\eta/8)^{1/2} E_S^2 E_{P2}^* \exp[j(\omega_f t + \phi_f)]$	Yes	0

Table 4.1 summarizes the phase relationships of all the FWM waves and the output ports through which they exit. ϕ_S , ϕ_{P1} and ϕ_{P2} are the phases of input signal, pump 1, and pump 2. Table 4.1 clearly shows that the FWM products (ω_{P2P2P1} , ω_{SSP1} , ω_{P1P1P2} ,

and ω_{SSP2}) leave through Output 1, whereas the rest (ω_{P2P2S} , ω_{P1P2S} , ω_{P2SP1} , ω_{P1P1S} , and ω_{P1SP2}) leave through Output 2. Therefore, at the outputs of the multicast channels (Output 2), the pumps, pump-pump idlers, and pump amplifier ASE noise can be greatly suppressed.

In addition, as the phases of pump 1 and pump 2 are constant and do not carry data information, the differential phase information and the amplitude information of the input signal can be preserved in the multicast channels.

4.3 Experimental performance of using loop mirror and non-loop mirror for wavelength multicasting

4.3.1 Multicasting using two pumps

4.3.1.1 Experimental setup

Fig. 4.2 shows the experimental setup of multicasting in the HNLF loop mirror using two pump lasers. The signal (S) at the wavelength of 1550.92 nm is first intensity modulated/phase modulated by 10-Gbit/s $2^{31}-1$ pseudo-random bit sequence (PRBS) data through the IM and phase modulator (PM). Next, the signal is amplified by EDFA 1. After the ASE noise is filtered, the signal (14-dBm) is coupled into the HNLF Sagnac loop via circulator 1.

Laser diode (LD) 2 (at 1551.72 nm denoted as P_I) and LD 3 (at 1554.12 nm

denoted as P_2) are used as pumps. These two pumps are combined and amplified by EDFA 3, which has a high saturated output power of around 32-dBm. Next, the pumps and EDFA 3 induced ASE noise are coupled into the HNLF loop via circulator 2. Tunable-wavelength filter (TF) 1 is used to select the desired multicast channel at port 3 of circulator 1. EDFA 2 is used to amplify the multicast channel, and TF 2 is used to reject the ASE noise before the eye diagram and BER are measured. VOA is used to adjust the optical power before the eye diagram and BER of a multicast channel are measured. In the case of DPSK, a 100-ps delay interferometer (DI) is employed to demodulate the 10-Gbit/s DPSK multicast channels before the eye diagrams and BER are measured.

In our experimental setup, the nonlinear coefficient of HNLF is $11\text{W}^{-1}\text{Km}^{-1}$ and the dispersion zero wavelength λ_0 is 1560 nm. The dispersion slope and the total fiber loss at λ_0 are 0.035 ps/km-nm^2 and 2.3 dB, respectively. The coupler used has a coupling ratio of 49:51. Note that the performance degradation of Sagnac loop mirror due to coupling ratio perturbation was thoroughly investigated [59].

To determine the FWM bandwidth of this HNLF, the pump wavelength and pump power need to be known [121]. The FWM bandwidth is wider when the pump wavelength is close to the zero dispersion wavelength of HNLF and the power of the pump increases [121]. This HNLF was used for FOPA experiments by other researchers in our lab [122], and from their measurement results, the 3-dB FWM bandwidth is 9 nm with 29-dB amplifier gain when the pump wavelength and power are set at 1559.35 nm and 27-dBm, respectively [122].

In order to achieve the best CE for all of the multicast channels, PC 1, PC 2, and PC

3 are adjusted to make sure the signal and the three pumps are co-polarized with each other.

Fig. 4. 2. Experimental setup for wavelength multicasting using two pumps in the loop structure.

The power of each pump after EDFA 3 is adjusted to 15.5-dBm. The SBS threshold of the CW laser in this 1-km HNLF is approximately 10-dBm [35]. Taking into consideration the insertion loss at circulator 2 and the 3-dB optical coupler, the effective optical power of the CW pump laser is around 11-dBm, close to the threshold value. Therefore, the SBS effect on the CW pump is small and can be neglected.

The experimental setup of the non-loop configuration is shown by Fig. 4.3 where all the device settings are the same as in the loop structure. All of the FWM-generated idlers, signal, and pumps exit from point B after passing through the HNLF. TF 1 is used to select the desired multicast channel for measurement. Output A and port 3 of

circulator 1 and 2 are connected to the attenuator (Att.) to avoid any reflections.

Fig. 4. 3. Experimental setup for wavelength multicasting using two pumps in non-loop structure.

4.3.1.2 Experimental results and discussion

Fig. 4.4 (a) and (b) show the optical spectra measured by the optical spectrum analyzer (OSA) at port 3 of circulator 1 and port 3 of circulator 2 when multicasting the OOK modulated signal. By adjusting PC 4 within the Sagnac loop mirror, the power of the two pumps, as well as the P_1 - P_2 generated idlers ($I_{P_2P_2P_1}$ at 1556.52 nm and $I_{P_1P_1P_2}$ at 1549.32 nm), can be suppressed by more than 30 dB at the output of the multicast channels (see Fig. 4.4 (a)). The background ASE noise is also suppressed by about 10 dB. At port 3 of circulator 2, the signal and multicast channels are suppressed significantly with a suppression ratio of about 30 dB (see Fig. 4.4 (b)). Due to the high level of background ASE noise, the suppressed multicast channels are not so obvious in Fig. 4.4 (b). If a perfect 50:50 coupler is employed, a higher suppression ratio

(approximately 40 dB) of the pumps and crosstalk can be achieved [119]. Nevertheless, the suppression ratio of around 33 dB, as obtained in our loop mirror, is high enough to enable clear eye diagrams of the overlapped multicast channels to be observed.

Fig. 4. 4. Measured optical spectra using two pumps. (a). Optical spectra at port 3 of circulator 1. (b).

Optical spectra at port 3 of circulator 2. (c). Optical spectra of the non-loop configuration.

The optical spectra of the non-loop experimental setup are illustrated in Fig. 4.4 (c). It can be seen from Fig. 4.4 (c) that the optical signal-to-noise ratio (OSNR) of the multicast channels is not as robust as that of the Sagnac loop configuration (see Fig. 4.4

(a)). This difference is due to the ASE noise arising from the pump amplifier.

The ripples in Figs. 4.4 (b) and (c) are due to the side modes of the DFB laser used.

Fig. 4. 5. BER curves of the BTB OOK signal and the multicast channels in loop configuration by using two pump lasers. L: loop configuration.

The BER performances of the OOK multicast signals for the loop and non-loop configurations are shown in Fig. 4.5 and Fig. 4.6, respectively. Fig. 4.7 shows their corresponding eye diagrams. The state of polarization (SOP) of the signal is fixed for all the multicast channels when the BER and eye diagrams are measured. Compared with the BTB input data signal, the maximum power penalty of the six multicast signals in the Sagnac loop configuration is approximately 1.2 dB. An extra power penalty of up to 1.1 dB is incurred by using the non-loop configuration compared to the loop configuration. This increased power penalty is due to the degradation of OSNR. In addition, the mark level of Ch 3 and Ch 6 can be seen to be much noisier compared with those of other channels. The main reason for this finding is that the converted

powers of Ch 3 and Ch 6 are about 3 dB lower than those of the other channels, and more ASE noise is introduced due to the noise figure (NF) of EDFA 2.

Fig. 4. 6. BER curves of the BTB OOK signal and the multicast channels in non-loop configuration by using two pump lasers. NL: non-loop configuration.

Fig. 4. 7. Eye diagrams of BTB OOK signal and multicast channels in loop and non-loop configurations by using two pump lasers. L: loop configuration. NL: non-loop configuration.

Fig. 4. 8. BER curves of the BTB DPSK signal and the multicast channels in loop configuration by using two pump lasers. L: loop configuration.

Fig. 4. 9. BER curves of the BTB DPSK signal and the multicast channels in non-loop configuration. NL: non-loop configuration.

The BER performances of the DPSK multicast signals for the loop and non-loop configurations are shown in Fig. 4.8 and Fig. 4.9, respectively. Fig. 4.10 shows the

corresponding eye diagrams. The maximum power penalty of the six multicast signals in the Sagnac loop configuration is approximately 1.4 dB compared with the BTB signal, and the maximum power penalty is 1.9 dB in the non-loop configuration.

Fig. 4. 10. Eye diagrams of BTB DPSK signal and multicast channels in loop and non-loop configurations by using two pump lasers. L: loop configuration. NL: non-loop configuration.

The detailed performance comparisons between the proposed Sagnac loop configuration and the non-loop configuration are summarized in Table 4.2. As the pumps and signal have a 3-dB coupling loss at the OC, the CE in the non-loop configuration is lower than that in the Sagnac loop configuration. There is approximately 10 dB OSNR of improvement in the loop configuration owing to the suppressed background ASE noise. Therefore, no filters are required to reject the pump amplifier ASE noise in the loop configuration. Note that using a filter to remove the pump amplifier ASE noise will inevitably introduce undesirable insertion loss to the pump power.

Chapter 4: Optical Wavelength Multicasting Based on FWM in an HNLF Sagnac Loop Mirror

Table 4. 2. Performance comparison between the loop (L) and non-loop (NL) structures (2 Pumps).

Channels	Wavelength (nm)	L/NL	CE (dB)	OSNR (dB)	Power penalty (dB)	
					OOK	DPSK
Ch 1	1548.52	L	-17	45	1	1.3
		NL	-21	34	1.4	1.8
Ch 2	1550.92	L	-	61	0.2	0.3
		NL	-	50	0.2	0.4
Ch 3	1552.52	L	-20	40	1.2	1.4
		NL	-23	28	2.3	1.9
Ch 4	1553.32	L	-17	43	0.7	0.9
		NL	-21	33	1.2	1.4
Ch 5	1554.92	L	-17	43	0.6	1.2
		NL	-20	33	1.3	1.8
Ch 6	1557.32	L	-20	38	1.1	1.4
		NL	-24	27	2.1	1.9

4.3.2 Multicasting using three pumps

4.3.2.1 Experimental setup

Fig. 4. 11. Experimental setup for wavelength multicasting in HNLF loop mirror using three pump lasers.

As there is a possibility that the intended multicast channel may be located at the

same wavelength as the pump-pump generated idler, we add LD 4 to verify that our Sagnac loop configuration can indeed filter the overlapped channel. In this experiment, the power of each pump after the EDFA 3 is still maintained at 15.5-dBm. Fig. 4.11 shows the experimental setup for wavelength multicasting in the loop mirror structure using three pump lasers. All of the parameters are the same in the two-pump multicasting structure.

The experimental setup of non-loop mirror-based configuration is similar to the one in Fig. 4.3 except one more LD 4 is added.

4.3.2.2 Experimental results and discussion

Fig. 4.12 (a) and (b) show the measured optical spectra at port 3 of circulator 1 and port 3 of circulator 2 when using three-pump lasers. Fig. 4.12 (c) shows the measured spectra in the non-loop configuration. It can be seen from Fig. 4.12 that ten usable multicast channels have been generated by the FWM effect in the HNLF loop. Because the wavelength of the multicast channel, $I_{P_2P_2S}$ at 1557.32 nm, is located at the same wavelength as LD 4 (P_3 at 1557.32 nm), and the power of the suppressed P_3 is still high at the output of the multicast channels, we did not measure the BER performance and eye diagram of this channel. According to Fig. 4.12 (c), five of the multicast channels (Ch 1, Ch 2, Ch 6, Ch 7, and Ch 9) are located at the same wavelengths as the other FWM generated idlers (I_{SSP_2} , $I_{P_1P_2P_3}$, $I_{P_1P_3P_2}$, $I_{P_2P_2P_1}$, and $I_{P_2P_3P_1}$). If we adopt the non-loop configuration, these multicast channels cannot be filtered, due to the in-band crosstalk. However, by using the Sagnac loop configuration, the other FWM-generated idlers (I_{SSP_2} , $I_{P_1P_2P_3}$, $I_{P_1P_3P_2}$, $I_{P_2P_2P_1}$, and $I_{P_2P_3P_1}$) will leave through port 3 of circulator 2

(see Fig. 4.12 (b)), whereas the five overlapped multicast channels will leave through port 3 of circulator 1 (see Fig. 4.12 (a)), which leads to wide openings in the eye diagrams of these overlapped channels.

Fig. 4. 12. Measured optical spectra using two pumps. (a). Optical spectra at port 3 of circulator 1. (b). Optical spectra at port 3 of circulator 2. (c). Optical spectra of the non-loop configuration.

Fig. 4. 13. BER curves of the BTB OOK signal and the multicast channels in loop configuration by using three pump lasers. L: loop configuration.

Fig. 4. 14. BER curves of the BTB OOK signal and the multicast channels in non-loop configuration by using three pump lasers. NL: non-loop configuration.

Fig. 4.13 and Fig. 4.14 show the BER performances of the OOK multicast signals in loop and non-loop configurations, respectively. The corresponding eye diagrams are

shown in Fig. 4.15. The BER performances and eye diagrams of the DPSK multicast signals in loop and non-loop configurations are described in Fig. 4.16, Fig. 4.17, and Fig. 4.18.

Fig. 4. 15. Eye diagrams of BTB OOK signal and multicast channels in loop and non-loop configurations by using three pump lasers. L: loop configuration. NL: non-loop configuration. OL: overlapped.

