Optical nanoelecteromechanical systems (NEMS) devices and nano fabrication processes

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**OPTICAL NANOELECTROMECHANICAL SYSTEMS
(NEMS) DEVICES AND NANO FABRICATION
PROCESSES**

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**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

2015

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**OPTICAL NANOELECTROMECHANICAL SYSTEMS
(NEMS) DEVICES AND
NANO FABRICATION PROCESSES**

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SUMMARY

This doctorate thesis focuses on the design, fabrication and testing of novel optical nanoelectromechanical systems (NEMS) devices. Specifically, a nano-actuator, a variable optical attenuator (VOA) and an optomechanical memory have been fabricated by nano-silicon-photonics fabrication processes.

The first part of the thesis reports a NEMS actuator driven by optical gradient force. The optical force driven actuator realized by Q-factor modulation of the ring resonator can achieve an actuation range of 14 nm with a resolution of 0.18 nm. An optical displacement sensor is integrated to measure the actuation distance through optomechanical effects.

The second part focuses on the development of a NEMS variable optical attenuator. In this design, optical attenuation is realized via a nano-waveguide-based optical directional coupler where the gap between waveguides is modulated by optical gradient force. Optical intensity can be attenuated to 10% of the original value with an actuation distance of at least 150 nm by tuning the wavelength of control light by 2 nm.

The third part works on the optomechanical memory based on an optical force-induced bistability. A doubly-clamped silicon beam is actuated by the optical gradient force and bistability occurs as a result of nonlinearity of the optomechanical effects. The memory states can be switched by controlling the optical power from -10 dBm to -6 dBm. The switching speed is less than 150 ns.

In conclusion, optical NEMS devices, including a nano actuator, a VOA and an optomechanical memory, are demonstrated on a silicon-on-insulator (SOI) platform using nano-silicon-photonics fabrication processes. These devices have numerous and interesting potential applications in next generation optical fibre communications and network systems.

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NOMENCLATURE

MEMS	Microelectromechanical systems
NEMS	Nanoelectromechanical systems
ORR	Optical ring resonator
VOA	Variable optical attenuator
FP	Fabry-Perot Cavity
WGM	Whisper gallery modes
ASE	Amplified spontaneous emission
EDFA	Erbium-doped fibre amplifiers
OSA	Optical spectrum analyzer
PD	Photo detector
RIE	Reactive ion etching
SOI	Silicon-on-insulator

CHAPTER 1

INTRODUCTION

1.1 Motivation

This PhD research topic is motivated by the potential of silicon photonics and NEMS technology in exploring new solutions and opportunities to add novelties and sophisticated functionalities for a wide range of traditional optical components and MEMS devices with potential applications in communication, biomedicine, and sensing industry.

Since 1965, after the prediction of Gordon Moore that the number of transistors on integrated circuits doubles every two years, integrated circuits have grown exponentially from the 30-transistor devices of 1965 to today's more than 4 billion transistors integrated on a fingernail size silicon chip [1]. After half of century of intense research and manufacturing investment, the performance of integrated circuits has gained tremendous improvement, and at the same time, the cost has dropped significantly. The fast growing semiconductor industry has totally changed and will keep changing the world we are living in.

Inspired by the materials and processes of microelectronics, researchers have long been fabricating microscopic machines such as beams, cantilevers, and

membranes [2]. These mechanical elements and microelectronic circuits that control them are generally referred to as microelectromechanical system (MEMS). The first idea on MEMS was proposed by the Richard Feynman way back in 1959 [3]. MEMS represents the coupling of semiconductor processing to mechanical engineering at microscale. The technology has grown enormously during the past decade. A wide range of products have been developed by numerous companies including both semiconductor giants and fledgling start-ups.

Based on the development of smart phones, biotechnology, and telecommunication, MEMS industry continues to expand every year. After half a century of development, MEMS devices are found all around our life. These include inertial sensor, microphone, biosensor and transducer. Among these MEMS devices, one of the most important is actuator, which is the key component in various MEMS devices. Of all types of actuator, capacitive comb drive actuator is the most developed linear actuator that utilizes electrostatic forces to act between two electrically conductive combs. Comb drive actuators typically operate at micrometer scale and are generally manufactured by bulk micromachining or surface micromachining on a silicon wafer substrate [4].

While the main stream microelectronics have moved into sub-100 nm length scale, very little has been done with MEMS at sub-micron scale. Not until the last decade, MEMS has been scaled down to sub-micron scale and correspondingly re-named nanoelectromechanical system (NEMS). Within this size regime, extremely high fundamental frequencies can be attained with very high mechanical responsivity, which can be further translated into high force sensitivity, low-power operation, and the ability to exploit nonlinear effects with modest control forces [5]. However,

challenges arise from such down-scaling, as the basic operational principle of many MEMS devices are no longer valid at nano-scale. For example, a capacitive actuator fails at sub-micron scale due to its extremely small surface area.

Although the potential of MEMS is exciting, its translation into cheap mass-produced commercial devices is very difficult due to long development cycles, lack of large volume production and standardization in fabrication and packaging. Current MEMS devices continue to employ different fabrication processes for different devices - a key constraint in the current MEMS industry.

On the other hand, the information explosion has changed the way the world is being connected. The thirst for information is driving a new era of communications, which will continue to spur the need for higher bandwidth technologies to keep pace with processor performance. In the past decades, fibre optics solutions are replacing traditional copper-based solutions, which can no longer meet the bandwidth and distance requirements needed for worldwide data communications [1]. Thus there is high demand for more efficient and cost-effective optical solutions. Currently, optical devices are large, bulky and mostly not fabricated from silicon. These optical devices are often custom-made and assembled from discrete components with very little automation, which are quite similar to MEMS devices and therefore relatively expensive. Optical technology to the mass market may happen only if high-volume manufacturing and assembly are brought to the optical world, just like the transistor industry [1].

To realize volume production of optical devices, silicon is always the best material. Silicon is not only the optimal material for electronics, but also a practical option for optics. Silicon is transparent for the commonly used IR communication

band, which is normally from 1.3 μm to 1.6 μm . The high refractive index of silicon (~ 3.5) in the above mentioned band also promises good light confinement and therefore low bending loss, which is extremely beneficial for highly compact optical devices.

Standard CMOS processing techniques can be used to sculpt optical waveguides onto a silicon surface [6-8]. The silicon waveguides are normally in the size of 500 nm to 1 μm to direct light in communication band. The lithography requirements needed to process waveguides with these sizes can be realized with no difficulties, meaning that it is totally possible to produce silicon-based photonic devices for the next decade with current fabrication technologies.

However, silicon photonics is not without problems or challenges. Several key devices, such as laser sources and detectors, are still fabricated on III-V materials. But silicon photonics have proven its potential to be the next generation technology for various applications, especially in the telecommunication industry [9, 10]. Silicon photonics has become one of the most promising photonic integration platforms in the last few years, which is mainly attributed to the combination of a very high index contrast and the availability of CMOS fabrication technology [1]. With CMOS-compatible fabrication technologies, it could be possible to process transistors alongside photonic devices, the combination of which could bring new levels of performance, functionality, power and size reduction, all at a lower cost [1].

On the other hand, advanced nano-silicon-photonics fabrication technology has advanced to considerable maturity in recent years; enabling the fabrication of nano-silicon-photonic circuits on silicon-on-insulator (SOI) wafers and integrating a variety of optical modulators, electromechanical actuators, detectors and light

sources when combined with bonded III-V semiconductor chips. The recent developments of fabrication technologies enable researchers to design and fabricate nanostructures with high quality and good repeatability.

Both NEMS and silicon photonics are presently developing fast. This new emerging field called optical NEMS is attracting more attention not only among research, but in industry. Optical NEMS can provide highly integrated nanoscale machines to manipulate light for various applications, especially in communication systems. It has attracted wide research interests in multi-disciplinary areas for their unique advantages. First, it's all silicon, the cheapest materials in the world. Second, it is fabricated using standard processes. Third, the unique optical spectrum, which is identical to the current fibre communication band. Fourth, high integrability, due to the previously mentioned CMOS-compatible fabrication platform. Fifth, it can be used to realize large range of optical. Last, it has numerous applications, ranging from sensors to active devices.

New approaches are being studied to develop new NEMS devices. For example, piezoelectric thin films have been investigated and initially demonstrated to solve the actuation issue in NEMS actuators.

Optical forces are widely used to manipulate microparticles such as living cell, DNA and bacteria. Only recently, optical gradient force, an example of such an optical force, has been exploited for actuating optomechanics devices [11].

Many opportunities exist if MEMS functions can be realized in NEMS, while utilizing nano-silicon-photonics technology. Optical NEMS realized with standard nanofabrication can provide a new platform for various applications, with low cost, compact size and good integrability. As critical component of optical NEMS devices,

NEMS actuators can provide many possibilities of implementing various mechanical functions. Specially, an optical NEMS actuator driven by optical gradient force is studied in this thesis. Additionally, two other important components in telecommunications such as variable optical attenuator and optical memory, are also demonstrated in this thesis.

Finally, the optical NEMS devices have the merits of low cost, low power consumption, high efficiency, ultrahigh sensitivity and good integratibility, which promise potential applications in biomedical engineering and the telecommunication industry.

1.2 Objectives

The main objective of this PhD thesis is to innovate and develop various novel optical NEMS devices fabricated via nano-silicon-photonic fabrication processes. Specifically, a NEMS actuator driven by optical gradient force is studied. The NEMS actuator is then used to provide efficient actuation for two other active NEMS devices: a variable optical attenuator (VOA) and an optomechanical memory. Theoretical analysis, chip designs, fabrication process developments and experimental studies are presented in this thesis.

The developed NEMS actuator is driven by optical gradient force and controlled via Q-factor attenuation of a ring resonator. It is capable of driving nano

structures with sub-nanometer accuracy. Theoretical models are used to guide both the optical and mechanical designs of the NEMS actuator. An optical ring resonator is designed and conducted to enhance the optical intensity and hence the optical force. An optical displacement sensor is also designed to measure the actuation distance through optomechanical effects. Nano-silicon-photonics fabrication processes are developed to fabricate the NEMS actuator. The actuation distance and accuracy of the NEMS actuator are demonstrated experimentally by controlling the Q-factor of the ring resonator.

The developed NEMS VOA is realized using an optical force-actuated optical directional coupler. The theoretical model of the directional coupler is numerically studied and calculated to guide the design of the VOA. An optical actuator driven by optical force is also demonstrated while the actuation distance is controlled by changing the wavelength of the pumping laser. Optical attenuation effects are experimentally tested. VOA arrays are also discussed.

Last, an optomechanical memory which utilizes the nonlinear properties of the optical gradient force is studied. The memory is designed with a ring resonator and a doubly-clamped silicon beam. The nonlinear properties of the optical gradient force and the bistability of the optical force that drives the doubly-clamped silicon beams are studied. The memory operation based on bistability are demonstrated. The switching speed of the optomechanical memory is also experimentally studied.