Ten error-free multicast channels can be obtained by using the loop configuration; however, only five error-free multicast channels can be obtained if the non-loop structure is used. It can be seen that Ch 10 has the maximum power penalty, due to its relatively small CE compared with the other channels. This penalty is owing to the fact that as the frequency detuning of the signal from the pump increases, the phase mismatching parameter also increases and leads to poor CE [123]. If an HNLF with a smaller dispersion slope [123, 124] is used, the CE of Ch 10 will remain as large as that of the other channels. The power penalty of Ch 10 is around 3.5 dB for the OOK signal and 2.7 dB for the DPSK signal in the loop configuration, and it increases to about 4.7 dB for the OOK signal and 3.7 dB for the DPSK signal in the non-loop configuration.

Due to the smaller CE, the overlapped Ch 1 has a large power penalty of about 3.4 dB for OOK signals and 2.2 dB for DPSK signals.

Fig. 4. 16. BER curves of the BTB DPSK signal and the multicast channels in loop configuration by using three pump lasers. L: loop configuration.

Fig. 4. 17. BER curves of the BTB DPSK signal and the multicast channels in non-loop configuration by using three pump lasers. NL: non-loop configuration.

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Fig. 4. 18. Eye diagrams of BTB DPSK signal and multicast channels in loop and non-loop configurations by using three pump lasers. L: loop configuration. NL: non-loop configuration. OL: overlapped.

Table 4. 3. Performance comparison between the loop (L) and non-loop (NL) structures with overlapped channels existing (3 pumps)

Channels	Wavelength (nm)	L/NL	CE (dB)	OSNR (dB)	Power penalty (dB)	
					OOK	DPSK
Ch 1	1547.72	L	-25	37	3.4	2.2
		NL				
Ch 2	1548.52	L	-18	42	1.7	1.3
		NL				
Ch 3	1550.92	L		54	0.2	0.3
		NL		23	0.8	0.8
Ch 4	1552.52	L	-21	40	1.3	1.4
		NL	-25	27	2.4	1.8
Ch 5	1553.32	L	-18	41	0.7	1.1
		NL	-21	29	1.3	1.6
Ch 6	1554.92	L	-18	41	1.5	1.6
		NL				
Ch 7	1556.52	L	-21	38	1	1.2
		NL				
Ch 8	1558.12	L	-21	36	0.7	1.3
		NL	-24	25	1.4	1.9
Ch 9	1560.52	L	-21	36	1.7	1.9
		NL				
Ch 10	1563.72	L	-28	29	3.5	2.7
		NL	-31	17	4.7	3.7

Table 4.3 gives detailed performance comparisons between the loop and non-loop configuration. The reason that Ch 3 has 23 dB OSNR in the non-loop configuration is

that the $P2$ - $P3$ -generated idler I_{P2P2P3} is located at the same wavelength as Ch 3 and introduces in-band crosstalk to Ch 3. Owing to the high input signal power, the power penalty of Ch 3 is approximately 0.8 dB for both OOK and DPSK signals. Moreover, a power penalty improvement of up to 1.2 dB can be seen to be achieved by using the loop configuration.

The following are some design considerations of this proposed multicasting scheme. First of all, the channel spacing between the adjacent multicast channels in this scheme is not equal, but we can carefully set the wavelengths of the pumps to make the multicast channels having equal spacing [93].

Second, the channel spacing of the pumps plays an important role in determining the wavelength spacing of the multicasting channels. According to Table 4.1, the wavelength of the multicasting channels depends on the wavelengths of the pumps and signal. The closer the pumps to the signal, the smaller the wavelength spacing is. On the other hand, the multicast channel spacing becomes large when the pumps are far away from the signal. In such case, the CE of the multicasting channels will be reduced if the FWM bandwidth of the HNLF is limited.

Finally, to the best of the author's knowledge, there is no report on multi-pump based FWM multicasting using four or more pump lasers. This is because the FWM process becomes rather complicated with four pumps and one signal.

4.4 Conclusions

In conclusion, we experimentally demonstrated an all-optical modulation and date

rate transparent wavelength multicasting technique using the FWM effect in an HNLF Sagnac loop. Our proposed design overcame the undesirable effect of pump-pump generated idlers overlapping with the multicast channels. The experimental results showed that the pumps and the pump-pump idlers can be greatly suppressed by more than 30 dB at the output of the multicasting channels. The background ASE noise arising from the pump amplifier had a suppression ratio of around 10 dB. Six and ten 10-Gbit/s OOK/DPSK multicast channels complying with the ITU grid were generated by using two- and three-pump lasers. The power penalty of these multicast channels was found to be less than 3.5 dB. If we employed the non-loop configuration, the eye diagrams of the overlapped multicast channels were closed, due to the in-band crosstalk arising from the pump-pump idlers. Comparing the proposed Sagnac loop configuration with the non-loop configuration, we observed that the former can achieve up to a 1.2-dB improvement in power penalty. Another advantage of the proposed technique was that the pump amplifier ASE noise can be suppressed at the output of the multicast channels without the need for an extra filter.

Nevertheless, the polarization states of the pumps and signal in this scheme need to be adjusted to obtain the best CE for all the multicast channels. As the SOP of the input data signal is generally random in practice, this situation requires that the SOPs of the pumps be adjusted to achieve the highest CE for all of the multicast channels.

Chapter 5 Optical Wavelength Multicasting Based on FWM with Reduced Polarization Sensitivity

5.1 Introduction

In Chapter 4, we demonstrated a FWM-based optical wavelength multicasting scheme in an HNLF-based Sagnac loop mirror capable of overcoming the undesirable effect of pump-pump generated idlers overlapping with the multicast channels.

However, to implement a multi-pump FWM-based multicasting scheme in a real system, an important practical issue that needs to be addressed is polarization sensitivity [93-98]. The polarization states of the pumps and signal need to be adjusted in order to obtain the best CE for all the multicast channels. As the SOP of the input data signal is generally random, this situation requires that the SOPs of the pumps be adjusted to achieve the highest CE for all the multicast channels. Otherwise, the CE fluctuation of the multicast channels due to the polarization sensitivity is more than 20 dB [125-130]. This fluctuation may not be practical for a real system.

Many schemes for realizing the FWM-based low polarization-sensitive WC have been reported [125-130]. However, for FWM-based low polarization-sensitive wavelength multicasting, little work can be found in the literature likely due to the operation's complexity [131-133]. In [131], the researchers proposed a polarization-insensitive wavelength multicasting scheme based on FWM in a PCF with residual birefringence. In that scheme, one optical pump was required to be coupled into the PCF precisely at 45 degree to the principal axes. In addition, only five error-free multicast channels, including the signal itself, were generated by using three-pump laser sources.

In this chapter, we propose and demonstrate a practical all-optical wavelength multicasting scheme based on the FWM effect in an HNLF and an SOA with reduced polarization sensitivity. Using three co-polarized probes with pre-defined wavelength separations, three beating gratings were generated to scatter the modulated signal far from the probes to avoid unwanted crosstalk [125, 126]. In this way, six new multicast channels that have rather small degrees of polarization dependence on the modulated signal were generated. Thus, seven multicast channels, including the signal itself, were obtained at the output of HNLF/SOA. Compared to the requirement of the precisely coupling conditions in [131], another advantage of our proposed scheme is that the co-polarized probes are easily obtained by using the polarization maintaining devices at the output of the laser sources.

Although both HNLF and SOA have been reported for low polarization-sensitive WC, their application to low polarization-sensitive wavelength multicasting was not reported in the previous study. The performance comparison pertaining to their

applications to our proposed low polarization-sensitivity wavelength multicasting scheme will be reported in Section 5.3 and 5.4. Experimental results showed that the power fluctuations of the converted multicast channels due to the polarization sensitivity were greatly reduced from more than 20 dB [125-130] to about 5 dB in an HNLF and 2.5 dB in an SOA. Moreover, both OOK and DPSK signals' multicasting were demonstrated.

5.2 Operation principle of polarization sensitivity-reduced FWM-based multicasting

Fig. 5. 1. Operation principle of this proposed polarization sensitivity reduced multicasting technique.

Fig. 5.1 illustrates the operation principle of this proposed polarization-sensitivity reduced multicasting technique. The signal (S) with electrical field ($\vec{E}_s$) is coupled into the HNLF/SOA with random polarization. Three probes (P_1 - P_3) with electrical fields ($\vec{E}_1$ - $\vec{E}_3$) are co-polarized with each other and coupled into the HNLF/SOA. Their

frequency separations are pre-defined, e.g., 100-GHz between P_2 and P_3 , 200-GHz between P_1 and P_2 , and 300-GHz between P_1 and P_3 . From Fig. 5.1, it can be seen that six FWM generated multicast channels are symmetrically located at both sides of the signal. In addition, other FWM-produced idlers also appear at the output of the HNLF/SOA. In order to separate the multicast channels from other FWM idlers, we set the frequency of the signal far from the probes.

We will first describe the operation principle of this proposed multicasting scheme in the HNLF. Taking the multicast channel at the frequency of $\omega_1 - \omega_2 + \omega_S$ as an example, this multicast channel is composed of two FWM idlers. Co-polarized probes P_1 and P_2 generate a beating grating, and this beating grating subsequently scatters the modulated signal. Consequently, two new FWM idlers are generated on both sides of the signal symmetrically with the frequencies of $\omega_1 - \omega_2 + \omega_S$, and $\omega_2 - \omega_1 + \omega_S$, respectively. These two idlers have constant powers with respect to any SOP of the signal [125].

On the other hand, S and P_2 also generate a beating grating. This beating grating then scatters P_1 to generate two idlers at the frequencies of $\omega_S - \omega_2 + \omega_1$, and $\omega_2 - \omega_S + \omega_1$. The power of these two idlers, however, depends strongly on the SOP of the signal. The power of the idlers reaches maximum value when the signal has the same polarization as the probes and becomes zero when the SOP of the signal is orthogonal to that of the probes.

Based on the above analysis, the electrical field of the multicast channel at the frequency of $\omega_1 - \omega_2 + \omega_S$ can be expressed as [126]:

$$\begin{aligned}\vec{E}_i = & (\vec{E}_1 \cdot \vec{E}_2^*) r(\omega_1 - \omega_2) \vec{E}_s \cdot \exp j [(\omega_1 - \omega_2 + \omega_s)t + (\phi_1 - \phi_2 + \phi_s)] \\ & + (\vec{E}_s \cdot \vec{E}_2^*) r(\omega_s - \omega_2) \vec{E}_1 \cdot \exp j [(\omega_s - \omega_2 + \omega_1)t + (\phi_s - \phi_2 + \phi_1)],\end{aligned}\quad (5.1)$$

where $r(\omega_1 - \omega_2)$ and $r(\omega_s - \omega_2)$ denote the relative CE functions, which decrease rapidly with the increase of the spacing between the two pumps [134]. For ease of discussion, the fiber loss is not taken into consideration.

As P_1 and P_2 are co-polarized with each other and θ represents the polarization angle between the signal and probes, the power of this channel can be expressed as [125]:

$$P_i = \vec{E}_i \cdot \vec{E}_i^* = P_1 P_2 P_s [r^2(\omega_1 - \omega_2) + r^2(\omega_s - \omega_2) \cos^2 \theta], \quad (5.2)$$

Because $r(\omega_s - \omega_2)$ is smaller than $r(\omega_1 - \omega_2)$, and the power of the second component in (5.2), which depends on the polarization angle θ between the signal and probes, can also be treated as a small variation of this multicast channel. Therefore, the polarization sensitivity of the multicast channels is greatly reduced.

Then, we replace the HNLF with an SOA in our proposed all-optical multicasting scheme and still take the multicast channel at the frequency of $\omega_1 - \omega_2 + \omega_s$ as an example. Similar to that in the HNLF, this channel is also composed of two FWM idlers. Suppose the gain (G) of the SOA is polarization-insensitive for simplicity, and we employ the lumped model to describe the FWM effect in the SOA [126]. The electrical field of this channel can be expressed as [126]:

$$\begin{aligned}\vec{E}_i = & \sqrt{G_1 G_2 G_S} (\vec{E}_1 \cdot \vec{E}_2^*) r(\omega_1 - \omega_2) \vec{E}_S \cdot \exp j[(\omega_1 - \omega_2 + \omega_S)t + (\phi_1 - \phi_2 + \phi_S)] \\ & + \sqrt{G_1 G_2 G_S} (\vec{E}_S \cdot \vec{E}_2^*) r(\omega_S - \omega_2) \vec{E}_1 \cdot \exp j[(\omega_S - \omega_2 + \omega_1)t + (\phi_S - \phi_2 + \phi_1)],\end{aligned}\quad (5.3)$$

where G_1 , G_2 and G_S represent the P_1 , P_2 , and S gains in the SOA, respectively. $r(\omega_1 - \omega_2)$ and $r(\omega_S - \omega_2)$ still represent the relative CE functions in the SOA and decrease rapidly with the increase of the spacing between the two pumps [135].

The power of this channel can be expressed as [126]:

$$P_i = \vec{E}_i \cdot \vec{E}_i^* = G_1 G_2 G_S P_1 P_2 P_S [r^2(\omega_1 - \omega_2) + r^2(\omega_S - \omega_2) \cos^2 \theta], \quad (5.4)$$

Because $r(\omega_S - \omega_2)$ is much smaller than $r(\omega_1 - \omega_2)$, and the power of the second component in (5.4), which also depends on the polarization angle θ , is treated as the variation to the overall power of this channel.

Likewise, the polarization sensitivity of the other multicast channels is significantly reduced as well.

To summarize, the power of the multicast channels is almost polarization insensitive to the input signal. In the existing results [93-98], the CE of the multicast channels depends on the polarization angle between the signal and the pumps, similar to that observed in the second FWM idler in (5.2) and (5.4). In addition, as the phases and amplitudes of the three probes are constant and do not carry any data information, it can be concluded from (5.1) and (5.3) that the phase and amplitude information of the signal can be preserved in all the multicast channels.

5.3 Experimental performance

5.3.1 Multicasting in HNLF

5.3.1.1 Experimental setup

The experimental setup is shown in Fig. 5.2. Three laser diodes (LD 1, LD 2, and LD 3 at 1548.52 nm, 1550.12 nm, and 1550.92 nm, respectively) that are multiplexed by a polarization maintaining wavelength division multiplexer (PM-WDM) are used as the probes. Because the three probes have the same SOPs when they emit from the LD sources, the SOPs of the probes remain co-polarized with each other when they are introduced to the subsequent HNLF. PC 1 is used to adjust the overall SOP of the three co-polarized probes. LD 4 (at 1558.12 nm), as the modulated signal, is intensity modulated/phase modulated by 10-Gbit/s $2^{31}-1$ PRBS data and then amplified by EDFA 1. A fixed-wavelength filter (FF) is used to reject the ASE noise. Different SOPs of the input modulated signal can be achieved by adjusting PC 2.

The power of each probe that is coupled to the HNLF is set to approximately 3-dBm, and the power of the modulated (OOK and DPSK) signal is approximately 12-dBm. At the receiver side, TF 1 is used to select the desired multicast channel at the output of HNLF. EDFA 2 is used to amplify this channel, and TF 2 is used to reject the ASE noise. VOA is used to adjust the optical power before the eye diagram and BER of a multicast channel are measured. A 100-ps DI is used to demodulate the 10-Gbit/s DPSK signal.

Fig. 5. 2. Experimental setup for FWM-based wavelength multicasting with reduced polarization sensitivity in HNLF.

The HNLF used in this experimental setup is the same as in Chapter 4. The nonlinear coefficient, zero dispersion wavelength, dispersion slope and total fiber loss are $11\text{W}^{-1}\text{Km}^{-1}$, 1560 nm, 0.035 ps/km-nm^2 , and 2.3 dB, respectively.

5.3.1.2 Experimental results and discussion

Fig. 5.3 (a) and (b) show the optical spectra at the output of the HNLF when the SOP of the modulated OOK signal is orthogonal and parallel to the three co-polarized probes. Seven multicast channels, including the signal itself, with 100 GHz spacing are individually located at 1555.72 nm (Ch 1), 1556.52 nm (Ch 2), 1557.32 nm (Ch 3), 1558.12 nm (Ch 4), 1558.92 nm (Ch 5), 1559.72 nm (Ch 6), and 1560.52 nm (Ch 7). As shown in Fig. 5.3, the difference in power level among the six FWM-generated multicast channels is within 1 dB. The CE, defined as the power of multicast channel over the power of output probe, is approximately -23.5 dB when the SOP of the signal

is orthogonal to the probes; it increases to approximately -18.5 dB when the SOP of the signal is parallel to the probes. By varying the SOP of the input signal, the CE varies from -18.5 dB to -23.5 dB. Therefore, the polarization sensitivity is greatly reduced, and this reduction results in only about a 5-dB conversion power fluctuation.

Fig. 5. 3. Optical spectra measured by the OSA when the OOK signal is orthogonal (a) and parallel (b) to the three co-polarized probes by using the HNLF.

In addition, we can see from Fig. 5.3 that the CE fluctuations of *Ia*, *Ib*, and *Ic* are more than 30 dB when the SOPs of the signal are varied. *Ia*, *Ib*, and *Ic* are generated by

the degenerate FWM between the signal (LD 4) and LD 1-3. The electrical field of I_a , for example, can be expressed as

$$\vec{E}_{Ia} = (\vec{E}_s \cdot \vec{E}_1^*) r(\omega_s - \omega_1) \vec{E}_s \cdot \exp j[(\omega_s - \omega_1 + \omega_s)t + (\phi_s - \phi_1 + \phi_s)], (5.5)$$

The power of I_a is

$$P_{Ia} = \vec{E}_{Ia} \cdot \vec{E}_{Ia}^* = P_s^2 P_1 r^2 (\omega_s - \omega_1) \cos^2 \theta, (5.6)$$

From the above equations, the converted power of I_a reaches maximum when the SOPs of the signal and the probes are co-polarized with each other ($\theta = 0$). It becomes zero when the signal and the probes are orthogonal polarized with each other ($\theta = 90^\circ$). This observation provides additional evidence that the FWM CE greatly depends on the polarization states between the signal and pumps if no special techniques are used to reduce the polarization sensitivity.

The number of other higher order FWM idlers in Fig. 5.3 (a) is found to be much less than that in Fig. 5.3 (b). This is because extra beating gratings will be generated among the signal and probes as the SOP of the modulated signal is parallel to the probes.

Fig. 5.4 and Fig. 5.5 show the BER curves and the corresponding eye diagrams of the OOK multicast channels. In contrast, the BER curves and eye diagrams of the DPSK multicast channels are shown in Fig. 5.6 and Fig. 5.7, respectively. All of the eye diagrams are measured when the SOP of the signal is orthogonally polarized to the probes.

Fig. 5. 4. BER curves of the BTB OOK signal and the multicast channels using HNLF. O: signal orthogonally polarized to probes. P: signal parallel polarized to probes.

Fig. 5. 5. Eye diagrams of the BTB OOK signal and the multicast channels using HNLF.

When the SOP of the input signal is parallel to the probes, the maximum power penalties of the OOK and DPSK multicast channels are less than 0.7 dB and 0.8 dB, respectively, at $\text{BER} = 10^{-9}$ compared to the BTB input signal. However, the maximum power penalties of the OOK and DPSK multicast channels increase to 1.5 dB and 1.25 dB, respectively, when the SOP of the input signal is orthogonal to the probes.

Fig. 5. 6. BER curves of the BTB DPSK signal and the multicast channels using HNLF. O: signal orthogonally polarized to probes. P: signal parallel polarized to probes.

Fig. 5. 7. Eye diagrams of the BTB DPSK signal and the multicast channels using HNLF.

The power penalty of Ch 4 is around 0.2 dB for both OOK and DPSK signals when the SOP of the signal is orthogonally polarized to the probes. As the powers of Ch 4 in Fig. 5.3 (a) and (b) are almost the same, little difference is expected on the eye diagram and the BER of Ch 4 for the co-polarized case.

Table 5.1 summarizes the power penalty performance of the six FWM-generated OOK and DPSK multicast channels when the signal is orthogonal (O) and parallel (P)

to the probes. It can be seen that there is about up to 1-dB power penalty difference for the OOK multicast signals (see Ch 3), whereas for the DPSK multicast signals, the power penalty difference is up to 0.75 dB (see Ch 2). This extra 1-dB and 0.75-dB power penalty is due to the 5-dB lower CE, and more ASE noise is introduced by EDFA 2.

Table 5. 1. Power penalties of the six FWM generated OOK and DPSK multicast channels at $\text{BER} = 10^{-9}$ when the signal is orthogonally (O) and parallel (P) to the probes.

	Power penalties of OOK signals (dB)		Power penalties of DPSK signals (dB)	
	P	O	P	O
Ch 1	0.35	0.8	0.25	0.95
Ch 2	0.7	1.25	0.4	1.15
Ch 3	0.5	1.5	0.7	1.25
Ch 5	0.4	1.1	0.8	1.05
Ch 6	0.55	0.9	0.6	1.1
Ch 7	0.3	0.6	0.5	0.85

By varying the SOP of the modulated signal, the residual 5-dB polarization fluctuation only results in approximately 1-dB and 0.75-dB power penalty differences to the OOK and DPSK multicast signals, respectively. These differences in power penalty can be further reduced by using an EDFA with a lower NF.

5.3.2 Multicasting in SOA

5.3.2.1 Experimental setup

The SOA-based multicasting experimental setup is shown in Fig. 5.8, which is similar to the experimental setup using the HNLF. LD 1 (at 1558.02 nm), LD 2 (at 1559.73 nm), and LD 3 (at 1560.49 nm) work as three probes, and their optical powers coupled into the SOA are set at 6.9-dBm, 3-dBm, and 4.1-dBm, respectively. The

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wavelength of the signal is 1548.73 nm, and the power of the signal coupled to the SOA is set at 7-dBm by using the VOA 1. PC 1 and PC 2 are used to adjust the SOPs of the co-polarized probes and signal.

Fig. 5. 8. Experimental setup for FWM-based wavelength multicasting with reduced polarization sensitivity in SOA.

Fig. 5. 9. The ASE gain spectrum of the SOA when the bias current is 500-mA.

The SOA being used here has a small signal gain of around 34 dB and a 16.5-dBm

saturation output power when the bias current is set at 550-mA. The carrier recovery time of this SOA is typically 10-ps, which does not cause any degradation on the eye diagrams of the 10-Gbit/s data signal. The ASE gain spectrum of the SOA when the bias current is 500-mA is shown by Fig. 5.9.

Fig. 5. 10. The measured polarization dependent gain difference of the SOA under different bias current.

Fig. 5.10 shows the measured polarization dependent gain (PDG) difference of the SOA when the bias current is set at 550-mA, 500-mA, 400-mA, and 300-mA. The gain difference can be seen to become small as the power of the input signal increases. The PDG difference is less than 1 dB when the power of the input signal is above -12.5-dBm. On the other hand, when increasing the bias current of the SOA, the PDG difference also decreases.

5.3.2.2 Experimental results

Fig. 5. 11. Optical spectra measured by the OSA when the OOK signal has minimum (a) and maximum (b) gain in the SOA due to the polarization dependent gain.

Fig. 5.11 shows the optical spectra at the output of the SOA when the SOPs of the three probes are fixed at randomly chosen states. The bias current of the SOA is set at 550-mA. Seven multicast channels can be seen individually located at 1546.26 nm (Ch 1), 1547.02 nm (Ch 2), 1547.97 nm (Ch 3), 1548.73 nm (Ch 4), 1549.49 nm (Ch 5), 1550.44 nm (Ch 6), and 1551.2 nm (Ch 7). Because the CE of FWM arising in the SOA is much higher than that in the HNLF, some high-order FWM idlers are also generated.

Once we assign the probes with the same wavelength separations as the configuration used in the HNLF (0.8 nm between LD 2 and LD 3, 1.6 nm between LD 1 and LD 2, and 2.4 nm between LD 1 and LD 3), some of the high-order FWM idlers will overlap with the multicast channels and consequently introduce significant in-band crosstalk. The eye diagrams of these multicast channels are severely degraded, and an error floor occurs at the BER of 10^{-4} . To avoid such crosstalk, we set the wavelengths of LD 1 at 1558.02 nm, LD 2 at 1559.73 nm, and LD 3 at 1560.49 nm. Thus, the crosstalk can be suppressed by using the TF 2.

Due to the PDG in the SOA, Fig. 5.11 (a) shows the optical spectra measured by the OSA when the OOK signal has minimum gain in the SOA by adjusting PC 2. In contrast, Fig. 5.11 (b) shows the optical spectra for which the OOK signal has maximum gain in the SOA by adjusting PC 2.

The PDG difference of the signal (Ch 4) can be seen to be around 2 dB. In addition, the conversion power of Ch 1-Ch 3 in Fig. 5.10 (a) is up to about 1.5 dB lower than that in Fig. 5.11 (b), whereas the conversion power of Ch 5-Ch 7 in Fig. 5.11 (a) is up to around 2.5 dB higher than that in Fig. 5.11 (b). This shows that the polarization sensitivity has been reduced to within 2.5 dB in the SOA. Moreover, Ch 2 and Ch 6 have the largest and lowest conversion powers in the generated multicast channels, respectively. Their conversion power differences are 6.5 dB in Fig. 5.11 (a) and 9.5 dB in Fig. 5.11 (b). The reason why the conversion power of Ch 5-Ch 7 is smaller than that of Ch 1-Ch 3 is that the relative CE function of wavelength up-conversion is smaller than that of the wavelength down-conversion in this SOA [135, 136].

Because the power conversion fluctuation in the SOA is less than 2.5 dB, we

believe that the power penalty difference is much smaller than that in the HNLF. We measure all the eye diagrams and BER curves by setting both PC 1 and PC 2 in a fixed random state.

Fig. 5. 12. BER curves of the BTB OOK signal and the multicast channels using SOA.

Fig. 5. 13. Eye diagrams of the BTB OOK signal and the multicast channels using SOA.

Fig. 5.12 and Fig. 5.13 show the BER curves and the corresponding eye diagrams of the OOK modulated multicast channels. Compared with the BTB case, the largest power penalty of these multicast channels can be seen to be less than 3.1 dB at $\text{BER} = 10^{-9}$.

Fig. 5. 14. BER curves of the BTB DPSK signal and the multicast channels using SOA.

Fig. 5. 15. Eye diagrams of the BTB DPSK signal and the multicast channels using SOA.