1.3 Major contributions

The major contributions of this PhD thesis lie in various aspects of the theoretical analysis, designs, fabrications and experiments of optical NEMS devices. The details are listed below:

- 1) The optical gradient force is studied. Particularly, the optical gradient force between a doubly-clamped silicon beam and a ring resonator is calculated. The cavity enhancement of the optical gradient force via the ring resonator is also discussed (see Chapter 3).
- 2) A NEMS actuator is proposed and experimentally tested. The mechanical arc actuator is controlled by the optical gradient force while the actuation distance is controlled by the Q-factor modulation of the ring resonator (see Chapter 3).
- 3) An optical displacement sensor is also integrated to sense nanometer scale displacement. The optomechanical effects are theoretically studied and simulated (see Chapter 3).
- 4) Nano-silicon-phonic fabrication processes for the NEMS actuator and other optical NEMS devices are developed (see Chapter 3).
- 5) A NEMS VOA is designed, fabricated and experimentally demonstrated. The VOA is realized by an optical directional coupler which is controlled by the optical gradient force. The theoretical model of the directional coupler is calculated and simulated (see Chapter 4).
- 6) The optical actuator controlled by wavelength detuning is demonstrated. The behaviour of the nano-actuator at various

wavelength detunings of the control light are studied and simulated (See Chapter 4).

- 7) The optical memories are designed, fabricated and experimentally demonstrated. The memory states are associated with two stable deformation positions of the doubly-clamped silicon beam, which can be switched by an actuator driven by optical gradient force (See Chapter 5).
- 8) The nonlinear properties of optical gradient force are studied. Due to its usage of an exponentially decayed evanescent wave, the optical gradient force shows high nonlinearity. The relationship between optical power and bistability of the doubly-clamped silicon beam is investigated (See Chapter 5).

1.4 Organization

The thesis is organized into six chapters. The introduction of the thesis covers the motivation, objectives, and major contributions as presented in this chapter. The motivation section explains why the PhD research is carried out. The objectives state the main focus of this thesis, and the major contribution section lists the innovations and important findings in both the theoretical and technological aspects.

In Chapter 2, the literature review of optical gradient force, optical microcavities and three types of NEMS devices, include a NEMS actuator, a VOA, and an optomechanical memory, is carried out. This chapter reviews the background

and start-of-art for optical gradient force based devices. The significance of the optical gradient force is discussed together with its applications in various aspects. Microcavities are studied and their significance in various applications of silicon photonics are discussed. Three types of NEMS devices are reviewed, including their importance, various design and implementation approaches and applications. All this important background work provides the vision and framework for the research of the entire thesis work and also lays the technological foundation on which the work of this thesis is built.

In Chapter 3, the theoretical analysis, fabrication and experimental testing of the NEMS actuator are presented. The actuator driven by optical gradient force is characterized. In-depth analysis of optical gradient force, mechanical response, Q-factor modulation and optical displacement sensing are studied, calculated and simulated. The process developed for the fabrication of the optical NEMS devices is also presented. Finally, the experimental results of the NEMS actuator based on Q-factor modulation are shown and discussed.

In Chapter 4, the theoretical analysis, fabrication and experimental testing of the NEMS VOA are presented. An optical directional coupler driven by optical gradient force is characterized, theoretically analyzed and numerically simulated. The actuation of the directional coupler which is realized via laser detuning is also discussed. This chapter also covers an in-depth analysis of optical attenuation and VOA array are presented. The fabrication processes of NEMS VOA are briefly discussed. The experimental testing results of the actuator controlled via laser detuning and optical attenuation are presented.

In Chapter 5, the theoretical analysis, fabrication and experimental results for optomechanical memory are presented. The nonlinear properties of the optical gradient force and the induced bistability are analysed. The operation and the architecture of the optomechanical memory are demonstrated. The fabrication processes of the optical NEMS devices are developed. The operation of the optomechanical memory and the time response of the NEMS memory are experimentally demonstrated.

Chapter 6 concludes the major contributions of this thesis followed by the recommendations for future work.

CHAPTER 2

LITERATURE SURVEY

This chapter is divided into three parts. The first part introduces optical force and its application. The second part presents two optical microcavities such as Fabry-Perot microcavities and ring resonators. The applications of these structures are also covered. The third part presents NEMS devices such as nano actuator, variable optical attenuator, optical memory and their applications.

2.1 Survey of optical force

2.1.1 Generation of optical force

Back in the 16th century, Johannes Kepler suggested that solar radiation caused the comet tails to point away from the sun [12]. In 1970, Arthur Ashkin from Bell Labs reported the detection of optical forces on micrometer sized particles for the first time [13]. Years later, Ashkin and colleagues reported the first observation of optical tweezers, which use a tightly focused beam of light to hold microscopic particles in three dimensions [14, 15]. Nowadays, optical force-based devices have been demonstrated in various fields ranging from biomedical to telecommunication applications.

Optical forces can be classified into two types, the scattering force and the gradient force as shown in Fig. 2.1. The optical scattering force originates from the momentum transfer of photons: the reflection of a photon onto an object can induce

Fig. 2.1: Schematic illustration of optical forces: the gradient force and the scattering force.

pressure over an object in the propagation direction. The pressure is generally referred to as “radiation pressure”, and the resulting force is called scattering force [16]. The radiation pressure was theoretically studied by James Clerk Maxwell in 1873 [17] and experimentally demonstrated by Pyotr Lebedev in 1901 [18] and by Ernest Fox Nichols and Gordon Ferrie Hull in 1903 [19].

The radiation pressure can be expressed as

$$P_{scatter} = Q_{PR} \langle S \rangle / c \quad (2.1),$$

where Q_{PR} is the coefficient of radiation pressure, $\langle S \rangle$ is the time averaged mean flux density and c is the speed of light. The energy flux density, also named Poynting vector, is expressed as $\vec{S} = \vec{E} \times \vec{H}$, in units of watts per square meter (W/m^2), where E and H are electrical and magnetic field respectively. The scatter force is generally too small to be detected under everyday circumstances due to its linear proportionality with the light’s flux density.

The optical gradient force is experienced by dipolar particles in a laterally varying electromagnetic (EM) field, which originate from the spatial variation of an intensity distribution [16]. When the polarizable microparticle is placed in a laterally varying optical field, an electric dipole is induced in the particle, and the positively and negatively charged sides of the dipole experience slightly different forces in the optical gradient field. The particle can be consequently accelerated towards the region with the strongest field [11]. The optical gradient force can be expressed as

$$F_{gradient} = \frac{1}{2} \chi \epsilon_0 \int_V \nabla E^2(r) d^3r \quad (2.2),$$

where χ is the electric susceptibility, ϵ_0 is the electrical permittivity of free space and r represents the direction of the electrical field gradient. Compared with the scattering force, whose typical magnitude is close to 3.3 pN/mW, the optical gradient force can provide a much larger force per photon when strong field gradients are available and the magnitude can reach up to 60 pN/mW for waveguide structures.

Optical gradient forces are mostly generated by a highly focused laser beam, which is commonly known as optical tweezers. Optical tweezers use a highly focused laser beam to provide an attractive or repulsive force. The ideal setup of optical tweezers is shown in Fig. 2.2 and the particle is trapped by the focused laser beam. Nowadays, optical tweezers have been studied in various field of biological research [20-27].

Fig. 2.2: Ideal setup of particle trapping via optical tweezers.

Besides using a highly focused beam, another approach has also been investigated to generate an optical gradient force. For instance, a strong field gradient in the near-field of waveguiding structures has been explored to actuate optomechanical devices. Initial theoretical work has been followed rapidly by several experimental demonstrations [11, 28-30].

Such a field gradient generated in waveguide structures is generally referred to as an evanescent wave. An evanescent wave is a near-field wave with an intensity that decays exponentially without absorption as a function of distance from the boundary at which the wave is formed [30]. The evanescent wave generally appears during internal reflection, as shown in Fig. 2.3 (a), or in nanoscale optical guiding structures such as waveguides and fibres, as shown in Fig. 2.3 (b). Microparticles or mechanical structures can then be attracted by the optical gradient force when they fall in the evanescent wave field.

The magnitude of the optical gradient force can be enhanced by increasing the electrical field gradient, which is extremely efficient at nano scales. Various studies have been done to investigate the effects of optical forces within silicon photonics devices. For this purpose, a new field called optomechanics has recently appeared and is fast developing [31].

Over the past five years, rapid progress has been made in understanding and experimentally demonstrating optomechanically actuated systems that exploit the gradient force [32, 33]. Through exploiting the evanescent field of guided wave structures, the gradient optical force allows for photon momentum to be exchanged over a distance approaching the wavelength of the light [33-36].

Fig. 2.3: Schematic illustration of evanescent wave in (a) total internal reflection of prism and (b) optical waveguide.

In this respect, several optomechanical devices have been reported recently, ranging from single beam mechanical structures, such as optical force driven single silicon beam [37-39], broadband all-photonic transduction of nanocantilevers [40], to double-beam structures [41-43], such as tunable bipolar optical interactions [44-46]. The optical gradient force has also been studied as an alternative actuation force for NEMS devices [47-49]. In order to further enhance the optomechanical interaction, optical resonators [50-62] and plasmonic based [63, 64] opto-mechanical structures have also been demonstrated.

The generation of optical forces is thus limited not only to the highly focused laser beam, but can also be achieved in various waveguide-based structures. Due to its special applications in nano-silicon-photonic circuits, the optical gradient force has expanded its application to various practical platforms.

2.1.2 Applications of optical force

The optical scattering force has been studied and exploited in various applications. The radiation pressure was initially studied as an actuation force for measuring the light intensity. However, to date, the most important application of optical scattering force is laser cooling, which can cool materials close to absolute zero. In 1997, various methods were developed to cool and trap atoms with laser light [65]. Laser cooling is primarily used for experiments in quantum physics to achieve temperatures of near absolute zero ($-273.15\text{ }^{\circ}\text{C}$). Now, laser cooling is extremely useful in quantum optics and high resolution spectroscopic measurements.

The optical scattering force has also been investigated in cavity optomechanics, from large scale Fabry-Perot interferometers to recent microscale structures and on-chip microtoroids [35, 58, 66-68]. It has been widely used to control and measure the position of micrometre to nanometer-sized particle [11, 65].

Compared with the optical scattering force, the development of optical gradient force is restricted by the development of laser technology. One of the most important applications of the optical gradient force is optical tweezers, which have been used to trap small particles in an evanescent field close to dielectric interfaces

or even in free space [27, 69-79]. These devices are widely used in biomedical applications to manipulate living cells, DNA and bacteria.

Various applications of optical gradient forces in nano-structures have been intensely investigated recently. For instance, evanescent wave-generated optical gradient forces have been initially demonstrated in NEMS devices, such as modulators [80], memories [48, 81], switches [82], couplers [45] and actuators [47, 49].

The dynamic behaviour of nano-structures is attractive due to its potential applications in both fundamental and applied sciences. Various optomechanical oscillators and resonators are demonstrated to achieve sensitive transduction, which are essential to many applications in mass, force, magnetic and displacement sensing [50, 54, 83, 84]. Nanomechanical oscillators are also ideal candidates for probing quantum limits of mechanical motion [32, 34].

Devices that utilize optical force have been developed, in conjunction with the developed nano-silicon-photonics fabrication technology. As the dimension of the devices is shrinking, more optical force based devices are expected to show up, especially in the fields of NEMS and bio-inspired devices.

2.2 Survey of optical microcavities

Optical microcavities play an extremely important role in modern optics, being fundamental not only in any laser device, but also as etalons for optical filtering and as tools for very accurate measurements and nonlinear optics experiments [85, 86]. Optical microcavities are also necessary to enhance optical gradient forces in nano-structures, such that light can be accumulated in small regions in order to enhance its intensity and thus generate a light intensity gradient [52].

Dielectric optical micro cavities are the key components for densely-integrated optical circuits, especially in nano-silicon-photonic circuits. Most of the microcavities are large compared to resonance wavelengths. The structure size of the microcavities can, however, be reduced to the order of wavelength by using materials with high refractive index contrast. As silicon has high refractive index and its associated fabrication technology is relatively matured, silicon-based microcavities have been widely studied for years and became key components in nano-silicon-photonic circuits.

Two basic types of microcavities are extremely important for this study: Fabry-Pérot (FP) microcavities and whispering gallery modes (WGM) microcavities.

2.2.1 Fabry-Perot microcavities

The Fabry-Perot (FP) resonator is named after Charles Fabry and Alfred Pérot who constructed it as an interferometer in 1897. The FP cavity is typically constructed using two highly reflecting mirrors arranged parallel, as shown in Fig. 2.4 (a), so

that standing waves form in the space between the two mirrors. The plane-mirror FP resonator is the most basic type and has been widely used in various applications, such as laser cavities, etalon and filters.

The transmission spectrum of the FP resonator is a function of wavelength that exhibits peaks of large transmission corresponding to the resonances of the cavity. The phase difference between the two reflection mirrors is given by

$$\varphi = 2\left(\frac{2\pi}{\lambda}\right)d \quad (2.3),$$

where d is the cavity length between the two mirrors and λ is the wavelength.

Fig. 2.4: Schematic illustration of: (a) an ideal FP cavity, (b) a photonic crystal based FP cavity, (c) a Bragg grating based FP cavity, and (d) a ring resonator based FP cavity.

The transmission coefficient T of the FP cavity can be written as

$$T = \frac{1}{1 + F \sin(\varphi/2)} \quad (2.4)$$

where $F = \frac{4R}{(1-R)^2}$ is the finesse and R is the reflectivity of both mirrors. The power

accumulation inside the FP cavity is very much dependent on the reflectivity of the mirrors. The FP cavity can therefore achieve high Q-factor with light confined through the design of high reflection mirrors.

Even though the FP cavity is simple and can achieve high Q-factor with proper coating, the embodiment of the free space mirror based type of resonator is incompatible with planar integrated technology and difficult to achieve at microscale. For this reason, in silicon photonics, the free space between mirrors is replaced by waveguide structures, and thus the key to establish a FP cavity in the silicon waveguide device is to fabricate mirror structures at both ends of waveguides.

The most common types of mirror structures include photonic crystal (Fig. 2.4(b)), Bragg grating (Fig. 2.4(c)), and ring resonator (Fig. 2.4(d)). All the three types of mirrors structures can achieve ultra-high reflectivity when they are properly designed. On one hand, most of the time, these designs have wavelength selectivity, meaning that high reflectivity can only be achieved in a narrow spectral range, which is normally less than 30 nm. A lot of effort has been investigated to achieve high reflection in a broader range. On the other hand, photonic crystals, Bragg gratings and ring resonators with high reflectivity can usually achieve a high Q-factor which is comparable with those of the traditional planar mirror FP cavities.

2.2.2 Whisper gallery modes ring resonator

Microcavities which are nearly equivalent to FP cavities can be constructed in planar waveguides using ring resonators, which is commonly named Whispering Gallery Modes (WGM) ring resonator [87, 88].

WGMs are a type of waves that can travel around a concave surface and were first discovered and investigated for sound waves [85]. WGMs can be interpreted as EM waves that circulate and are strongly confined within the resonator's structure [89]. In terms of geometric optics, the confinement is described by optical rays which are totally internally reflected and focused by the surface itself as shown in Fig. 2.5 (a).

The optical ring resonator (ORR) is a special optical cavity, which consists of a closed waveguide loop and a bus waveguide coupled to the closed loop as shown in Fig. 2.5 (b), which is also commonly referred to as an 'all-pass' ring resonator. When light of the appropriate wavelength is guided by the bus waveguide, it is partially coupled into the waveguide loop, and the intensity inside the loop is enhanced after multiple circulations due to constructive interference. The ORR is of particular interest in waveguide photonics because it provides not only light confinement but also wavelength selectivity.

The WGM ring resonator is commonly described mathematically using the transfer matrix method, the electrical field in different positions of the ring resonators as shown in Fig. 2.5 (b), can be expressed as [87, 90]:

Fig. 2.5: (a) Ray tracing of the whisper gallery modes in a ring resonator and (b) Energy flow in an ‘all-pass’ ring resonator.

$$\begin{bmatrix} E_{in} \\ E_{out} \end{bmatrix} = \frac{i}{k} \begin{bmatrix} 1 & -t \\ t & 1 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} \quad (2.5),$$

where t and k are transmission and coupling coefficients of the waveguide-ring coupler, respectively, and which must satisfy the relation $t^2 + k^2 = 1$. After one round inside the ring resonator, the electrical field E_2 can be expressed as [87]

$$E_2 = e^{\alpha_{ring}\pi R} \cdot e^{ik2\pi R} \cdot E_1 \equiv \beta e^{i\phi} E_1 \quad (2.6),$$

where all parameters characterize different geometrical as operational features of the ORR: α_{ring} is the attenuation coefficient, R is the radius, k is the wave factor, β is the single pass amplitude transmission and ϕ is the single pass phase shift. The resonance wavelength of the ring resonator occurs when $e^{i\phi}$ is equal to zero.

The ring resonator can provide light intensity buildup and wavelength selectivity due to constructive interference at the coupler. The building up factor is defined as [87]:

$$B = \left| \frac{E_2}{E_{in}} \right|^2 = \frac{(1-t^2)\beta^2}{1-2t\beta\cos(\phi)+t^2\beta^2} \quad (2.7).$$

The maximum ratio of circulating power to incident power can be achieved at the wavelength for which resonance occurs ($\phi = m2\pi$) with low loss coefficient ($\beta \approx 1$), which is shown in Fig. 2.6.

Fig. 2.6 : Schematic illustration of building-up factor versus phase shift for the ring resonator.

The WGM ring resonators can be fabricated by nano-silicon-photonic processes in compact size and achieve extremely high Q-factors.

2.2.3 Applications of optical microcavities

WGM ring resonators play an important role in silicon photonics, because of the unprecedented compact size of silicon ring resonators [85, 91], which have been used as fundamental building blocks for a variety of applications [87, 91] such as filters [92], sensors [93-98], optical delay lines [99-101], switches [102, 103] and modulators [104-107].

Nano-silicon-photonic ring resonator based spectral filters are the earliest application of ORRs, which is very useful in telecommunications and data communication of multiplex or demultiplex WDM signals [91]. Spectral filters, especially high-order filters, can provide a more uniform passband over a wider wavelength range, and a larger extinction ratio outside the passband [91].

Nano-silicon-photonic ring resonators are also suitable for optical delay lines due to the ability to store optical energy in resonance [99-101, 108]. The ring resonators also show strong dispersion near resonance and therefore a large group delay, sorting the optical signal before releasing it. This large group delay, combined with a relatively large bandwidth and low insertion loss, provides an ideal combination for optical buffers [91].

Nano-silicon-photonic ring resonators are also used to design different types of sensors, especially label-free biosensors [109-111], because the transmission spectrum of ORRs heavily depends on the resonator's direct environment and can be

made with large quality factor, large extinction and low insertion loss. Such small sized, low cost and good integrability nano-silicon-photonic ring resonators have been commonly applied in various disposable biosensors.

Another important component in silicon photonics is the optical modulator, which can also be built using a nano-silicon photonic ring resonator. In the past few years, a lot of work has been done to investigate electro-optic modulators [107]. By modulating the optical length of the ring, the resonance peak is shifted and the transmission/reflection of the cavity is changed. The advantage of the modulators is that they are quite compact and can be actuated directly as a lumped element with high operation frequency of up to 25 GHz [91]. The small area of the ring resonator reduces the necessary power to modulate and hence is one of the most economical modulators in terms of modulation energy per bit [107].

In summary, integrated ring resonators have emerged in the last few years in integrated optics and have found their way into many applications, especially in telecommunication devices and biosensors. These integrated ring resonators can be fabricated by nano-silicon-photonic fabrication processes and are particularly suited for monolithic integration with other components [88].

2.3 Survey of NEMS devices

MEMS actuators and sensors have been developed in different areas such as telecommunication, aerospace, chemical and biomedical [112-117]. However, with the increasing demand for high resonant frequency and low force constant, which is the applied force per displacement [118-120], a new generation nanoelectromechanical systems (NEMS) is in rapid development.

Due to their nanoscale dimensions, NEMS devices are suitable for a multitude of technological applications such as ultrafast sensors, actuators and signal processing components [121-127]. Various NEMS devices have been developed and nano-actuators are presently a hot topic in the research of NEMS.

2.3.1 NEMS Actuator

In the past decade, silicon-based MEMS devices, especially MEMS actuators, have been employed in a variety of optical and radio frequency (RF) devices such as optical switches and RF relays, which are compatible with on-chip integration with high reliability and low cost [62, 128-131]. These MEMS actuators, especially the silicon comb-drive electrostatic actuators, are among the most frequently utilized actuators in MEMS [132]. MEMS actuators are compatible with simple design rules and massive fabrication processes, being characterized by high accuracy, easy control and large displacement [131].

Fig. 2.7: Schematic illustration of parallel-plate capacitive actuator (a) without electrostatic force and (b) with electrostatic force.

However, the microscale dimensions of these MEMS actuators have restricted both the speed and the precision of actuation. When the dimensions are further scaled down to nanoscale, traditional actuation methods, such as the electrostatic force, can be difficult to be used because of the correspondingly decreased capacitance and increased impedance, making the devices susceptible to thermal noise, limiting their applications for high resolution actuation. Furthermore, the capacitance decreases to levels comparable to spurious sources of background capacitance in NEMS, thus limiting electrostatic actuation strategies.