The BER curves and the corresponding eye diagrams of the DPSK modulated multicast channels are illustrated by Fig. 5.14 and Fig. 5.15, and the maximum power penalty of these multicast channels is less than 1.1 dB.

The detailed power penalties of OOK and DPSK multicast channels are summarized in Table 5.2.

According to Fig. 5.12 and Fig. 5.14, the multicast channels Ch 5-Ch 7 have higher

power penalties than do Ch 1-Ch 3. This difference is because the former channels have lower conversion powers than do the latter channels, and more ASE noise is introduced by EDFA 2. This difference in power penalty among different multicast channels can be further reduced by using an EDFA with lower NF. In addition, the reason why the OOK multicast signals have a higher power penalty than that of the DPSK signals is that the XGM effect in the SOA degrades the quality of the OOK multicast signals. This XGM effect is much less significant for DPSK multicast signals owing to its constant envelope in the time domain.

Table 5. 2. Power penalties of the OOK and DPSK multicast channels at $\text{BER} = 10^{-9}$ when the signal is fixed at a random polarization state.

	Power penalties of OOK signals (dB)	Power penalties of DPSK signals (dB)
Ch 1	1.0	0.45
Ch 2	1.9	0.35
Ch 3	2.2	0.25
Ch 4	0.7	0.15
Ch 5	3.1	0.9
Ch 6	2.9	1.1
Ch 7	2.5	0.8

Fig. 5.16 gives the optical spectra at the output of the SOA when the bias current is set at 550-mA, 450-mA, 350-mA, and 250-mA, respectively. The input SOPs of the signal and the three probes are both set at a fixed random state. From Fig. 5.16, we can see that a higher bias current results in a higher gain and conversion power to the signal and multicast channels. The gain and conversion power difference of the signal and multicast channels is within 5 dB and 10 dB when the bias current of the SOA is varied from 250-mA to 550-mA.

Fig. 5. 16. Optical spectra at the output of the SOA when the bias current of the SOA is 550-mA (a), 450-mA (b), 350-mA (c), and 250-mA (d).

5.3.2.3 Discussion

The experimental results show that seven multicast channels can be obtained using either the HNLF or the SOA. Although the residual polarization sensitivity in the SOA is approximately 2.5 dB smaller than that in the HNLF, the power difference among the generated multicast channels is around 9.5 dB in the SOA, which is much higher than the 1-dB difference measured in the HNLF. Due to the high FWM CE in the SOA,

another issue that needs to be addressed is the crosstalk generated from other high-order FWM idlers when the SOA is used for multicasting. It is found that the BER error floor at 10^{-4} will occur if we assign the probes with the same wavelength separations as the same configuration used in the HNLF. However, this issue can be resolved by slightly detuning the wavelength separations of the probes, e.g., setting LD 1 at 1558.02 nm, LD 2 at 1559.73 nm, and LD 3 at 1560.49 nm.

Moreover, the maximum power penalty of the OOK multicast signals in the SOA is approximately 3.1 dB, which is about 1.6 dB higher than that in the HNLF. This difference is due to the XGM effect-induced crosstalk in the SOA. Such crosstalk can be suppressed when the phase modulated signals are multicasting, e.g., the maximum power penalty of the DPSK multicast signals is reduced to 1.1 dB in the SOA.

5.4 Conclusions

In summary, we proposed and experimentally demonstrated another all-optical modulation format and bit rate transparent wavelength multicast scheme based on the FWM effect in both an HNLF and an SOA. By using three co-polarized probes and a modulated signal, seven multicast channels were generated. The proposed multicast scheme can significantly reduce the polarization sensitivity from more than 20 dB to about 5 dB in the HNLF and to 2.5 dB in the SOA. The low polarization sensitivity led to a difference of less than 1 dB in the power penalty of the multicast channels. We reported a comprehensive multicasting performance comparison of the OOK and DPSK signals in the HNLF and the SOA. The converted power difference between the generated multicast channels in the SOA was found to be around 9.5 dB, and this

difference was much higher than the 1-dB difference measured in the HNLF. This larger conversion power difference is due to the fact that the CE function of wavelength up-conversion is smaller than that of the wavelength down-conversion in the SOA. In addition, the maximum power penalties of the DPSK multicast channels in the HNLF and the SOA were less than 1.25 dB and 1.1 dB, respectively. In comparison, the maximum power penalty of the OOK multicast channels in the SOA was approximately 3.1 dB, which was 1.6 dB higher than that in the HNLF. This difference is due to the XGM effect-induced crosstalk. Such crosstalk in the SOA can be suppressed when the phase modulated signals are used for multicasting.

Chapter 6 Optical Wavelength Multicasting Based on XGM and Cascaded FWM in an SOA Using Single Pump Laser Source

6.1 Introduction

In Chapter 4 and Chapter 5, we proposed and demonstrated two optical wavelength multicasting schemes based on the FWM effect, where at least two pumps or probes were required in order to obtain several multicast channels. It is noted that temperature controllers (TEC) are necessary to stabilize the emission wavelengths of these LDs and increase the implementation cost. Therefore, it is highly desirable to design an all-optical wavelength multicasting scheme with none or only a single LD to obtain as many multicast channels as possible.

In [74, 75], the multicasting scheme based on SPM without any external laser source was proposed. By spectrum slicing the SPM-broadened signal, several multicast

channels were obtained. In addition, by XGM with the ASE noise in an SOA, four multicast channels can also be obtained [80]. However, the data rate cannot be too high because of the large intensity noise originating from the spectrum spliced ASE noise carrier [80].

While in [103], eleven multicast channels were obtained by using XGM, XPM, and cascaded FWM effects in an HNLF with single pump laser. This is the largest reported number of obtained multicast channels in HNLF by using a single pump laser.

In this chapter, we demonstrate an optical wavelength multicasting by combining XGM, and cascaded FWM effects in an SOA by using only a single pump laser source, which can yield seven 10-Gbit/s OOK multicast channels with 100 GHz wavelength spacing [137]. The number of multicast channels demonstrated is the highest reported for a single laser configuration in an SOA.

6.2 Operation principle

The operation principle, illustrated in Fig. 6.1, is straightforward. A high power signal (S) and a pump (P) at frequency of ω_s and ω_p are injected into the SOA. For the safe operation of SOA, the total input power should not be too large. In addition, the SOPs of the signal and pump need to be co-polarized to each other in order to obtain the best performance.

The data information of the signal is modulated to the pump via the XGM effect. Then two degenerated FWM idles at frequency of $\omega_s + \Delta\omega$ and $\omega_s - \Delta\omega$ are generated. Here $\Delta\omega$ denotes the frequency difference between the pump and signal. Finally, more

FWM idlers with the frequency spacing of $\Delta\omega$ are generated via the cascaded FWM effects. All the FWM idlers preserve the amplitude information of the signal. Thus, the pump, signal, and FWM idlers are used as the multicast channels at the output of the SOA.

Fig. 6. 1. Operation principle of the optical wavelength multicasting scheme based on XGM and cascaded FWM using single pump source.

6.3 Experimental setup and discussion on results

6.3.1 Experimental setup

Fig. 6.2 shows the experimental setup. The light source, LD 1, (at 1558.17 nm) is intensity modulated by a 10-Gbit/s data stream ($2^{31}-1$ PRBS) and amplified by EDFA 1. VOA 1 is used to adjust the probe signal power coupled into the SOA. LD 2 (at 1557.36 nm) is used as the pump laser source. EDFA 2 is used to amplify the power of the pump. The pump and probe signal are then multiplexed by a WDM before injected into the SOA. The powers of the pump and probe signal launched into the SOA are set

Chapter 6: Optical Wavelength Multicasting Based on XGM and Cascaded FWM in an SOA Using Single Pump Laser Source

to 11.8-dBm and 5.8-dBm, respectively. PC 1 and PC 2 are used to adjust the polarization states of the pump and signal to obtain the best CE for all the multicast channels. The SOA used here is the same as used in Chapter 5, which has a small signal gain of about 34 dB, and a 16.5-dBm saturation output power, when the bias current is set at 550-mA. At the receiver side, another WDM with 100 GHz wavelength spacing is used to de-multiplex all the multicast channels at the output of the SOA. EDFA 3 is used to amplify this channel and a TF is used to further reject the ASE noise. VOA 2 is used to adjust the optical power before the eye diagram and BER of the multicast channels are measured.

Fig. 6. 2. Experimental setup of the 1-to-7 wavelength multicasting in an SOA using single-pump laser source.

6.3.2 Experimental results and discussion

Fig. 6.3 shows the optical spectra measured by the OSA at the output of SOA. The bias current of the SOA is 550-mA. It can be seen that seven multicast channels, including the pump and probe signal, are generated with 100 GHz wavelength spacing. These multicast channels are individually located at 1554.94 nm (Ch 1), 1555.75 nm

(Ch 2), 1556.55 nm (Ch 3), 1557.36 nm (Ch 4), 1558.17 nm (Ch 5), 1558.98 nm (Ch 6), and 1559.79 nm (Ch 7), which comply with the ITU grid. Ch 4 (*P*) is generated by means of the XGM effect in the SOA. Ch 3 and Ch 6 are generated by the degenerate FWM effect. The OSNR of these multicast channels is over 30 dB.

Fig. 6. 3. Optical spectra measured by the OSA at the output of the SOA.

The BER performance and the corresponding eye diagrams (zero level indicated) are shown in Fig. 6.4 and Fig. 6.5. It can be seen that Ch 4 has the largest power penalty, about 3.3 dB at $\text{BER} = 10^{-9}$. This is owing to the high DC power coming from the pump (see the eye diagram of Ch 4). Nevertheless, we believe by slightly detuning the central wavelength of TF to filter one side-band, which is similar to the vestigial sideband (VSB) modulation signal [138], DC component in Ch 4 can be further suppressed, and the BER performance of Ch 4 can be improved. In addition, the data format of Ch 4 is inverted to the original signal due to the XGM operation principle

[78]. Nevertheless, the data format of Ch 4 can be easily converted back by using a NOT gate at the receiver side. While for the other multicast channels, Ch 7 has the maximum power penalty, which is about 1.5 dB. This is due to the lower OSNR, and more ASE noise is introduced by EDFA 3. This relatively larger power penalty can be further reduced by using an EDFA with lower NF. Ch 3 suffers a high noise level at bit '0', which is due to the relative small pump-to-signal ratio that increases the effect of inter-symbol interference (ISI) in the SOA [139].

Fig. 6. 4. BER curves of the BTB signal and the multicasting channels.

It is worth noting that the powers of the seven multicast channels are not equal, however, we may use the power equalization technique to make them having the same power level [140]. In addition, the channel spacing can be further adjusted to 50 GHz or even 25 GHz, the CE of the multicast channels can be further increased, and more channels can be obtained (e.g., the cascaded FWM idlers next to Ch 1 and Ch 7 can be used due to the improved OSNR), but this will require the WDM to have very good

suppression performance to separate these multicast channels without crosstalk. Lastly, the bit rate of the multicast channels can be easily increased to 40-Gbit/s or even higher because the carrier recovery time of this SOA is typically 10-ps.

Fig. 6. 5. Eye diagrams of the BTB signal and the multicasting channels.

6.4 Conclusion

In summary, we experimentally demonstrated a simple all-optical wavelength multicasting technique that had the highest number of multicast channels in an SOA for a single pump laser source. Combining the XGM and FWM (including cascaded FWM) effects in an SOA, seven 10-Gbit/s multicast channels with 100 GHz wavelength spacing were successfully demonstrated. The experimental results show that the CE of these multicast channels was larger than -27 dB and the maximum power penalty was less than 3.3 dB at $\text{BER} = 10^{-9}$. The channel spacing can be reduced to 50 GHz or even

25 GHz and the data rate can be increased to 40-Gbit/s and beyond. In addition, it should be possible to use an ultra-long bulk SOA that has a very high FWM efficiency [141] to further increase the number of multicast channels.

Unfortunately, only OOK signal can be used for wavelength multicasting in this scheme. In addition, the SOPs of the signal and pumps need to be adjusted to obtain the best CE for all the multicast channels.

Chapter 7 Conclusions and Future Work

7.1 Conclusions

All-optical processing technologies are highly desirable for next generation optical networks, due to the critical urgency in moving the processing functions from the electrical to the optical domain in order to solve the electrical bottleneck issue.

All-optical processing technologies span many research topics, and this thesis focused on the all-optical buffering and wavelength multicasting technologies.

In Chapter 3, we proposed an optically controlled loop buffer, which demonstrated better performance in terms of number of achievable re-circulations compared to other similar structures. This loop buffer consists of an SOA-based loop mirror as a fast switch to realize the writing and reading of packets and a circulator-based optical reflector to achieve internal re-circulations. Variable delay time per circulations can be achieved by adding fibers with different lengths between the loop mirror and the circulator. From the experimental results, the packet data signals with pattern “1010011000101111”, both at 2.5-Gbit/s and 10-Gbit/s were able to maintain good quality after 24 and 16 circulations, respectively. Moreover, by using the negative control format, as many as 36 circulations can be obtained for the 2.5-Gbit/s data packet.

In Chapter 4, we proposed and experimentally demonstrated an all-optical modulation format and data rate transparent wavelength multicasting technique using the FWM effect in an HNLF Sagnac loop. This proposed design overcame the undesirable effect of pump-pump generated idlers overlapping with the multicast channels. The experimental results showed that the pumps and the pump-pump idlers can be greatly suppressed by more than 30 dB at the output of the multicasting channels. Six and ten 10-Gbit/s OOK/DPSK multicast channels complying with the ITU grid were generated by using two- and three-pump lasers, respectively. The power penalty of these multicast channels was found to be less than 3.5 dB. In addition, we also investigated the multicasting performance in a non-loop configuration for comparison. Also we discovered that the eye diagrams of the overlapped multicast channels were closed due to the in-band crosstalk arising from the pump-pump idlers. Comparing the proposed Sagnac loop configuration with the non-loop configuration, we observed that the former can achieve up to a 1.2-dB improvement in terms of the power penalty. Another advantage of the proposed technique is that pump amplifier ASE noise can be suppressed by 10 dB at the output of the multicast channels without the need to have an extra filter, which has the effect of not incurring the insertion loss due to the filter.

In Chapter 5, we proposed and experimentally demonstrated another all-optical modulation and data rate transparent wavelength multicasting scheme based on the FWM effect in an HNLF and an SOA, respectively. Seven multicast channels were generated by using three co-polarized probes and a modulated signal. Meanwhile, the polarization sensitivity of the generated multicast channels was significantly reduced from more than 20 dB to about 5 dB in the HNLF and 2.5 dB in the SOA. The low polarization sensitivity led to a difference of less than 1 dB in the power penalty of the

multicast channels. Comprehensive multicasting performance comparisons of the OOK and DPSK signals in the HNLF and the SOA were reported. The converted power differences of the generated multicast channels in the SOA was found to be around 9.5 dB, much higher than the 1 dB difference measured in the HNLF. In addition, the maximum power penalties of the DPSK multicast channels in the HNLF and SOA were less than 1.25 dB and 1.1 dB, respectively. In comparison, the maximum power penalty of the OOK multicast channels in the SOA was around 3.1 dB, which was 1.6 dB higher than that in the HNLF. This difference is due to the XGM effect induced crosstalk. Such crosstalk in the SOA can be suppressed when phase modulated signals are used.

In Chapter 6, we experimentally demonstrated a simple all-optical wavelength multicasting technique that has the highest number of multicast channels in an SOA for a single pump laser source. Combining the XGM and FWM (including cascaded FWM) effects in an SOA, seven 10-Gbit/s multicast channels with 100 GHz wavelength spacing were successfully demonstrated. The experimental results showed the CE of these multicast channels to be larger than -27 dB and the maximum power penalty of these multicast channels to be less than 3.3 dB at $\text{BER} = 10^{-9}$. Moreover, the channel spacing can be reduced to 50 GHz or even 25 GHz, and the data rate can be increased to 40-Gbit/s and beyond.

7.2 Suggestions for future work

For optical buffering technology, fiber delay line based optical loop buffer currently seems to be the best candidate for practical implementation.

The SOA used in the multicasting schemes has a shorter carrier recovery time than that for the proposed loop buffer. Thus, we can employ this SOA in the loop buffer to demonstrate the buffering performance at the data rate of 40-Gbit/s and beyond for future work. The buffering performance of advanced modulation formats, such as DPSK, will be studied too.

In recent years, SOA-based loop buffers have been demonstrated with photonics integration [142]. This promising progress gives hope to possible practical use of loop buffer in future.

Fig. 7. 1. Three stages cascaded DLOBs with increased delay range.

Moreover, it is highly desirable to enhance the variable delay range of the loop buffer. Fig. 7.1 illustrates the operating principle of cascaded DLOBs, which can greatly increase the delay range [143]. In DLOB 1, the delay time per loop is T slots, whereas the delay times per loop in DLOB 2 and DLOB 3 are $10T$ and $100T$, respectively. The packets can be buffered in the first DLOB within the range of 0 to $9T$. The second stage DLOB has the delay time step as 0, $10T$, $20T$, $\dots$, and $90T$. The

third stage has the step 0, 100T, 200T,, and 900T. As a result, the delay range can vary from 0 to 999T, whereas the number of required circulations for any delay time between 0 to 999T is totally no larger than 27 in the three DLOBs. This demonstrates the amazing performance of loop buffers and sheds light on how to enhance the delay range in a scalable fashion.

Another issue that needs to be addressed is that only one packet can be buffered per time slot in most of the loop buffers. In [112], two packets at different wavelengths were demonstrated to be written into and read from the DLOB simultaneously. Further research is expected to carry out reading and writing of several packets asynchronously.

The ultimate goal for optical buffer is to fulfill similar functions as the electrical buffer. In other words, many optical signals, as long as they are smaller than the buffer capacity, can be arbitrarily written into and read from the buffer without any degradation. Meanwhile, the optical buffer should be transparent to the modulation format and data rate of the signal.

Moreover, it would be even more optimal if some other all-optical processing technologies can be integrated into the buffer, such as optical signal regeneration, and optical wavelength conversion/multicasting.

For the all-optical wavelength multicasting technology, a lot of research works and results have been reported. The most important feature of the multicasting scheme is data rate and modulation format transparency. Second, it is highly desirable to obtain as many multicast channels as possible by using less pumps or probes. Its ability to arbitrarily select the multicast channels at different wavelengths is another attractive

feature.

To the best of the author's knowledge, the world record for the largest number of multicast channels obtained in single-pump modulated FOPA is forty [86]. However, this scheme is not data modulation format transparent.

Fig. 7. 2. Operation principle of the dual stage optical wavelength multicasting scheme.

In this research, we propose a dual stage optical wavelength multicasting scheme based on the FWM effect to achieve 100 multicasting channels, which will be the world record. This multicasting scheme is data rate and modulation format transparent to the signal. Fig. 7.2 illustrates the operation principle.

As shown in Fig. 7.2, the input signal at λ_f will be first multicast to ten channels from λ_a to λ_j by the first stage multicast module. These ten generated multicast channels are with large wavelength spacing to each other. Then, each multicast channel will go

through the second stage multicast module, and another ten multicast channels are generated at each multicast module. Finally, by multiplexing these multicast channels, 100 multicast channels can be obtained at different wavelengths.

The operation of the multicast module is based on the multi-pump FWM effect, which provides the modulation format and data rate transparency. In Chapter 4, we demonstrated that ten multicast channels can be obtained by using three pump lasers. Thus, each multicast module needs only three pump lasers. In addition, some of the pumps may be shared by several multicast modules, which can further reduce the total number of pump lasers in use.

However, the most critical part in this scheme lies in the multicast module at the first stage. The input signal needs to be multicast to ten multicast channels, which should have large wavelength spacing between each of them. Then, the nonlinear medium for achieving such wideband wavelength multicasting becomes highly essential.

As multicasting can also be implemented in the network layer, more interesting results will emerge if physical and network layer multicasting can be taken into consideration simultaneously.

Finally, besides optical buffering and optical wavelength multicasting technologies, many other interesting topics that are essential to next generation optical networks need to be addressed.

Publication List

Author's publications

- [1] **D. Wang**, T. H. Cheng, Y. K. Yeo, Z. Xu, J. Liu, and Y. Wang, “Optically controlled loop buffer using a SOA loop mirror and a circulator based reflector,” *Opt. Commun.*, vol. 282, no. 20, pp. 4052-4056, Oct. 2009 (related to Chapter 3).
- [2] **D. Wang**, T. H. Cheng, Y. K. Yeo, J. Liu, Z. Xu, Y. Wang, and G. Xiao, “All-optical modulation transparent wavelength multicasting in a highly nonlinear fiber Sagnac loop mirror,” *Opt. Exp.*, vol. 18, no. 10, pp. 10343-10353, May 2010 (related to Chapter 4).
- [3] **D. Wang**, T. H. Cheng, Y. K. Yeo, Y. Wang, Z. Xu, J. Liu, and G. Xiao, “Optical wavelength multicasting based on four wave mixing in highly nonlinear fiber with reduced polarization sensitivity,” in *Proc. OFC/NFOEC'2010*, Paper JWA47, 2010 (related to Chapter 5).
- [4] **D. Wang**, T. H. Cheng, Y. K. Yeo, Z. Xu, Y. Wang, G. Xiao, and J. Liu, “Performance comparison of using SOA and HNLF as FWM medium in a wavelength multicasting scheme with reduced polarization sensitivity,” *J. Lightw. Technol.*, vol. 28, no. 24, pp. 3497-3505, Dec. 2010 (related to Chapter 5).
- [5] **D. Wang**, T. H. Cheng, Y. K. Yeo, Y. Wang, Z. Xu, and G. Xiao, “7×10-Gbit/s all-optical wavelength multicast based on cross-gain modulation and cascaded

four-wave mixing effects in an SOA using single pump laser source,” in *Proc. OFC/NFOEC’2011*, Paper JWA40, 2011 (related to Chapter 6).

Author’s other publications

- [1] **D. Wang**, Y. K. Yeo, T. H. Cheng, Y. Wang, Z. Xu, and J. Liu, “A Space-Diversity Optical Labeling Scheme with Optical Labels Derived from ASE Noise,” in *Proc. ICICS’2009*, Paper TuA6, 2009.
- [2] S. Wang, **D. Wang**, C. Lu, T. H. Cheng, and P. K. A. Wai, “Multiple Raman pump assisted fiber optical parametric amplifiers,” *J. Lightw. Technol.*, vol. 29, no. 17, pp. 2601-2608, Sept. 2011.
- [3] S. Wang, **D. Wang**, T. H. Cheng, C. Lu, and P. K. A. Wai, “Polarization-independent Raman-assisted fiber optical parametric amplifier,” in *Proc. ICOCN’2011*, 2011.
- [4] T. H. Cheng, Y. K. Yeo, **D. Wang**, Y. Wang, G. Xiao, and Z. Xu, “All-optical wavelength multicasting,” in *Proc. ICOCN’2011*, Invited Paper, 2011.
- [5] Y. K. Yeo, Z. Xu, **D. Wang**, J. Liu, Y. Wang, and T. H. Cheng, “High-speed optical switch fabrics with large port count,” *Opt. Exp.*, vol. 17, no. 13, pp. 10990-10997, Jun. 2009.
- [6] Z. Xu, T. H. Cheng, Y. K. Yeo, Y. Wang, **D. Wang**, and J. Liu, “Simultaneous erasure and rewriting of a subcarrier-multiplexed label in an all-optical label swapping scheme,” *Opt. Exp.*, vol. 18, no. 13, pp. 1974-1980, Jan. 2010.
- [7] J. Liu, T. H. Cheng, Y. K. Yeo, Y. Wang, L. Xue, **D. Wang**, and X. Yu, “Degenerate four-wave mixing based all-optical wavelength conversion in a semiconductor optical amplifier and highly-nonlinear photonic crystal fiber

- parametric loop mirror,” *Opt. Commun.*, vol. 281, no. 21, pp. 5415-5419, Nov. 2008.
- [8] J. Liu, T. H. Cheng, Y. K. Yeo, Y. Wang, L. Xue, Z. Xu, and **D. Wang**, “Light beam coupling between standard single mode fibers and highly nonlinear photonic crystal fibers based on the fused biconical tapering technique,” *Opt. Exp.*, vol. 17, no. 5, pp. 3115-3223, Mar. 2009.
- [9] J. Liu, Y. K. Yeo, Y. Wang, L. Xue, **D. Wang**, W. Rong, L. Zhou, G. Xiao, X. Yu, and T. H. Cheng, “Pump-suppressed nondegenerate four wave mixing in a highly nonlinear photonic crystal fiber Sagnac loop,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 24, pp. 2129-2131, Dec. 2008.
- [10] J. Liu, T. H. Cheng, Y. K. Yeo, Y. Wang, L. Xue, W. Rong, L. Zhou, G. Xiao, **D. Wang**, and X. Yu, “Stimulate Brillouin scattering based broadband tunable slow light conversion in a highly nonlinear photonic crystal fiber,” *J. Lightw. Technol.*, vol. 27, no. 10, pp. 1279-1285, May 2009.
- [11] J. Liu, T. H. Cheng, Y. K. Yeo, Y. Wang, L. Xue, N. Zhu, Z. Xu, and **D. Wang**, “All-optical continuously tunable delay with a high linear chirp rate fiber Bragg grating based on four wave mixing in a highly nonlinear photonics crystal fiber,” *Opt. Commun.*, vol. 282, no. 22, pp. 4366-4369, Nov. 2009.
- [12] Y. K. Yeo, Z. Xu, C. Y. Liaw, **D. Wang**, Y. Wang, and T. H. Cheng, “A 448×448 optical cross-connect for high performance computers and Multi-Terabit/s Routers,” in *Proc. OFC/NFOEC’2010*, Paper OMP6, 2010.
- [13] Z. Xu, T. H. Cheng, Y. K. Yeo, Y. Wang, X. Cheng, J. Liu, and **D. Wang**, “Simultaneous triple data transmissions on a single wavelength,” in *Proc. ECOC’2009*, Paper 10.51, 2009.