The capacitance of a parallel-plate capacitor, as shown in Fig. 2.7, can be expressed as

$$C_0(g) = \frac{\epsilon_r \epsilon_0 A}{g} \quad (2.8)$$

where ϵ_r is the relative permittivity of the medium between the capacitor's plates, ϵ_0 ($= 8.854 \times 10^{-12}$ F/m) is the permittivity of vacuum, A is the common surface area of the plates and g is the gap between plates. However, when the dimensions of the electrodes are comparable with the distance between them, the capacitance caused by its sidewalls and even the back side of the electrodes may play an important role [133]. Capacitance in NEMS devices decreases by orders of magnitude due to the shrinkage in size. For example, the capacitance of a $340 \text{ nm} \times 200 \text{ nm} \times 10 \text{ }\mu\text{m}$ waveguide with 200 nm gap is approximate 2.25×10^{-16} F.

The electrostatic force can therefore be expressed as

$$F_N = \gamma \frac{\partial C_0}{\partial g} V^2 \quad (2.9)$$

where γ is the correction factor of force for the fringe effect. The electrostatic force that can be developed between the plates of the capacitor made of the above mentioned waveguides is approximately 7.5×10^{-8} N when the applied voltage is 10 V. The electrostatic force has a value of the same order of magnitude as that of the optical gradient force, which is approximate 1×10^{-8} N when the optical power is 100 mW for the same waveguide structures. The theoretical calculation is shown in section 3.2.1 of Chapter 3.

When voltage is applied over the silicon waveguide, resistance can be very high due to the small dimensions of the waveguide. The resistivity for p -type doped silicon with a doping concentration of $4 \times 10^{14} \text{ cm}^{-3}$ is approximately 33.4 $\Omega\text{-cm}$, resulting in a resistance of the above mentioned waveguide of around 50 M Ω . To reduce the resistance for practical usage, a high doping concentration is necessary,

which would therefore induce losses to optical signals as high doping levels in Si modify its refractive index and introduce a non-negligible extinction coefficient.

To overcome the limitation of capacitive actuation in NEMS devices, various other actuation methods were proposed, including piezoelectric, electrothermal and magnetomotive actuation [134, 135].

One of the most promising NEMS actuation technologies is based on piezoelectric effects [60, 136-138]. Lead zirconate titanate and AlN are two commonly used piezoelectric materials that have already been used for the fabrication of actuators and MEMS switches. The well-established piezoelectric actuation mechanism offers the advantages of extremely low power consumption and linear actuation [130]. The challenge of this type of piezoelectric actuator remains in the materials deposition technology, due to limited control on the crystalline orientation and increased internal stresses in thin films [60].

Thermal actuation offers an alternative solution that can be used in nanoscale devices [139-143]. These actuators require two layers of different materials with different thermal expansion coefficients. The structures can either be in the shape of a silicon beam [140] or a shell [141]. Localized Joule heating of two materials causes different expansion and results in bending either in plane or out of plane. Even though the electrothermal actuator can achieve large actuation distances with good accuracy, the main limitation lies in its speed.

The optical gradient force has been one of the most attractive approaches, beside the traditional actuation methods, to realize an effective NEMS actuation, due to its capability to easily generate mechanical deformation of nanoscales [144-147]. The optical gradient force can be increased in evanescently coupled nanoscale

waveguides due to the enhanced gradient of the optical field intensity [47, 49]. To further enhance the optical gradient force, cavity enhancement via WGM ring resonator is employed to provide strong interaction for optical routing with low input energy due to the ORR's high Q-factor [82, 145], which can provide efficient actuation for various NEMS devices.

2.3.2 NEMS VOA

An optical attenuator is a device used to reduce the power level of an optical signal, either in free space or in waveguide structures. The variable optical attenuator (VOA) plays an important role in optical fibre communication systems and MEMS integrated VOAs have been developed and applied for communication networks [148-156].

The MEMS-integrated VOAs generally utilize MEMS actuators to control a shutter or a mirror, which can block or redirect light from propagating between fibres and waveguides [153, 157]. The advantages of these MEMS VOAs include high extinction ratio, low power consumption, mechanical stability, low cost and small size [115]. Besides the MEMS-based VOAs, other implementations, based on other operational principles including thermal-optical effects [151, 158, 159], electro-optical [160-162], and opto-optical [163] have been demonstrated. However, in term of specifications, including tuning speed, attenuation coefficient and power consumption, the MEMS-based VOAs remain the most performant [115].

However, stronger demand for highly integrated and compact devices has restricted the applications of the MEMS VOAs due to their large scale actuator.

Highly integrated and compact VOAs driven by NEMS actuator can be possible if one can integrate VOAs onto planar optical waveguide circuits.

Coupling between rectangular waveguides has been studied since 1969 [164]. After that, various approaches have been made to utilize the directional coupler as an optical attenuator or switch [154, 162, 165-171]. Waveguide-based NEMS VOAs have also been demonstrated [172, 173].

Waveguide based VOAs can play an increasingly important role in nanophotonic circuits. With the advances in the development of optical gradient forces, NEMS actuators driven by optical gradient forces are likely to provide effective attenuation for VOAs.

2.3.3 NEMS Memory

The explosion of information usage in modern society challenge the way we store and process information. There is always a strong demand for high speed, energy efficient and compact approaches to store signals in the current high speed and high capacity data processing systems. Even though the electromagnetic memory is still in dominant position in current memory market, mechanical memory, especially MEMS memory, is still an important player due to its advantages such as high temperature range (over 2000 °C) and faster speed (microsecond level) compared to conventional non-volatile memory (1-5 ms). MEMS/NEMS memories have been developed for more than 20 years. Most of them were based on either mechanical bistability [139, 174-179] or material-based bistability [180]. The first MEMS non-volatile memory cell was inventoried in 1990, using a buckled doubly-

clamped silicon beam switched by electrostatic force [175]. However, such a MEMS memory cell has significant drawbacks, such as large scale and low speed. A NEMS memory based on pull-in bistability has been recently studied and presented to meet the requirement of compactness and high speed [176, 177].

On the other hand, there is a high demand for compact, high speed and low power consumption memories due to the fast development of fibre optics based telecommunication systems, which can be integrated with planar semiconductor technology for buffering of decisions and telecommunication data. [181, 182]. Future optical routing and switching will also require high-speed and low-power optical processing of digital signals. Therefore, ultra-small, low-power, all-optical switching and memory elements, such as all-optical random access memory (RAM), as well as photonic integrated circuits of many such elements, are in great demand for all-optical signal buffering, switching and processing. Silicon-on-insulator is considered to be a promising platform to accommodate such photonic circuits in large-scale configurations [183].

One approach is based on the nonlinear properties of silicon [184]. Photonic crystals have also been proposed to realize optical bistability on a silicon chip via two photon absorption [185]. Another approach is to employ gain manipulation of coupler interference, which utilizes the bistability of a microdisk cavity with saturable absorber [186].

Recently, non-volatile mechanical memories based on nanomechanical resonators have been reported, based on the mechanical bistability of a silicon nanobeam driven by an optical gradient force [81].

The development of nano-silicon-photonic circuits and all optical computing require highly compact optical memories. However, the current approaches either require special materials, such as magnetic materials as highly nonlinear optical materials, or complex electrostatic force actuated mechanical structures, which typically are bulky, slow and power inefficient. A NEMS all-optical memory based on optomechanical effects has a great potential in optical signal buffering, switching and processing on silicon photonic circuits due to its high speed, small size and good integrability.

2.4 Summary

In this chapter, the basic concepts of optical force, optical microcavities and NEMS devices were reviewed and discussed. A literature survey was conducted to fulfill two major objectives of this PhD project. First, to explain how actuation can be achieved using nano-structures through optical gradient forces, with the help of microcavities. Second, to summarize functional optical NEMS devices based on optical gradient force that have been previously reported in literature.

Optical forces, especially optical gradient forces, have been widely used in various structures with miniature scale ranging from micro to nano. Such forces can be generated, for instance, through evanescent wave interaction, which can be achieved in nano structures, such as waveguides, ring resonators and slot waveguides. So far, optical forces have been utilized in some applications, such as bioparticle

manipulations and optomechanical devices. By proper design, optical forces can be an ideal actuation tool in NEMS devices.

Even though the magnitude of the optical gradient force may not be high enough for usage in most applications, microcavities can be integrated to further enhance the force. Microcavities are able to accumulate light in limited space, and enhance the optical intensity gradient. For this purpose, WGM ring resonators are the most important and widely used structures in planar optical devices. Many nano-silicon-phonic devices have indeed been developed based on WGM ring resonators, such as filters and modulators, which provide a platform for optical force-based integrated devices.

Lastly, several NEMS devices are also reviewed. These include actuators, VOAs and optical memories. The development of NEMS actuator remains technically challenging, due to their nanoscale dimensions. The optical gradient force can therefore play an important role in the design and realization of the optical NEMS actuator. Traditional VOAs and memories are normally big in size and complex in fabrication. Optical NEMS provide a platform with which various functions can be realized using the new silicon photonic technology and the optical gradient force.

In summary, NEMS devices have been developed to realize functions which are normally realized by traditional MEMS devices, with better performance, smaller size and lower power consumption. But challenges remain for NEMS devices, such as inefficient actuation through electrical approaches, so that realizing a performant NEMS actuator is the key to realize various functional NEMS devices. The optical gradient forces have been exploited in various nanoscale structures, such as ring resonators and beams. However, little has been done to realize functional devices.

The optical gradient force exploited NEMS devices, which can be fabricated by nano-silicon-photonic processes, are promising tools for the realization of various functions and, therefore, show great potential for applications in biomedical, telecommunication and sensor industries.

CHAPTER 3

THE NEMS ACTUATOR

This chapter presents the design, fabrication and experiment of the nano-electro-mechanical systems (NEMS) actuator driven by an optical gradient force and controlled by the Q-factor attenuation of a ring resonator. The theoretical model covering the Q-factor attenuation of the ring resonator, the *p-i-n* junction modulator and nanoscale displacement sensing are presented. The mechanical and optical design of the NEMS actuator is also covered, followed by a discussion on the nano-silicon-phonic fabrication process using silicon-on-insulator wafers. Finally, the experimental results are presented and discussed.

3.1 Design of NEMS actuator

Fig. 3.1: Schematic of NEMS actuator.

The schematic of the NEMS actuator is shown in Fig. 3.1. It mainly consists of three parts: a tunable actuation ring resonator, a sensing ring resonator and a mechanical arc nano-actuator. The two ring resonators are optically connected by a nano-silicon bus waveguide which goes through the actuating ring first and then splits into two waveguides, with the upper one in the immediate vicinity of the sensing ring. The input light can be coupled in and out of the actuation ring resonator and the sensing ring resonator through the bus waveguide.

The mechanical arc nano-actuator is realized using a doubly-clamped beam, whose schematic structure is shown in Fig. 3.2. The nano-actuator consists of three arcs, named central arc and side arcs. The central arc and each of the side arcs are $20.3\ \mu\text{m}$ in radius (R) and $200\ \text{nm}$ in width (w). The central angle is 30° for central arc and 15° for side arcs, respectively. The anti-arc design makes the mechanical arc easy to

deform along the x -direction while maintaining a good stability in the z - and y -directions.

The nano-silicon-photonic waveguides are designed to be 450 nm wide so as to allow single mode transmission. The outer radius is 20 μm for the actuation ring resonator, and 10 μm for the sensing ring resonator, respectively. A 100-mW broadband light, with bandwidth equal to 5 nm, is coupled from the bus waveguide to the actuation ring resonator. Due to optical energy accumulation in the actuation ring resonator, optical gradient force is generated between the actuation ring and the mechanical arc nano-actuator and the mechanical arc is deformed toward the actuation ring. Meanwhile, the displacement of the mechanical arc can be measured by the sensing ring resonator by measuring the resonance wavelength shift.

Fig. 3.2: Mechanical illustration of doubly-clamped beam which makes up the arc nano-actuator.

Fig. 3.3: Schematic illustration of spectrum analysis for the actuation measurement.

The displacement of the mechanical arc nano-actuator is controlled by the actuation ring resonator through the Q-factor variation of the actuation ring resonator. The spectrum of both ring resonators' resonance wavelengths upon actuation is shown in Fig. 3.3. When the electrical current is applied through the *p-i-n* junction of the actuation ring resonator, the Q-factor of the actuation ring resonator is reduced, the gradient force is also reduced, and then the mechanical arc is deformed. The displacement of the mechanical arc nano-actuator results in an effective refractive index change of the sensing ring, which can be measured by the shift ($\Delta\lambda_s$) in resonance wavelength. Therefore, the wavelength shift of the sensing ring is observed and the displacement of the mechanical arc nano-actuator can be determined.

3.2 Theoretical analysis and numerical simulation

3.2.1 Optical gradient force

The optical gradient force is generated due to evanescent wave coupling, which has been studied in various papers and has also been discussed in Chapter 2. Optical gradient forces developed between two waveguides can be either attractive or repulsive, depending on the symmetry of the propagating modes. In each case, the optical gradient force can be calculated either by means of the Maxwell stress tensor or energy conservation.

In this thesis, the force is derived based on energy conservation, which is an efficient method for a uniformly distributed waveguide system and can be derived directly from the dispersion properties of the waveguide. Fig. 3.4 shows the simplified structure of two waveguides, where the two parallel silicon waveguides (refractive index $n = 3.45$) are separated by a gap s and each waveguide has a cross section of dimensions $W \times H$.

Fig. 3.4 Schematic representation of two waveguides: (a) Top view and (b) Cross-sectional view.

The total optical energy in such a highly symmetric system can be measured by means of quantum mechanics or simply the light propagation parameters, which can be expressed as

$$U = N\hbar\omega = \frac{PLn_g}{c} \quad (3.1)$$

where N is total photon number, $\hbar$ is the reduced plank constant, ω is the eigenmode frequency, P is the input optical power, L is the length of the waveguides, n_g is the group index of mode, and c is the speed of light in vacuum. Both the eigenmode frequency ω and group index n_g are further related to effective refractive index n_{eff} as [187]

$$\omega = \frac{\omega_0}{n_{eff}} \quad (3.2), \text{ and}$$

$$n_g = n_{eff} - \lambda \cdot \frac{\partial n_{eff}}{\partial \lambda} \quad (3.3),$$

where ω_0 is the eigenmode frequency in vacuum.

Assuming that the two waveguides are approaching each other, the energy conservation imposes that the total energy change must be the same as the change in mechanical energy induced by the optical gradient force. The optical force is therefore the total energy U change per gap between waveguide gap s changes, and can be expressed as [187, 188]

$$F = -\frac{\partial U}{\partial s} \Big|_k = -\frac{\partial(N\hbar\omega)}{\partial s} \Big|_k = -N\hbar \frac{\partial \omega}{\partial s} \Big|_k = -\frac{1}{\omega} \frac{\partial \omega}{\partial s} \Big|_k U \quad (3.4),$$

where k is the wave vector, which is conserved because of the preservation of translational invariance. Due to the fact that both U and ω are related to the effective refractive index, the force is simplified as

$$F = \frac{1}{n_{eff}} \cdot \frac{\partial n_{eff}}{\partial s} \cdot \frac{PLn_g}{c} = \frac{1}{cn_{eff}} \cdot \frac{\partial n_{eff}}{\partial s} \left(n_{eff} - \lambda \cdot \frac{\partial n_{eff}}{\partial \lambda} \right) \cdot P.L \quad (3.5).$$

The force per unit length per unit power is expressed as

$$\frac{F}{LP} = \frac{1}{cn_{eff}} \cdot \frac{\partial n_{eff}}{\partial s} \left(n_{eff} - \lambda \cdot \frac{\partial n_{eff}}{\partial \lambda} \right) \quad (3.6).$$

The normalized force is now related to two dispersion coefficient expressed as $\frac{\partial n_{eff}}{\partial \lambda}$ and $\frac{\partial n_{eff}}{\partial s}$, which can be simulated using an optical eigenmode solver, such as Lumerical MODE.

The dispersion diagram of the two silicon ($n = 3.47$) waveguide system with $W = 450$ nm and $H = 220$ nm is shown in Fig. 3.5 (a), while Fig. 3.5 (b) shown the electrical field distribution when the gap between waveguide is 150 nm. The effective refractive index decreases when the gap between the waveguide increases and the effective refractive index is larger for shorter wavelengths.

The normalized optical gradient force for the above mentioned two-waveguide system is plotted in Fig. 3.6. The force is linearly related to the power transmitted and decreases exponentially as the gap between the waveguides increases. The blue dashed line is the exponential fitting of the optical gradient force, which is expressed as

$$F_n = \frac{F}{P \cdot L} = A \cdot \exp\left(\frac{-s}{B}\right) + C \quad (3.7),$$

where A equals to -12.27, B equals to 63.24 and C equals to -0.39. The exponential curve of the optical force indicates that the optical force can be enhanced by reducing the gap between waveguides.

Fig. 3.5: (a) Effective refractive index of two evanescent wave coupled waveguides at different wavelength and (b) TE mode electrical field distribution.

Fig. 3.6: Optical force and exponential fitting at $\lambda=1550$ nm.

The piconewton scale optical gradient force can only show effects for nano scale structures. To further enhance the optical gradient force so that it can be implemented in devices, the optical power must be increased and the structures should be optimized. In this thesis, whisper galley mode (WGM) ring resonators are used to increase the light power, while vary narrow silicon beam will be employed to increase the dispersion coefficient.

3.2.2 Mechanical response of arc actuator

In the NEMS actuator, an attractive optical force is generated between the actuation ring and mechanical arc. Due to large radius and smaller gap in-between, the force can be simplified using the equation derived for the two-waveguide systems.

Two forces acted on the mechanical arc actuator, the optical gradient force generated by the ring resonator, and the mechanical spring force due to the deformation of the arc actuator. The optical gradient force is proportional to the optical power in the ring resonator, and increases exponentially as gap decreases. At small displacement (< 10 nm), the optical force changes is within 5 % when the gap between the actuation ring and nano-actuator is around 150 nm, as shown in Fig. 3.6. Therefore, based on the small actuation displacement of the actuator, the optical force is considered to be constant during the actuation process. Moreover, the mechanical displacement of the arc actuator is linearly proportional with the actuation force at small displacements. Then, the maximum displacement of the arc actuator is linearly related to optical power, as shown in Fig. 3.7, where the mechanical displacement of the nano arc actuator was simulated using COMSOL.

The deformation of the mechanical arc is due to the attractive optical gradient force. Initially, the gap between the mechanical arc and the sensing ring is g_0 without light. When the applied optical power inside the actuation ring is P_0 , the force pulls the mechanical arc away from the sensing ring and now the gap in the middle becomes $g_0 + \Delta g$. The displacement of the mechanical arc Δg is related to the normalized optical force as $F_{normalized} = K \Delta g$, where K is the effective spring constant of the silicon mechanical arc. Fig. 3.7(b) shows the deformation of the mechanical arc, in which red indicates the largest a larger deformation of arc nano-actuator and the blue colour indicates the smallest deformation.

Fig. 3.7: (a) Simulated maximum displacement of the arc nano-actuator at various optical powers, and (b) demonstration of mechanical deformation of the arc nano-actuator.

3.2.3 Q-factor modulation through p - i - n junction

The Q-factor of the ring resonator is one of the most important parameters for the targeted nano-actuator design because a higher Q-factor means lower rate of

energy loss in the cavity. Hence, a higher Q-factor of the ring resonator can increase the amplitude of the generated optical gradient force.

The Q-factor of the ring resonator is dominated by the external loss and the intrinsic loss. The external loss, which is due to the coupling loss between the waveguide and the ring resonator, is related to the coupling coefficient k . The intrinsic loss is related to the ring resonator itself, such as its surface roughness and the absorption of nano-silicon-photonic waveguide. The surface roughness of the waveguide is well controlled by the fabrication process and the absorption coefficient α of silicon is normally quite low in the C and L communication bands in which the devices is intended to be operated.

The Q-factor of the ring resonator with one bus waveguide side coupler can be expressed as [91]

$$Q = \frac{\omega}{\Delta\omega_{FWHM}} = \frac{\pi n_{eff} L \sqrt{t\beta}}{\lambda(1-t\beta)} \quad (3.8),$$

where ω is the frequency of light, $\Delta\omega_{FWHM}$ is the full-wave half maximum at resonance, n_{eff} is the effective refractive index, L is the effective perimeter of the actuation ring, t is the transmission coefficient of the waveguide-ring coupler, β is the round trip gain and λ is the resonance wavelength. In this equation, the transmission coefficient t is related to the coupling coefficient as $t^2 + k^2 = 1$ due to energy conservation. The round trip gain β is related to the absorption coefficient α as $\beta^2 = e^{-\alpha L}$.

Either the coupling coefficient k or the absorption coefficient α can be used in order to manipulate the Q-factor of the ring resonator. However, the coupling

coefficient is difficult to be manipulated due to the small effective coupling area. The coupling coefficient is very sensitive to the gap between the waveguide and the ring resonator. In this case, the gap is kept at its minimum value of 200 nm.

The absorption coefficient α is therefore the only suitable parameter which can be varied to control the Q-factor by p - i - n junction light modulator. The round trip gain is related to the change of absorption coefficient which can be expressed as

$$\beta^2 = e^{-\alpha L} = \beta_0^2 e^{-\Delta\alpha L} \quad (3.9),$$

where β_0 is the round trip gain without modulation. While the coupling conditions remains the same, the Q-factor is only related to the round trip gain, which is modulated by the p - i - n junction optical modulators, as shown in Fig. 3.8.