- [14] T. H. Cheng, Y. K. Yeo, Y. Wang, G. Xiao, L. Zhou, **D. Wang**, Z. Xu, and J. Liu, "Design of a 100Tb/s multicast-capable optical packet router," in *Proc. CMC'2010*, Paper vol. 2, pp. 18-22, Invited Paper, 2010.
- [15] J. Liu, Y. K. Yeo, Y. Wang, **D. Wang**, L. Xue, G. Xiao, L. Zhou, T. H. Cheng, "Broad-band tunable four wave mixing based wavelength converter with filterless pump suppression", in *Proc. OECC'2008*, Paper TuF6, 2008.
- [16] J. Liu, T. H. Cheng, Y. K. Yeo, Y. Wang, Z. Xu, and **D. Wang**, "Fused biconical tapered technique based light beam coupling between a single mode fiber and a high nonlinearly photonic crystal fiber," in *Proc. OFC/NFOEC'2009*, Paper JThA18, 2009.
- [17] T. H. Cheng, J. Liu, Y. K. Yeo, Y. Wang, Z. Xu, and **D. Wang**, "Hi-Fi all-optical continuously tunable delay with a high linear chirp rate fiber Bragg grating based on four-wave mixing in a highly-nonlinear photonics crystal fiber," in *Proc. OFC/NFOEC'2009*, Paper JWA31, 2009.

Bibliography

- [1] G. Keiser, *Optical Fiber Communications*. McGraw-Hill, 2000.
- [2] D. T. Neilson, “Photonics for switching and routing,” *IEEE J. Select. Top. Quantum. Electron.*, vol. 12, no. 14, pp. 669–678, Jul. /Aug. 2006.
- [3] Internet World Statistics, <http://www.internetworldstats.com>.
- [4] L. G. Roberts, “Beyond Moore’s law: Internet growth trends,” *Computer*, vol. 33, no. 1, pp. 117-119, Jan. 2000.
- [5] M. Camera, “100GbE optical transport, appropriate modulation formats, and impact on deployed transport networks,” in *Proc. OFC/NFOEC’2010*, Paper NME3, 2010.
- [6] K. Kasai, T. Omiya, P. Guan, M. Yoshida, T. Hirooka, and M. Nakazawa, “Single-channel 400 Gbit/s, OTDM-32 RZ-QAM coherent transmission over 225 km using an optical phase-locked loop technique,” in *Proc. OFC/NFOEC’2010*, Paper OThD6, 2010.
- [7] Y. Ma, Q. Yang, Y. Tang, S. Chen, and W. Shieh, “1-Tb/s single-channel coherent optical OFDM transmission over 600-km SSMF fiber with subwavelength bandwidth access,” *Opt. Exp.*, vol. 17, no. 11, pp. 9421-9427, May 2009.
- [8] H. Hu, M. Galili, O. Leif, J. Xu, H. C. H. Mulvad, C. Peucheret, A. Clausen, and P. Jeppesen, “Error-free transmission of serial 1.28 Tbaud RZ-DPSK signal,” in *Proc. ECOC’2010*, Paper P4.18, 2010.
- [9] H. C. H. Hulvad, *et al.*, “Demonstration of 5.1 Tbit/s data capacity on a single-wavelength channel,” *Opt. Exp.*, vol. 18, no. 2, pp. 1438-1443, Jan. 2010.

- [10] D. Hillerkuss, *et al.*, “Single source optical OFDM transmitter and optical FFT receiver demonstrated at line rates of 5.4 and 10.8Tbit/s,” in *Proc. OFC/NFOEC’2010*, Paper PDPC1, 2010.
- [11] Q. Qian, *et al.*, “101.7-Tb/s (370×294-Gb/s) PDM-128QAM-OFDM transmission over 3×55-km SSMF using Pilot-based phase noise mitigation,” in *Proc. OFC/NFOEC’2011*, Paper PDPB5, 2011.
- [12] J. Sakaguchi, *et al.*, “109-Tb/s (7×97×172-Gb/s SDM/WDM/PDM) QPSK transmission through 16.8-km homogeneous multi-core fiber,” in *Proc. OFC/NFOEC’2011*, Paper PDPB6, 2011.
- [13] P. Winzer, “Challenges and evolution of optical transport networks,” in *Proc. ECOC’2010*, Paper We.8.D.1, 2010.
- [14] Michael J. O’Mahony, *et al.*, “Future optical networks,” *J. Lightw. Technol.*, vol. 24, no. 12, pp. 4684-4696, Dec. 2006.
- [15] R. S. Tucker, P.-C. Ku, and C. J. Chang-Hasnain, “Slow light optical buffers: Capabilities and fundamental limitations,” *J. Lightw. Technol.*, vol. 23, no. 12, pp. 4046-4066, Dec. 2005.
- [16] J. Wang, J. Sun, Q. Sun, D. Wang, X. Zhang, D. Huang, and M. M Fejer, “PPLN-based flexible optical logic AND gate,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 3, pp. 211-213, Feb. 2008.
- [17] S. B. Yoo, “Wavelength conversion technologies for WDM network applications,” *J. Lightw. Technol.*, vol. 14, no. 6, pp. 955-966, Jun. 1996.
- [18] C.-S Brès, N. Alic, E. Myslivets, and S. Radic, “Scalable multicasting in one-pump parametric amplifier,” *J. Lightw. Technol.*, vol. 27, no. 3, pp. 356-363, Mar. 2009.
- [19] K. K. Chow, and C. Shu, “All-optical signal regeneration with wavelength

- multicasting at 6×10 Gb/s using a single electro-absorption modulator,” *Opt. Exp.*, vol. 12, no. 3, pp. 3050-3054, Jun. 2004.
- [20] C. Bornholdt, J. Slovak, and B. Sartorius, “Semiconductor-based all-optical 3R regenerator demonstrated at 40 Gbit/s,” *Electron. Lett.*, vol. 40, no. 3, pp. 192-194, Feb. 2004.
- [21] R. Slavík, *et al.*, “All-optical phase and amplitude regenerator for next-generation telecommunications systems,” *Nature Photon.*, vol. 4, no. 10, pp. 690-695, Sep. 2010.
- [22] K. Mishina, S. Kitagawa, and A. Maruta, “All-optical modulation format conversion from on-off-keying to multiple-level phase-shift-keying based on nonlinearity in optical fiber,” *Opt. Exp.*, vol. 15, no. 13, pp. 8444-8453, Jun. 2007.
- [23] M. Shen, X. Xu, T. I. Yuk, and K. K. Y. Wong, “A 160-Gb/s OTDM demultiplexer based on parametric wavelength exchange,” *IEEE J. Quantum Electron.*, vol. 45, no. 11, pp. 1309-1316, Nov. 2009.
- [24] C.-S. Brès, A. O. J. Wiberg, B. P.-P. Kuo, J. M. Chavez-Boggio, C. F. Marki, N. Alic, and S. Radic, “Optical Demultiplexing of 320 Gb/s to 8×40 Gb/s in Single Parametric Gate,” *J. Lightwave Technol.*, vol. 28, no. 4, pp. 434-442, Feb. 2010.
- [25] J. Wang, S. R. Nuccio, H. Huang, X. Wang, J.-Y. Yang, and A. E. Willner, “Optical data exchange of 100-Gbit/s DQPSK signals,” *Opt. Exp.*, vol. 18, no. 23, pp. 23740-23745, Nov. 2010.
- [26] Y. Gao, Y. Dai, C. Shu, and S. He, “Wavelength interchange of phase-shift-keying signal,” *IEEE Photon. Technol. Lett.*, vol. 22, no. 11, pp. 838-840, Jun. 2010.
- [27] K. Lau, S. H. Wang, L. Xu, C. Lu, H. Y. Tam, and P. K. A. Wai, “All-optical multicast switch employing Raman-assisted FWM in dispersion-shifted fiber,” *IEEE*

Photon. Technol. Lett., vol. 20, no. 20, pp. 1730-1732, Oct. 2008.

[28] N. Ophir, J. Chan, K. Padmaraju, A. Biberman, A. C. Foster, M. A. Foster, M. Lipson, A. L. Gaeta, and K. Bergman, "Continuous Wavelength Conversion of 40-Gb/s Data Over 100 nm Using a Dispersion-Engineered Silicon Waveguide," *IEEE Photon. Technol. Lett.*, vol. 23, no. 2, pp. 73-75, Jan. 2011.

[29] K. K. Chow, S. Yamashita, and S. Y. Set, "Carbon-Nanotube-Deposited PLC waveguide for Four-wave mixing based wavelength conversion," in *Proc. OFC/NFOEC'2010*, Paper OTuB4, 2010.

[30] J. Liu, Y. K. Yeo, Y. Wang, L. Xue, D. Wang, W. Rong, L. Zhou, G. Xiao, X. Yu, and T. H. Cheng, "Pump suppressed nondegenerate four-wave mixing in a highly nonlinear photonics crystal fiber Sagnac loop," *IEEE Photon. Technol. Lett.*, vol. 20, no. 24, pp. 2129-2131, Dec. 2008.

[31] M. D. Pelusi, V. G. Ta'eed, L. Fu, E. Magi, M. R. E. Lamont, S. Maden, S. D.-Y. Choi Bulla, D. A. P. Luther-Davies, and B. J. Eggleton, "Applications of highly-nonlinear Chalcogenide glass device tailored for high-speed all-optical signal processing," *IEEE J. Select. Top. Quantum. Electron.*, vol. 14, no. 3, pp. 529-539, May/Jun. 2008.

[32] P. V. Mamyshev, "All-optical data regeneration based on self-phase modulation effect," in *Proc. ECOC'1998*, Paper p. 475, 1998.

[33] K. J. Blow, N. J. Doran, B. K. Nayar, and B. P. Nelson, "Two-wavelength operation of the nonlinear fiber loop mirror," *Opt. Lett.*, vol. 15, no. 4, pp. 248-250, Feb. 1990.

[34] A. O. Wiberg, C. S. Brès, B. P. Kuo, J. Chavez Boggio, N. Alic, and S. Radic, "Polychromatic Sampling for High-Speed Real-Time Processing," in *Proc.*

OFC/NFOEC'2010, Paper OWB1, 2010.

- [35] P. Agrawal, *The Nonlinear Fiber Optics*, 4th edition. (Academic, 2007).
- [36] S. Yao, *et al.*, "A unified study of contention-resolution schemes in optical packet-switched networks," *J. Lightw. Technol.*, vol. 21, no. 3, pp. 672-682, Mar. 2003.
- [37] P. Gambini, "Transparent optical packet switching: network architecture and demonstrators in the KEOPS project," *IEEE J. Select. Areas Commun.*, vol.16, no. 7, pp. 1245-1259, Sep. 1998.
- [38] A. V. Turukhin, V. S. Sudarshanam, M. S. Shahriar, and J. A. Musser, "Observation of ultraslow and stored light pulses in a solid," *Phys. Rev. Lett.*, vol. 88, no.2, pp. 023602-1–023602-4, Jan. 2002.
- [39] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, "Observation of ultraslow light propagation in a ruby crystal at room temperature," *Phys. Rev. Lett.*, vol. 90, no. 11, pp. 113903-1–113903-4, Mar. 2003.
- [40] J. E. Sharping, Y. Okawachi, and A. L. Gaeta, "Wide bandwidth slow light using a Raman fiber amplifier," *Opt. Exp.*, vol. 13, no. 16, pp. 6092–6098, Aug. 2005.
- [41] D. Dahan, and G. Eisenstein, "Tunable all-optical delay via slow and fast light propagation in a Raman assisted fiber optical parametric amplifier: A route to all-optical buffering," *Opt. Exp.*, vol. 13, no. 16, pp. 6234–6249, Aug. 2005.
- [42] F. Liu, Q. Li, Z. Zhang, M. Qiu, and Y. Su, "Optically tunable delay line in silicon microring resonator based on thermal nonlinear effect," *IEEE J. Select. Top. Quantum. Electron.*, vol. 14, no. 3, pp. 706-712, May/Jun. 2008.
- [43] T. Katayama, T. Ooi, and H. Kawaguchi, "4-Bit All-Optical Buffer Memory with Shift Register Function Using Polarization Bistable VCSELs," in *Proc. OFC/NFOEC'2009*, Paper JThA33, 2009.

- [44] Z. Zhu, A. M. C. Dawes, and D. J. Gauthier, “12-GHz-bandwidth SBS slow light in optical fibers,” in *Proc. OFC/NFOEC’2006*, Paper PDP1, 2006.
- [45] J. Liu, T. H. Cheng, Y. K. Yeo, Y. Wang, L. Xue, W. Rong, L. Zhou, G. Xiao, D. Wang, and X. Yu, “Stimulate Brillouin Scattering Based Broad-Band Tunable Slow-Light Conversion in a Highly-Nonlinear Photonic Crystal Fiber,” *J. Lightw. Technol.*, vol. 27, no. 10, pp. 1279-1285, May 2009.
- [46] Z. Zhu, A. M. C. Dawes, D. J. Gauthier, L. Zhang, and A. E. Willner, “Broadband SBS slow light in an optical fiber,” *J. Lightw. Technol.*, vol. 25, no. 1, pp. 201- 206, Jan. 2007.
- [47] K. Y. Song, and K. Hotate, “25 GHz bandwidth Brillouin slow light in optical fibers,” *Opt. Lett.*, vol. 32, no. 3, pp. 217–219, Feb. 2007.
- [48] E. Cabrera-Granado, O. G. Calderon, S. Melle, and D. J. Gauthier, “Observation of large 10-Gb/s SBS slow light delay with low distortion using an optimized gain profile,” *Opt. Exp.*, vol. 16, no. 20, pp. 16032–16042, Sept. 2008.
- [49] T. H. Cheng, J. Liu, Y. K. Yeo, Y. Wang, Z. Xu, and D. Wang, “Hi-Fi All-Optical Continuously Tunable Delay with a High Linear-Chirp-Rate Fiber Bragg Grating Based on Four-Wave Mixing in a Highly-nonlinear Photonic Crystal Fiber,” in *Proc. OFC/NFOEC’2009*, Paper JThA31, 2009.
- [50] N. Alic, E. Myslivets, S. Moro, B. P. P. Kuo, R. M. Jopson, C. J. McKinstrie, and S. Radic, “1.83- μ s wavelength-transparent all-optical delay,” in *Proc. OFC/NFOEC’2009*, Paper PDPA1, 2009.
- [51] Y. Dai, X. Chen, Y. Okawachi, A. C. Turner-Foster, M. A. Foster, M. Lipson, A. L. Gaeta, and C. Xu, “1 μ s tunable delay using parametric mixing and optical phase conjugation in Si waveguides,” *Opt. Exp.*, vol. 17, no. 9, pp. 7004–7010, Apr. 2009.