The p - i - n junction optical modulator is realized by forward biasing the p - i - n junction. The waveguide is designed as a rib structure, which is sandwiched between p -type and n -type doped silicon. When an injection current is pumped through the silicon waveguide from p -type doped silicon to n -type doped silicon, the refractive index of silicon is modulated. The imaginary part of the refractive index is directly related to the absorption. The intrinsic absorption α is related to free carrier density is given as [107]:

$$\Delta\alpha = -\left[8.5 \times 10^{-18} \cdot \Delta N + 6.0 \times 10^{-18} \cdot \Delta P\right] \quad (3.10),$$

where ΔN and ΔP are the injected electron and hole concentrations, respectively.

The electron and hole concentrations are related to the injection current I as

$$\Delta N = \Delta P = I\tau / eSl \quad (3.11),$$

where τ is the free carrier recombination time, e is elementary charge of the electron, S is the effective area of the silicon waveguide cross section and l is the length of the ring's intrinsic zone.

The intrinsic absorption of silicon is proportional to the injection current, meaning that by increasing the current/voltage across the p - i - n junction, the Q-factor of the ring resonator can be attenuated.

Fig. 3.8: Schematic illustration of top view and cross-section view of p - i - n junction based ring resonator.

3.2.4 Actuation controlled by Q-factor attenuation

The mechanical arc nano-actuator is driven by optical gradient force. The power within the ring resonator is enhanced due to high Q-factor. The power enhancement is measured by the building-up factor B , such that the power within the ring resonator can be written as $P_a = B \cdot P_{in}$, where P_{in} is the optical power transmitted inside the waveguide.

Both the Q-factor and the building-up factor B measure the power enhancement properties of the ring resonator, meaning that both B and Q are closely related to the round trip gain/loss. The building-up factor B is defined as

$$B = \frac{k^2 \beta^2}{(1 - t\beta)^2} \quad (3.12)$$

where t and k are the transmission coefficient and the coupling coefficient between the waveguide and the ring resonator, respectively. Due to the relationship between the intrinsic absorption and the injection current across the $p-i-n$ junction, the building-up factor B is further related to the injection current.

The nano-scale displacement Δg of the mechanical arc nano-actuator is linearly related to optical power. In such a case, the displacement Δg is therefore related to the Q-factor, which can be expressed as

$$\Delta g = \frac{F}{K} = \left[-\frac{1}{\omega} \frac{d\omega}{dg} \right]_k \cdot \frac{L_{couple}}{v_g} \cdot B P_{in} \cdot \frac{1}{K} \quad (3.13),$$

where L_{couple} is the coupling length, v_g is the group velocity and A ($=$

$$\left[-\frac{1}{\omega} \frac{d\omega}{dg} \right]_k \cdot \frac{L_{couple}}{v_g} \cdot \left[\frac{k^2 \lambda^2}{(\pi n_{eff} L)^2 t} \cdot \beta P_{in} \right] \cdot \frac{1}{K})$$

is the Q-factor tuning coefficient.

Therefore, Eq. 3.13 can be simplified as $\Delta g = A \cdot Q^2$.

For a broadband light source, the Q-factor tuning coefficient A is considered to be constant due to multiple resonance wavelengths within the operational the spectral range.

The tuning efficiency is defined as $\frac{d(\Delta g)}{dQ}$, which is $A \cdot Q$, hence it increases

with the Q-factor. In other words, the tuning efficiency is optimized to be highest so that even a small change in the Q-factor can induce a large actuation displacement.

In summary, the displacement Δg can be controlled by the Q-factor, which provides an effective control of the nanoelectromechanical actuator through varying the current of p - i - n junction between the ring resonators.

3.2.5 Optical displacement sensing

Displacement measurements at the nanometer scale are challenging, especially for the traditional MEMS devices. This chapter will describe how the displacement of the proposed actuator is measured optically.

The resonance wavelength of the ring resonator is related not only to the refractive index of the materials, but also to the surrounding environment's refractive index. For nanoscale waveguide structures, the surrounding influence is even more significant. In other words, the light travelling within the waveguide of the ring

resonator is affected by the geometry of the waveguide, and the refractive indices of both the waveguide core material and the surrounding environment. Effective refractive index is introduced to measure the light transmission properties in such a waveguide system.

The resonance wavelength of the ring resonator can be expressed as

$$m\lambda = 2\pi R n_{eff} \quad (3.14),$$

where m is an integration number, λ is the resonance wavelength, R is the radius of ring resonator and n_{eff} is the effective refractive index of the ring resonator system. When the environmental conditions change, the effective refractive index n_{eff} and the resonance wavelength λ change, shifting the resonance wavelength to a new value λ' , which is expressed as

$$\Delta\lambda = \lambda' - \lambda = \frac{\Delta n_{eff}}{n_{eff}} \lambda \quad (3.15),$$

where λ' is the new resonance wavelength while $\Delta\lambda$ and Δn_{eff} are the change in resonance wavelength and effective refractive index, respectively.

In this design, an optical displacement sensor is integrated on the same chip together with the NEMS actuator in order to measure the nano-scale displacement of the mechanical arc through the opto-mechanical effect. The displacement sensor consists of the sensing ring resonator and a small mechanical arc, which is attached to the opposite side of the mechanical arc actuator. The mechanical arc sensor is close to the sensing ring resonator as shown in Fig. 3.9(a). The displacement of the arc actuator can affect the electrical field distribution in the gap between the sensing ring

Fig. 3.9: (a) Schematic illustration of displacement sensor design, and (b) the electrical field distribution deal with various gap values of the displacement sensor.

resonator and the mechanical arc sensor, which is simulated by COMSOL and shown in Fig. 3.9(b). The waveguide is 450 nm wide and 220 nm high while the arc sensor is 200 nm wide and 220 nm high. When the gap is 50 nm, a very high electrical field is present within the gap between the ring resonator and the mechanical arc sensor as

shown in Fig. 3.9(b). As the gap increases to 150 nm, most of this electrical field become distributed in the core of waveguide. Based on the electrical field distribution, more optical energy within the gap means a smaller effective refractive index due to a smaller refractive index of the surrounding environment.

To quantitatively measure the system's effective refractive index change upon the displacement of the mechanical arc actuator, the opto-mechanical coefficient is defined as

$$g_{om} = \Delta n_{eff} / \Delta g \quad (3.16),$$

where Δn_{eff} and Δg are the changes of the effective refractive index and the gap between the mechanical arc sensor and sensing ring resonator respectively.

Fig. 3.10: Effective refractive index n_{eff} and opto-mechanical coefficient g_{om} of the sensing ring resonator versus the gap value.

The resonance wavelength shift of the sensing ring can be defined as

$$\Delta\lambda = \frac{g_{om} \cdot \lambda}{n_{eff}} \Delta g \quad (3.17)$$

The resonance wavelength shift $\Delta\lambda$ is therefore linearly related to the gap change Δg . The actuation distance of the mechanical arc actuator can therefore be obtained by directly observing the wavelength shift of the sensing ring resonator.

The displacement sensor's sensitivity relies mainly on the opto-mechanical coefficient. In order to design a high performance displacement sensor, the opto-mechanical coefficient is maximized such that a large wavelength shift can be observed for a small displacement. The effective refractive index and the opto-mechanical coefficient of the sensing ring resonator were simulated by COMSOL, and the results are shown in Fig. 3.10. When the mechanical arc sensor is away from the sensing ring resonator, the gap increases, and as a consequence, the n_{eff} decrease rapidly while g_{om} first increases rapidly and then saturates.

3.3 Fabrication processes on Silicon-on-Insulator (SOI) substrate

The NEMS actuator is fabricated by CMOS compatible silicon-nano-photonics fabrication processes. The silicon-based nano-photonics fabrication has advantages, such as low cost of the material, and the availability of mature and well-characterized processing techniques, which are not only compatible with CMOS processes but also allow for straightforward integration with electronic components in the same substrate [1].

The vast majority of silicon photonic devices studied in this work have been fabricated using Silicon-On-Insulator (SOI) wafers, which consist of a thin layer of crystalline silicon on an insulating layer. The most common SOI structure found in nano-silicon-photonics circuits is silicon-on-silicon dioxide (SiO_2), in which a uniform layer of SiO_2 is sandwiched between a thick silicon substrate and a thin crystalline silicon structure layer. The buried SiO_2 has a refractive index of 1.46, which is significantly lower than that of the crystalline silicon layer which is approximately 3.47. Hence, this SOI structure can be used to form a nano silicon waveguide structure while the oxide layer can also be used for micromachining either as a sacrificial buffer layer or an etch-stopper layer.

The core technology of nano-silicon-photonics fabrication processes is silicon etching using reactive ion etching (RIE), which has the merits of high selectivity, anisotropy, arbitrary structure profiles, easy integration and simple process.

Fig. 3.11: Fabrication process flow of nano-silicon-photonic devices.

The fabrication process flow of the nano-silicon-photonic waveguide circuit on 8 inch SOI wafers is summarized in Fig. 3.11. The surface layer of crystalline

silicon has a thickness of 220 nm, the buried SiO₂ has a thickness of 2 μm and the substrate silicon has a thickness of 700 μm (Fig. 3.11 (a)).

First, on top of the structure silicon layer, a thin layer (70 nm) of SiO₂ is deposited by low temperature plasma-enhanced chemical vapor deposition (PECVD), which works as hard mask for the subsequent patterning of the silicon structure using RIE. On top of the hard mask, a 90 nm Bottom-Anti-Reflective Coating (BARC) and 700 nm photoresist (PR) is dispensed on the thin SiO₂. The BARC layer is important to achieve a small line width using photolithographic patterning. The nanostructure layer, including the waveguides and the ring resonator, is patterned by deep UV lithography, followed by development and hard-bake, as shown in Fig. 3.11 (b). The PR pattern is examined carefully to ensure that the line width can meet the design requirements.

The first RIE etches through the PR protected 70-nm-thick SiO₂ layer where the nanostructures are patterned. Then, the PR layer is stripped as shown in Fig. 3.11(c). Now the waveguide and ring resonator patterns are transferred from PR to the 70-nm-thick SiO₂ hard mask.

To ensure the quality of the waveguide structures, two steps are important i.e. hard mask and BARC deposition, which are necessary for small scale structures ($< 1 \mu\text{m}$). The hard mask is necessary because PR is quite thick as compared with the silicon structure and it also encounters loss during silicon etch, which can affect the line width and sidewall surface roughness. The BARC is necessary here to reduce the standing wave effect of the lithography, and as such it is a necessary layer for narrow line width structures.

To realize the *p-i-n* junction and metal connection, part of the ring resonator waveguide is rib waveguide, which can be fabricated by a two-step silicon etch. First, silicon etch is carried out by RIE using SiO₂ hard mask so that a thin (80 nm) layer of silicon is left (Fig. 3.11 (d)). This step of RIE is the most critical step in the nano fabrication processes to ensure the quality of the waveguide profile, including the sidewall roughness and line width to minimize the loss of the waveguide.