- [52] S. R. Nuccio, O. F. Yilmaz, S. Khaleghi, X. Wu, L. Christen, I. Fazal, and A. E. Willner, “tunable 503 ns optical delay of 40-Gb/s RZ-OOK and RZ-DPSK using a new wavelength scheme for phase conjugation to reduce residual dispersion and increase delay,” *Opt. Lett.*, vol. 34, no. 12, pp. 1903–1905, Jun. 2009.
- [53] Frazen A., “Synchronisation in optical packet based network,” PhD thesis, Strathclyde University, Nov. 1999.
- [54] P. R. Pruncal, “Optically processed self-routing, synchronization, and contention resolution for 1D and 2D photonic switching architectures,” *IEEE J. Quantum Electron.*, vol. 29, no. 2, pp. 600-612, Feb. 1993.
- [55] Y. K. Yeo, J. Yu, and G. K. Chang, “A dynamically reconfigurable folded-path time delay buffer for optical packet switching,” *IEEE Photon. Tech. Lett.*, vol. 16, no. 11, pp. 2559–2561, Nov. 2004.
- [56] C.-H. Chen, D. Wolfson, L. A. Johansson, D. J. Blumenthal, and L. A. Coldren, “Demonstration of 40 Gbit/s optical packet synchronisation using fiber Bragg gratings and fast-tunable wavelength converters,” *Electron. Lett.*, vol. 42, no. 6, pp. 367-369, Mar. 2006.
- [57] R. Langenhorst, M. Eiselt, W. Pieper, G. GroBkopf, R. Ludwig, L. Kuller, E. Dietrich, and H. G. Weber, “Fiber loop optical buffer,” *J. Lightw. Technol.*, vol. 14, no. 3, pp. 324-335, Mar. 1996.
- [58] A. Liu, C. Wu, Y. Gong, and P. Shum, “Dual-Loop Optical Buffer (DLOB) Based on a 3×3 Collinear Fiber Coupler,” *IEEE Photon. Tech. Lett.*, vol. 16, no. 9, pp. 2129–2131, Sept. 2004.
- [59] M. Eiselt, W. Pieper, and H. G. Weber, “SLALOM: Semiconductor Laser Amplifier in a Loop Mirror,” *J. Lightw. Technol.*, vol. 13, no. 10, pp. 2099- 2112, Oct.

1995.

[60] A. J. Poustie, K. J. Blow, and R. J. Manning, "All-optical regenerative memory for long term data storage," *Opt. Commun.*, vol. 140, no. 4-6, pp. 184-186, Aug. 1997.

[61] A. Agarwal, L. Wang, Y. Su, and P. Kumar, "All-optical loadable and erasable storage buffer based on parametric nonlinearity in fiber," *J. Lightw. Technol.*, vol. 23, no. 7, pp. 2229-2238, Jul. 2005.

[62] A. M. Liu, C. Q. Wu, M. S. Lim, Y. D. Gong, and P. Shum, "Optical buffer configuration based on a 3×3 collinear fiber coupler," *Electron. Lett.*, vol. 40, no. 16, pp. 1017-1019, Aug. 2004.

[63] C. C. Lee, P. K. A. Wai, H. Y. Tam, L. Xu, and C. Wu, "10-Gb/s wavelength transparent optically controlled buffer using photonics-crystal-fiber-based nonlinear optical loop mirror," *IEEE Photon. Technol. Lett.*, vol. 19, no. 12, pp. 898-900, Jun. 2007.

[64] T. Kawanishi, S. Oikawa, K. Higuma, and M. Izutsu, "Electrically Tunable Delay Line Using an Optical Single-Side-Band Modulator," *IEEE Photon. Tech. Lett.*, vol. 14, no. 10, pp. 1454-1456, Oct. 2002.

[65] T. Sakamoto, A. Okada, O. Moriwaki, M. Matsuoka, and K. Kikuchi, "Variable optical delay circuit using highly nonlinear fiber parametric wavelength converters," *Electron. Lett.*, vol. 39, no. 2, pp. 198-200, Jan. 2003.

[66] G. N. Rouskas, "Optical layer multicast: Rationale, building blocks, and challenges," *IEEE/ACM Trans. Network*, vol. 17, no. 1, pp. 60-65, Jan. /Feb. 2003.

[67] B. Prabhakar, N. McKeown, and R. Ahuja, "Multicast scheduling for input-queued switches," *IEEE J. Select. Areas Commun.*, vol. 15, no. 5, pp. 855-866, Jun. 1997.

- [68] F. Bauer, and A. Varma, "Degree-constrained multicasting in point-to-point networks," in *Proc. IEEE INFOCOM'1995*, vol. 4, pp. 369–376, 1995.
- [69] L. H. Sahasrabuddhe, and B. Mukherjee, "Light-trees: Optical multicasting for improved performance in wavelength-routed networks," *IEEE Commun. Mag.*, vol. 37, no. 2, pp. 67–73, Feb. 1999.
- [70] L. H. Sahasrabuddhe, and B. Mukherjee, "Multicast routing algorithms and protocols: A tutorial," *IEEE Network*, vol. 14, no. 1, pp. 90–102, Jan. /Feb. 2000.
- [71] S. Sankaranarayanan, and S. Subramaniam, "Comprehensive performance modeling and analysis of multicasting in optical networks," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 11, pp. 1399–1413, Nov. 2003.
- [72] B. Chen, and J. Wang, "Efficient routing and wavelength assignment for multicast in WDM network," *IEEE J. Sel. Areas Commun.*, vol. 20, no. 1, pp. 97–109, Jan. 2002.
- [73] B. M. N. K. Singhal, "Architectures and algorithm for multicasting in WDM optical mesh networks using opaque and transparent optical cross-connects," in *Proc. OFC'2001*, Paper TuG8, 2001.
- [74] C. H. Kwok, S. H. Lee, K. K. Chow, C. Shu, C. Lin, and A. Bjarklev, "Polarization-insensitive all-optical wavelength multicasting by self-phase modulation in a photonic-crystal fiber," in *Proc. CLEO'2006*, Paper CTuD4, 2006.
- [75] M. Ghandour, S. Liu, D. K. Hunter, D. Simeonidou, R. Nejabati, and P. Petropoulos, "Ultra high performance media multicasting scheme over wavelength-routed networks," in *Proc. OFC/NFOEC'2010*, Paper JThA40, 2010.
- [76] G. Contestabile, A. Maruta, S. Sekiguchi, K. Morito, M. Sugawara, and K. Kitayama, "All-optical wavelength multicasting in a QD-SOA," *IEEE J. Quantum*

Electron., vol. 47, no. 4, pp. 541-547, Apr. 2011.

[77] K. K. Wong, G. W. Lu, K. C. Lau, P. K. A. Wai, and L. K. Chen, "All-optical wavelength conversion and multicasting by cross-gain modulation in a single-stage fiber optical parametric amplifier," in *Proc. OFC/NFOEC'2007*, Paper OTuI4, 2007.

[78] G. Contestabile, N. Calabretta, R. Proietti, and E. Ciaramella, "Double-stage cross-gain modulation in SOAs: An effective technique for WDM multicasting," *IEEE Photon. Technol. Lett.*, vol. 18, no. 1, pp. 181-183, Jan. 2006.

[79] M. Matsuura, N. Kishi, and T. Miki, "All-optical regenerative multicasting for WDM downstream by dual-stage cascaded SOA-based wavelength converter," in *Proc. ECOC'2006*, Paper Th3.4.4, 2006.

[80] D. Liu, J. H. Ng, and C. Lu, "Wavelength conversion based on cross-gain modulation of ASE spectrum of SOA," *IEEE Photon. Technol. Lett.*, vol. 12, no. 9, pp. 1222-1224, Sept. 2000.

[81] J. Yu, X. Zheng, F. Liu, C. Peucheret, Anders T. Clausen, Henrik N. Poulsen, and Palle Jeppesen, " 8×40 Gb/s 55-km WDM transmission over conventional fiber using a new RZ optical source," *IEEE Photon. Technol. Lett.*, vol. 12, no. 3, pp. 912-914, Jul. 2000.

[82] N. Yan, H.-D. Jung, I. T. Monroy, H. D. Waardt, and T. Koonen, "All-optical multi-wavelength conversion with negative power penalty by a commercial SOA-MZI for WDM wavelength multicast," in *Proc. OFC/NFOEC'2007*, Paper JWA36, 2007.

[83] H. S. Chung, R. Inohara, K. Nishimura, and M. Usami, "All-optical multi-wavelength conversion of 10 Gbit/s NRZ/RZ signals based on SOA-MZI for WDM multicasting," *Electron. Lett.*, vol. 41, no. 7, pp. 432-433, Mar. 2005.

[84] M. Karasek, J. Vojtech, and J. Radil, "Multicasting at 10 Gb/s and 40 GHz

using a hybrid integrated SOA Mach-Zehnder interferometer,” in *Proc. OFC/NFOEC'2009*, Paper JWA26, 2009.

[85] G. Contestabile, N. Calabretta, M. Presi, and E. Ciaramella, “Single and multicast wavelength conversion at 40 Gb/s by means of fast nonlinear polarization switching in an SOA,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 12, pp. 2652-2654, Dec. 2005.

[86] C.-S Brès, J. M. C. Boggio, N. Alic, and S. Radic, “1-to-40 10-Gb/s channel multicasting and amplification in wideband parametric amplifier,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 16, pp. 1417-1419, Aug. 2008.

[87] Q. Lin, R. Jiang, C. F. Marki, C. J. McKinstrie, R. Jopson, J. Ford, G. P. Agrawal, and S. Radic, “40-Gb/s optical switching and wavelength multicasting in a two-pump parametric device,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 11, pp. 2376-2378, Nov. 2005.

[88] C.-S Brès, A. O. J. Wiberg, B. P.-P. Kuo, N. Alic, and S. Radic, “Wavelength multicasting of 320-Gb/s channel in self-seeded parametric amplifier,” *IEEE Photon. Technol. Lett.*, vol. 21, no. 14, pp. 1002-1004, Jul. 2009.

[89] L. Xu, N. Chi, K. Yvind, L. J. Christiansen, L. K. Oxenløwe, J. Mørk, P. Jeppesen, and J. Hanberg, “7×40 Gb/s base-rate RZ all-optical broadcasting utilizing an electroabsorption modulator,” *Opt. Exp.*, vol. 12, no. 3, pp. 717- 723, Feb. 2004.

[90] K. K. Chow, and C. Shu, “All-optical wavelength conversion with multicasting at 6×10 Gbit/s using electroabsorption modulator,” *Electron. Lett.*, vol. 39, no. 19, pp. 1395-1397, Sept. 2003.

[91] O. F. Yilmaz, S. R. Nuccio, S. Khaleghi, J.-Y. Yang, L. Christen, and A. E. Willner, “Optical multiplexing of two 21.5 Gb/s DPSK signals into a single 43 Gb/s

DQPSK channel with simultaneous 7-fold multicasting in a single PPLN waveguide,” in *Proc. OFC/NFOEC'2009*, Paper OThM4, 2009.

[92] C. W. Chow, C. S. Wong, and H. K. Tsang, “All-optical modulation format conversion and multicasting using injection-locked laser diodes,” *J. Lightw. Technol.*, vol. 22, no. 11, pp. 2386-2392, Nov. 2004.

[93] Mable P. Fok, and C. Shu, “Multipump four-wave mixing in a photonic crystal fiber for 6×10 Gb/s wavelength multicasting of DPSK signals,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 15, pp. 1166-1168, Aug. 2007.

[94] G. W. Lu, K. S. Abedin, and T. Miyazaki, “DPSK multicast using multiple-pump FWM in Bismuths highly nonlinear fiber with high multicast efficiency,” *Opt. Exp.*, vol. 16, no. 26, pp. 21964-21970, Dec. 2008.

[95] Y. Wang, C. Yu, T. Luo, L. Yan, Z. Pan, and A. E. Willner, “Tunable all-optical wavelength conversion and wavelength multicasting using orthogonally polarized fiber FWM,” *J. Lightw. Technol.*, vol. 23, no. 10, pp. 3331-3338, Oct. 2005.

[96] G. Contestabile, M. Presi, and E. Ciaramella, “Multiple wavelength conversion for WDM multicasting by FWM in an SOA,” *IEEE Photon. Technol. Lett.*, vol. 16, no. 7, pp. 1775-1777, Jul. 2004.

[97] Mable P. Fok, and C. Shu, “Performance investigation of one-to-six wavelength multicasting of ASK-DPSK signal in a highly nonlinear Bismuth oxide fiber,” *J. Lightw. Technol.*, vol. 27, no. 15, pp. 2953-2957, Aug. 2009.

[98] B. Wu, S. Fu, J. Wu, P. Shum, N. Q. Ngo, K. Xu, X. Hong, and J. Lin, “40 Gb/s multifunction optical format conversion module with wavelength multicast capability using nondegenerate four-wave mixing in a semiconductor optical amplifier,” *J. Lightw. Technol.*, vol. 27, no. 20, pp. 4446-4454, Oct. 2009.

- [99] A. Camerlingo, F. Parmigiani, X. Feng, F. Poletti, P. Horak, W. H. Loh, D. J. Richardson, and P. Petropoulos, "Multichannel wavelength conversion of 40-Gb/s nonreturn-to-zero DPSK signals in a lead-silicate fiber," *IEEE Photon. Technol. Lett.*, vol. 22, no. 15, pp. 1153-1155, Aug. 2010.
- [100] A. Biberman, B. G. Lee, A. C. Turner-Foster, M. A. Foster, M. Lipson, A. L. Gaeta, and K. Bergman, "Wavelength multicasting in silicon photonic nanowires," *Opt. Exp.*, vol. 18, no. 17, pp. 18047-18055, Aug. 2010.
- [101] D. Lu, G. Mezosi, B. Li, M. I. Memon, Z. Wang, M. Sorel, S. Jian, and S. Yu, "All-optical multicast based on cavity-enhanced four-wave-mixing in semiconductor ring laser," in *Proc. OFC/NFOEC'2009*, Paper JThA55, 2009.
- [102] L.-S. Yan, A.-L. Yi, W. Pan, B. Luo, and J. Ye, "Simultaneous NRZ-to-RZ format conversion and one-to-six error-free channel multicasting using a single pump in a highly nonlinear fiber," *Opt. Exp.*, vol. 18, no. 20, pp. 21404-21409, Sep. 2010.
- [103] A. Yi, L. Yan, B. Luo, W. Pan, J. Ye, and Z. Chen, "One-to-Eleven (11×10-Gb/s) all-optical NRZ-to-RZ format conversion and wavelength multicasting using a single pump in a highly nonlinear fiber," in *Proc. OFC/NFOEC'2011*, Paper OThE5, 2011.
- [104] J. Xu, *et al.*, "SOA-based OTDM-DPSK demultiplexing assisted by offset-filtering," in *Proc. OFC/NFOEC'2011*, Paper OWG8, 2011.
- [105] R. J. Manning, X. Yang, R. P. Webb, R. Giller, F. C. Garcia Gunning, and A. D. Ellis, "The 'Turbo-switch' a novel technique to increase the high-speed response of SOAs for wavelength conversion," in *Proc. OFC/NFOEC'2006*, Paper OWS8, 2006.
- [106] S. Fu, W. Du, P. Shum, C. Wu, and L. Zhang, "Measurement of SOA linewidth enhancement factor with a Sagnac fiber loop," *IEEE Photon. Technol. Lett.*, vol. 18, no.

18, pp. 1934-1936, Sep. 2006.

[107] Y. Li, *et al.*, "Power equalization for SOA-based dual-loop optical buffer by optical control pulse optimization," *IEEE J. Quantum Electron.* vol. 43, no. 6, pp. 508-516, June 2007.

[108] D. Wang, T. H. Cheng, Y. K. Yeo, Z. Xu, J. Liu, and Y. Wang, "Optically controlled loop buffer using a SOA loop mirror and a circulator based reflector," *Opt. Commun.*, vol. 282, no. 20, pp. 4052-4056, Oct. 2009.

[109] Q. Xu, M. Yao, Y. Dong, W. Cai, and J. Zhang, "Experimental demonstration of pattern effect compensation using an asymmetrical Mach-Zehnder interferometer with SOAs," *IEEE Photon. Technol. Lett.*, vol. 13, no. 12, pp. 1325-1327, Dec. 2001.

[110] L. Schares, C. Schmidt, H. G. Weber, L. Occhi, and G. Guekos, "Phase dynamics of semiconductor optical amplifiers at 10-40GHz," *IEEE J. Quantum Electron.*, vol. 39, no. 11, pp. 1394-1407, Nov. 2003.

[111] H. Hu, *et al.*, "640 Gbit/s and 1.28 Tbit/s polarization insensitive all optical wavelength conversion," *Opt. Exp.*, vol. 18, no. 10, pp. 9961-9966, Apr. 2010.

[112] C. Tian, C. Wu, Z. Li, and N. Guo, "Dual-wavelength packets buffering in dual-loop optical buffer," *IEEE Photon. Technol. Lett.*, vol. 20, no. 8, pp. 578-580, Apr. 2008.

[113] S. Fu, P. Shum, N. Q. Ngo, C. Wu, Y. Li, and C. C. Chan, "An enhanced SOA-based double-loop optical buffer for storage of variable length packet," *J. Lightw. Technol.*, vol. 26, no. 4, pp. 425-431, Feb. 2008.

[114] A. H. Gnauck, and P. J. Winzer, "Optical phase-shift-keyed transmission," *J. Lightw. Technol.*, vol. 23, no. 1, pp. 115-130, Jan. 2005.

[115] Y. J. Wen, J. Mo, Y. Wang, and C. Lu, "Advanced data modulation techniques

- for WDM transmission,” *IEEE Commun. Mag.*, vol. 44, no. 8, pp. 58-65, Aug. 2006.
- [116] X. Zhou, and Y. Yu, “Multi-level, multi-dimensional coding for high speed and high-spectral efficiency optical transmission,” *J. Lightw. Technol.*, vol. 27, no. 16, pp. 3641-3653, Aug. 2009.
- [117] K. Mori, T. Morioka, and M. Saruwatari, “Optical parametric loop mirror,” *Opt. Lett.*, vol. 20, no. 12, pp. 1424-1426, Jun. 1995.
- [118] E. A. Swanson, and J. D. Moores, “A fiber frequency shifter with broad bandwidth, high conversion efficiency, pump and pump ASE cancellation, and rapid tunability for WDM optical networks,” *IEEE Photon. Technol. Lett.*, vol. 6, no. 11, pp. 1341-1343, Nov. 1994.
- [119] T. Torondidis, B.-E. Olsson, H. Sunnerud, M. Karlsson, and P. A. Andrekson, “Fiber-optics parametric amplifier in a loop mirror configuration,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 2, pp. 321-323, Feb. 2005.
- [120] J. Liu, T. H. Cheng, Y. K. Yeo, Y. Wang, L. Xue, D. Wang, and X. Yu, “Degenerate four-wave mixing based all-optical wavelength conversion in a semiconductor optical amplifier and highly-nonlinear photonic crystal fiber parametric loop mirror,” *Opt. Commun.*, vol. 281, no. 21, pp. 5415-5419, Nov. 2008.
- [121] M. E. Marhic, N. Kagi, T. K. Chiang, and L. G. Kazovsky, “Broadband fiber optical parametric amplifiers,” *Opt. Lett.*, vol. 21, no. 8, pp. 573-575, Apr. 1996.
- [122] J. Yang, J. Hu, C. Yu, Y. K. Yeo, and Y. Wang, “Multi-channel 80-GHz pulse train generation based on four-wave mixing in highly nonlinear fiber,” in *Proc. OECC’2009*, Paper TuA5, 2009.
- [123] A. Zhang, and M. S. Demokan, “Broadband wavelength converter based on four-wave mixing in a highly nonlinear photonic crystal fiber,” *Opt. Lett.*, vol. 30, no.

18, pp. 2375-2377, Sept. 2005.

[124] M. Takahashi, K. Mukasa, and T. Yagi, "Full C-L band tunable wavelength conversion by zero dispersion and zero dispersion slope HNLF," in *Proc. ECOC'2009*, Paper P1.08, 2009.

[125] J. Ma, J. Yu, C. Yu, Z. Jia, X. Sang, Z. Zhou, T. Wang, and G. K. Chang, "Wavelength conversion based on four-wave mixing in high-nonlinear dispersion shifted fiber using a dual-pump configuration," *J. Lightw. Technol.*, vol. 24, no. 7, pp. 2851-2858, Jul. 2006.

[126] J. P. R. Lacey, M. A. Summerfield, and S. J. Madden, "Tunability of polarization-insensitive wavelength converters based on four-wave mixing in semiconductor optical amplifier," *J. Lightw. Technol.*, vol. 16, no. 12, pp. 2419-2427, Dec. 1998.

[127] G. Contestabile, L. Banchi, M. Presi, and E. Ciaramella, "Investigation of transparency of FWM in SOA to advanced modulation formats involving intensity, phase, and polarization multiplexing," *J. Lightw. Technol.*, vol. 27, no. 19, pp. 4256-4261, Oct. 2009.

[128] T. Hasegawa, K. Inoue, and K. Oda, "Polarization independent frequency conversion by fiber four-wave mixing with a polarization diversity technique," *IEEE Photon. Technol. Lett.*, vol. 5, no. 8, pp. 947-949, Aug. 1993.

[129] K. Inoue, "Polarization independent wavelength conversion using fiber four-wave mixing with two orthogonal pump lights of different frequencies," *IEEE Photon. Technol. Lett.*, vol. 12, no. 11, pp. 1916-1918, Nov. 1994.

[130] K. K. Y. Wong, M. E. Marhic, K. Uesaka, and L. G. Kazovsky, "Polarization-Independent two-pump fiber optical parametric amplifier," *IEEE Photon. Technol. Lett.*,

vol. 14, no. 7, pp. 911-913, Jul. 2002.

[131] Y. Dai, and C. Shu, "Polarization-insensitive wavelength multicasting of RZ-DPSK Signal Based on four-wave mixing in a photonic crystal fiber with residual birefringence," in *Proc. OFC/NFOEC'2010*, Paper OWP7, 2010.

[132] D. Wang, T. H. Cheng, Y. K. Yeo, Y. Wang, Z. Xu, J. Liu, and G. Xiao, "Optical wavelength multicasting based on four wave mixing in highly nonlinear fiber with reduced polarization sensitivity," in *Proc. OFC/NFOEC'2010*, Paper JWA47, 2010.

[133] D. Wang, T. H. Cheng, Y. K. Yeo, Z. Xu, Y. Wang, G. Xiao, and J. Liu, "Performance comparison of using SOA and HNLF as FWM medium in a wavelength multicasting scheme with reduced polarization sensitivity," *J. Lightw. Technol.*, vol. 28, no. 24, pp. 3497-3505, Dec. 2010.

[134] O. Aso, and S. Namiki, "Recent advances of ultra-broadband fiber optics wavelength converters," in *Proc. IEEE LEOS'2000 Annu. Meeting*, Paper pp. 683-684, 2000.

[135] J. Zhou, N. Park, J. W. Dawson, K. J. Vahala, M. A. Newkirk, and B. I. Miller, "Efficiency of broadband four-wave mixing wavelength conversion using semiconductor traveling-wave amplifiers," *IEEE Photon. Technol. Lett.*, vol. 6, no. 1, pp. 50-52, Jan. 1994.

[136] F. Girardin, *et al.*, "Low-noise and very high-efficiency four-wave mixing in 1.5-mm-long semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 9, no. 6, pp. 746-748, Jun. 1997.

[137] D. Wang, T. H. Cheng, Y. K. Yeo, Y. Wang, Z. Xu, and G. Xiao, "7×10-Gbit/s all-optical wavelength multicast based on cross-gain modulation and cascaded four-

wave mixing effects in an SOA using single pump laser source,” in *Proc. OFC/NFOEC’2011*, Paper JWA40, 2011.

[138] S. Bigo *et al.*, “10.2 Tbit/s (256×42.7 Gbit/s PDM/EDM) transmission over 100 km Teralight fiber with 1.28 bit/s/Hz spectral efficiency,” in *Proc. OFC’2001*, Paper PD25, 2001.

[139] M. A. Summerfield, and R. S. Tucker, “Optimization of pump and signal powers for wavelength converters based on FWM in semiconductor optical amplifiers,” *IEEE Photon. Technol. Lett.*, vol. 8, no. 10, pp. 1316-1318, Oct. 1996.

[140] H. Yoon, S. Bae, S. J. Ahn, and N. Park, “Reference level free multichannel gain equalization and transient gain suppression of EDFA with differential ASE power monitoring,” *IEEE Photon. Technol. Lett.*, vol. 11, no. 3, pp. 316-318, Mar. 1999.

[141] P. Runge, C.-A. Bunge, K. Petermann, M. Schlak, W. Brinker, and B. Sartorius, “Widely tunable short-pulse generation with ultralong semiconductor optical amplifiers,” *J. Lightw. Technol.*, vol. 28, no. 5, pp. 754-760, Mar. 2010.

[142] E. F. Burmeister, J. P. Mack, H. N. Poulsen, J. Klamkin, L. A. Coldren, D. J. Blumenthal, and J. E. Bowers, “SOA gate array recirculating buffer for optical packet switching,” in *Proc. OFCNFOEC’2008*, Paper OWE4, 2008.

[143] Y. Wang, C. Wu, Z. Wang, and X. Xin, “A new large variable delay optical buffer based on cascaded double loop optical buffers (DLOBs),” in *Proc. OFCNFOEC’2009*, Paper OWA4, 2009.