After cleaning the wafers, another PR layer is spin coated and the rib waveguide pattern is transferred by lithography. The waveguide structures are still covered by the hard mask and the rib waveguides are covered by the PR. Another RIE process is carried to etch the non-covered silicon to the buried SiO₂ layer. After PR strip and wet clean, the waveguides structures including the ring resonator, bus waveguide, rib structures of *p-i-n* junction and mechanical arc actuator are formed. The SEM images of the silicon waveguide after two step RIE processes are shown in Fig. 3.12. Both the 450-nm-wide waveguide silicon waveguide and the 175-nm gap between the waveguides are formed, as shown in Fig. 3.12 (a). The zoom-in view of the 220-nm-thick silicon waveguide, which is covered by the top SiO₂ layer, is shown in Fig. 3.12(b). The waveguide with 80 nm rib structures is shown in Fig. 3.12(c) and (d).

The next step is to selectively dope the silicon in order to form the *p-i-n* junction, which requires two lithography as shown in Fig. 3.11 (f) and (g). Before lithography, a 50-nm-thick SiO₂ layer is deposited to protect the silicon rib structure from the high speed dopants during the doping process. The PR works as a protection layer for the non-doped part and the wafer is doped with boron and phosphorus by ion implantation. The doping concentration is $2 \times 10^{14} \text{ cm}^{-3}$ for both *p*-type and *n*-

type regions, while the doping energy is 20 and 40 keV, respectively. After doping and PR clean, the wafer is annealed at 1050 °C for 5 sec using Rapid Thermal Anneal (RTA) to ensure uniform distribution of dopants.

Next, the cladding SiO_2 layer is deposited using high-density plasma (HDP) CVD at low temperature, as it provides good filling properties and a high deposition rate. However, the corner of the silicon waveguide may be damaged due to the high

Fig. 3.12: SEM images of waveguide structures after two RIE processes and subsequent wafer cleaning. (a) Waveguide structures with 175 nm gap. (b) Zoom-in view of 220-nm-thick waveguide with hard mask. (c) and (d) Waveguide with rib structures.

Fig. 3.13: SEM images of metal structures after metal etching.

pressure during the deposition process. To overcome this problem with the HDP oxide, an 80 nm undoped silicon glass (USG) is deposited using PECVD before the 2 μm HDP oxide deposition to protect the silicon structure.

After the two-step SiO₂ CVD deposition, the silicon layer is covered by SiO₂, which has the same thickness as the buried oxide layer, to ensure the symmetric profile of wave transmitting inside the waveguide core. The metal connection for the *p-i-n* junction is then fabricated. The via-hole pattern is transferred to the PR using lithography, followed by the RIE process to etch through the 2- μm -thick cladding oxide and stop at the silicon layer, as shown in Fig. 3.11(h). Part of the doped silicon in the rib structures are exposed for metal connection.

After PR strip and wafer clean, a thin TaN layer is deposited first to ensure good conductivity and adhesion for the 70 nm thick Al layer that will be deposited subsequently over the whole wafer such that the via-hole is filled by Al. The metal pattern is transferred from the mask to the PR through another lithography. The metal is then etched away and the PR is striped as shown in Fig. 3.11 (i). The SEM images

of the wafer after metal etch are shown in Fig. 3.13, where show the Al filled via-hole and the TaN layer under the Al layer are easily noticed.

In order to easily dice the wafer into small pieces, deep trenches are also necessary. Two trenches are etched to protect the sidewall of subsequent diced device chip, which is used for fibre-to-waveguide coupling. A 100- μm -wide trench layer is patterned first followed by a 4- μm oxide etch, which includes both the cladding oxide and buried oxide, as shown in Fig. 3.11 (j). After the PR strip, a 40-nm Al_2O_3 is deposited, so that both the top oxide cladding (including metal layer), trenches and the trench sidewalls are all covered, as shown in Fig. 3.11 (k). Several materials, like amorphous silicon, had initially been considered for this purpose but the Al_2O_3 was the optimal choice as it has the most numerous favourable properties. Al_2O_3 exhibits better optical properties since it has a refractive index of 1.746, which is much closer to SiO_2 which is 1.46, compared to amorphous silicon, which is around 3.5. Furthermore, Al_2O_3 layer can act as protection layer during the subsequent HF vapour release process due to its good chemical inertness.

In order to expose the movable structures as well as the metal pad for electrical connection, the window pattern is transferred from the mask to the PR using lithography, as shown in Fig. 3.11 (l). The Al_2O_3 is etched first such that the cladding oxide is exposed. In order to reduce the duration of the subsequent HF vapour release process, another RIE process is carried out to etch through part of the entire thickness (2 μm) of the 1.5- μm cladding oxide as shown in Fig. 3.11 (m). The metal pad remains unchanged due to the high selectivity of RIE oxide etchant.

Before the final release process, a second narrow trench (94 μm) is etched in the same lanes using PR as mask, to a depth of 100- μm in silicon substrate using deep RIE process as shown in Fig. 3.11 (n) , top facilitate the wafer dicing.

The final step is to release the moveable micromachined structure from the substrate (Fig. 3.11 (o)). The Al_2O_3 again serves as a protection layer to prevent the non-released oxide from being etched during the release processes since only SiO_2 in the window region needs to be etched. Two alternative releasing processes were developed, a buffered oxide etchant (BOE) wet etch and a HF vapor etch. In the BOE wet etch, the waveguide is damaged since the BOE can etch the waveguide even though the etching rate is quite small. The damage is nevertheless important as it induces quite significant losses to the nano scale waveguide. To overcome the limitations of the BOE wet etch, a HF vapor release process was developed. The HF vapor only reacts with SiO_2 but not with silicon waveguide and Al_2O_3 protection layer, which ensures a good profile of the waveguide with a very smooth surface and thus improves optical performance. Furthermore, the HF vapor can reduce the stiction problem and increase the yield of devices. The SEM images of fabricated NEMS actuators after the HF vapor release process are shown in Fig. 3.14.

Two critical issues are important in the optimization of the fabrication processes: the silicon waveguide etching and the HF release process. The PR pattern and hard mask pattern of the waveguide structures should be checked carefully to ensure a good line width and uniformity. The release process is also critical. Due to the residual stress of SOI wafer, the bulking of the released beams can be destructive. The structure design was optimized to release residual stress and avoid stiction, by testing different beam structures with different geometrical parameters.

(a)

(b)

Fig. 3.14: SEM images of fabricated NEMS actuators: (a) zoom-in view of the release window, and (b) overview of the NEMS actuator.

In summary, a fabrication process has been developed to realize nano-silicon-phonic NEMS devices on SOI wafers. Two RIE processes are performed first, followed by doping and the cladding oxide deposition. Subsequently, via-holes are etched and metal contact are fabricated. Lastly, the release etch window is patterned and the movable structure is released using HF vapour. Finally, the wafer is diced using dicing machine and the chips are used for test measurement.

3.4 Experimental results and discussions

3.4.1 Experimental setup

The devices is tested by coupling light in and out of the devices using lensed fibre (OZ optics). Light coupling is the challenge in the nano-device experiment. High loss is expected when the input light is coupled directly from single mode lensed fibre to the waveguide due to mode size difference, which is 2.5 μm for the lensed fibre and 450 nm for the waveguide. In order to reduce the coupling loss, a mode size converter is implemented at both the input and output ports of the waveguide, as shown in Fig. 3.15. The mode size converter is a specially designed waveguide with its width gradually increasing from 200 nm to 450 nm. The mode width for the 200-nm-wide waveguide is approximately 2.5 μm , such that the mode mismatch between the lensed fibre and the waveguide is minimized. The coupling loss between the lensed fibre and the waveguide is experimentally measured, which is approximately 3 dB.

Fig. 3.15: Schematic illustration of the light coupling between the lensed fibre and the waveguide mode size converter.

The lensed fibre is aligned with the waveguide using an optical alignment system (FiconTEC), which can actively align the lensed fibre with the device under test (DUT), so that light can be coupled in and out of the actuator through the nano-silicon waveguide with minimum loss. The experimental setup is shown in Fig. 3.16.

A 12-dBm broadband light is generated by an Amplified Spontaneous Emission (ASE) light source (Amonics ALS-CL-13). After passing through the bandpass filter (BPF) (Alnair BVF-200CL), only light with 5-nm-spectral bandwidth

Fig. 3.16: Experimental setup for NEMS actuator characterization.

is transmitted, whereby the central wavelength is 1555 nm, matching the actuation ring's resonance wavelength. The filtered light is amplified by an Erbium Doped Fibre Amplifier (EDFA) (Amonics EDFA-CL-27) and passes through a 2/98 splitter. 2% of the light is transmitted to a photodetector (PD) for power monitoring while most of the light is coupled from the lensed fibre to the bus waveguide. The light with the wavelengths equal to the actuation ring's resonance wavelength accumulate within the ring to generate the actuation optical force. The transmitted light at both output ports is sent to an optical spectrum analyzer (OSA) (Ando AQ6317B) for analysis. A source measurement unit (SMU) is connected with the metal pad to provide forward bias voltage for the *p-i-n* junction while monitoring the bias current.

3.4.2 Q-factor modulation of the ring resonator

The transmission spectra of the actuation ring is studied to characterize the Q-factor of the ring resonator. The Q-factor can be measured by monitoring the transmission spectra of the ring resonator and be manipulated by controlling the current injection into the *p-i-n* junction.

During the experiments, the forward bias current injected into the *p-i-n* junction is increased from 0 mA to 16 mA. The transmission spectra of the actuation ring is recorded by the OSA as shown in Fig. 3.17. The resonance wavelength of the actuation ring increases from 1553.3 nm to 1556.2 nm. The increment of the resonance wavelength is due to the thermal effect of the *p-i-n* junction, which has limited effect on the loss of the silicon waveguide and the Q-factor attenuation is therefore only affected by the current injected through the *p-i-n* junction.

Fig. 3.17: Transmission spectra of the actuation ring for different currents injected into the *p-i-n* junction.

Fig. 3.18: Q-factor modulation as a function of the injection current.

The Q-factor of the actuation ring is calculated based on the spectra shown in Fig. 3.17, and decreases nonlinearly from above 15×10^3 for no injection currents to around 6×10^3 for the maximum injection current of 16 mA. The Q-factor variation is summarized in Table 3.1 and shown in Fig. 3.18.

The Q-factor attenuation with increasing the injection current reduces the amplitude of the circulating optical power inside the ring resonator and so does the optical gradient force. The building-up factor, which is used to measure the level of power accumulating in the ring resonator, can be derived from the Q-factor. The dependence of the calculated building-up factor on the injection current is shown in Fig. 3.19. The building-up factor is reduced from 17 (For $I = 0$) to only 3 (for $I = 16$ mA), which means that the optical power is reduced and so does the optical force.

Fig. 3.19: Building-up factor B versus the function of current I .

The Q-factor variation with injection current depends on the structural properties of the $p-i-n$ junction of the ring resonator, which provides an efficient mechanism of power control. The amplitude of the optical force can be manipulated by tuning the bias current of the $p-i-n$ junction of the ring resonator and the actuation distance can therefore be modulated.

3.4.3 Characterization of NEMS actuator

The NEMS actuator is characterized by monitoring the transmission spectra of the sensing ring resonator while monitoring the forward bias current. The transmission spectra of the sensing ring resonator at various bias currents are shown in Fig. 3.20.

Fig. 3.20: Transmission spectra of sensing ring resonator with increased bias current.

The optical force is reduced when the injection current in the $p-i-n$ junction increases because the optical energy is reduced in the actuation ring resonator. Thus, the mechanical arc nano-actuator is driven towards the sensing ring resonator which causes the 0.18 nm red shift from 1552.04 nm to 1552.22 nm of resonance wavelength of the sensing ring resonator.

The 0.18-nm wavelength shift of the sensing ring resonator corresponds to a 14 nm displacement of the nano-actuator according to the optomechanical coefficient. The actuation distance is linearly related to the forward bias current as shown in Fig. 3.21.

According to Eq. 3.13, the displacement Δg is related to the Q-factor since $\Delta g = A \cdot Q^2$. This is plotted in Fig. 3.22. The red line shows the theoretical relationship while the blue square shown the measured data.

Fig. 3.21: Displacement of the actuator versus the injection current.

Fig. 3.22: Displacement of the nano-actuator versus the Q-factor of the actuation ring resonator.

The experimental data of the actuation ring and the sensing ring are summarized in Table 3.1, which lists the sensing ring resonator's wavelength, Q-factor of the actuation ring resonator, derived building-up factor (B) and the displacement of the mechanical arc nano-actuator (Δg) at different bias current levels.

Table 3.1: Experimental data of the NEMS actuator.

<i>Current (mA)</i>	<i>Sensing ring resonator's wavelength (nm)</i>	<i>Q-Factor</i>	<i>Building-up factor B</i>	<i>Displacement Δg (nm)</i>
0	1552.040	15226	15.32	16.059
4	1552.072	14657	12.90	13.515
8	1552.114	13878	9.71	10.176
12	1552.160	10367	6.22	6.519
16	1552.216	6650	1.97	2.067

The accuracy of the nano-actuator is experimentally tested by repeating the measurements by more than 20 times. Based on statistical average of the measurement data, the measured wavelength shift of the sensing ring based on OSA had a deviation of 5.5%. Because of the linear relationship between wavelength shift and displacement, the accuracy of Δg is 95%.

The change of displacement Δg as a function of building-up factor B and Q-factor agrees well with the theoretical analysis based on Eq. 3.13, indicating that the actuation can be achieved through the Q-factor tuning of the ring resonator. The sensitivity of the NEMS actuator is 0.875 nm/mA while the resolution is 0.78 nm due to the detection limit of the optical spectrum analyzer (e.g. 0.01 nm).

3.5 Summary

In conclusion, a NEMS actuator based on the variation of the Q-factor of a ring resonator with the bias current injected through a *p-i-n* junction was designed, fabricated and experimentally demonstrated. The nano-actuator is driven by an evanescent wave-coupled optical gradient force and controlled through an electro-optical ring modulator via Q-factor tuning. Nano-scale displacement was measured through an integrated sensing ring resonator utilizing the opto-mechanical effects. A 0.18-nm wavelength shift was observed when the injected bias current was 16 mA, which corresponds to a displacement of 14 nm. The advantages of the NEMS actuator include small dimension, low power consumption and high potential applications in nano-manipulation, nano-sensing and NEMS devices.

The design, fabrication and experiment of the NEMS actuator is summarized as follows:

- a) A nano actuator controlled by Q-factor modulation is demonstrated for the first time. Normally, optical power is controlled by an optical attenuator or directly from a laser source. In the chapter, an effective Q-factor variation method is provided, namely by modifying the bias current of *p-i-n* junction. The relationship between the Q-factor and the optical power was then determined.
- b) The actuator is driven by an optical gradient force. Compared to the traditional electrostatic actuator, the optical gradient force is more efficient for nanoscale actuation. It can applied in optical devices, making them capable to work even in a noisy electromagnetic environment.
- c) The nano actuator is integrated with a nanoscale displacement sensor. Through shifting the wavelength of the optical ring resonator, the actuation distance of the nano actuator can be measured efficiently and accurately.
- d) The NEMS actuator has a sensitivity of 0.875 nm/mA and a resolution of 0.78 nm.

CHAPTER 4

NEMS VARIABLE OPTICAL ATTENUATOR

This chapter presents the design, fabrication and experimental testing of a NEMS variable optical attenuator (VOA) driven and controlled by optical gradient force. The design of the NEMS VOA, which include both optical and mechanical aspects, is introduced first. The basic theory of rectangular waveguide and optical directional coupler is presented, followed by studying the basic principles used for optical actuation and optical attenuation. Subsequently, nano-silicon-photonics fabrication processes are developed and the fabricated NEMS VOA is presented. Finally, the experimental results are presented and discussed.

4.1 Design of NEMS VOA

Fig. 4.1: Schematic of NEMS variable optical attenuator.

The schematic of the NEMS VOA is shown in Fig. 4.1, which consists of a control waveguide, a ring resonator enabled optomechanical actuator, and a directional waveguide coupler. The high power single wavelength control light, whose wavelength is close to the resonance wavelength of the ring resonator, can couple from the control waveguide to the ring resonator. Due to high Q-factor of the ring resonator, light accumulates inside the ring resonator with optical gradient force generated between the ring resonator and the mechanical arc actuator as shown in Fig. 4.2(a). The power level of the signal light is modulated after passing through the directional coupler, while the attenuation is controlled by the actuation distance of the optomechanical actuator.

The optomechanical actuator consists of a ring resonator, an arc-shaped doubly-clamped silicon beam, and a coupler waveguide. The doubly-clamped silicon

Fig. 4.2: Schematic illustration of NEMS VOA driven by optical gradient force.

beam can move only along the x -direction while being fixed and hence motionless along the y - and z -directions. The central arc opening angle Φ is 40° while the side arc opening angle Φ' is 20° . The outer radius R of the arc beam is $20.4 \mu\text{m}$ and the width of the beam w is 200 nm .

The actuation distance is controlled by tuning the wavelength of the control light. When the wavelength of the control light is increased from the blue-detuned wavelength to the resonance wavelength of the ring resonator, the optical force is increased because more energy is coupled into the ring resonator. The arc actuator therefore moves towards the ring resonator and remains stable at the new balance position. Meanwhile, the displacement of the actuator can change the coupling coefficient of the directional coupler, which functions as a VOA.

The optical directional coupler consists of two waveguides of equal width: one is the coupler waveguide which is driven and controlled by the optomechanical actuator, and the other one is the signal waveguide. Light transmitting inside the

signal waveguide slowly couples to the coupler waveguide when propagating along the z direction, and the coupling efficiency depends on the gap between the coupler waveguide and signal waveguide. The length of the coupler waveguide is designed such that all light can be coupled back to the signal waveguide when the actuator is at rest.

The intensity of the signal light drops when the actuation distance increases, as shown in Fig. 4.3. The intensity attenuation of the signal light versus the actuation distance of the optomechanical actuator is sinusoidal, but the attenuation of the signal light is treated as linear in the central, which is defined as 10% - 90% of maximum intensity level (red dotted line in Fig. 4.3). When the control light wavelength is λ_1 ,

Fig. 4.3: Intensity attenuation of signal light versus the actuation distance of the actuator.

the actuation distance is Δg_1 , and the light intensity in the signal waveguide is I_1 . When the control light wavelength increases to λ_2 , the actuation distance increases to Δg_2 , and the light intensity in the signal waveguide is I_2 .

In summary, the attenuation of the signal light is controlled by tuning the gap in the directional coupler, which can be manipulated by the optomechanical actuator.

4.2 Theoretical analysis and numerical simulation

4.2.1 Basic theory of rectangular waveguide

The core part of the NEMS VOA is the waveguide directional coupler, where light can be coupled between the two waveguides. To investigate the energy flow in the coupler, light transmission in a single waveguide is first studied.

An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum. The most common types of optical waveguides include optical fibres and rectangular waveguides. Optical waveguides are the basic components of nano-silicon-photonic circuits.

Fig. 4.4: Schematic of an ideal rectangular waveguide.

In silicon photonics, the silicon waveguide provides good light confinement and thus low loss in guiding light due to the high refractive index of silicon. The ideal silicon waveguide is shown in Fig. 4.4. The refractive index of silicon core is $n_c = 3.47$ in the C and L communication bands. The cladding of the silicon waveguide can either be silicon dioxide ($n_s = 1.46$) or air ($n_s = 1$). The red curve in Fig. 4.4 shows the single mode energy distribution, where most of the energy is confined in the core while decays exponentially at the edge.

In nano-silicon-photonic circuits, the waveguides are designed as 450 nm wide because of low loss (3 dB/cm) while maintaining single mode transmission. 220-nm or 340-nm thick is chosen based on mechanical stability. The thickness has minimal influence over the transmission mode because only TE mode is supported and transmitted. The simulations results of electrical field distribution for both TE and TM modes are shown in Fig. 4.5. The electrical field drops sinusoidally when it approaches the edge and decays exponentially at the cladding layer. The exponentially decayed evanescent wave is of particular interest for various applications, as it provides an interesting interaction field for energy transfer. The electric field shows discontinuities at the edge due to high refractive index contrast.

Fig. 4.5: Transverse modes in a silicon waveguide: (a) TE and (b) TM modes.

Fig. 4.6: Schematic illustration of the fundamental mode in a slab waveguide.

To characterize the modes in rectangular waveguide, the formation of fundamental mode in the slab waveguide is studied, as shown in Fig. 4.6. The slab waveguide, also called planar waveguide, consists of three layers of materials of refractive indices n_s , n_c and n_s , extending infinitely in the direction parallel to their interfaces. The middle layer has a thickness of $2a$, while top and bottom layers are semi-infinite in thickness. There is only one intensity maxima in the x -direction of the fundamental mode and there are three important parameters to characterize the mode: the transversal wave factor k , the longitudinal wave factor β , and the attenuation coefficient γ . The transversal electrical field (E_y) distribution in the core and cladding layer is defined as $A\cos(kx)$ and $A\cos(ka)e^{-\gamma(x-a)}$, respectively, where A is the maximum electrical field intensity and the normal electric field (E_y) is continuous at the boundary.

The mode in the rectangular waveguide can be treated as the superposition of fundamental modes of two perpendicular slab waveguides. For a symmetric rectangular waveguide, the fundamental mode is described as E_{11}^x and E_{11}^y , as the magnetic field is zero along the x - and y -directions, respectively. In this chapter, only E_{11}^x is characterized since $|E_x| \gg |E_y|$.

In order to solve the propagation properties of E_{11}^x mode, the wave equation is obtained for $H_x = 0$ as [189]

$$\frac{\partial^2 H_y}{\partial x^2} + \frac{\partial^2 H_y}{\partial y^2} + (k^2 n^2 - \beta^2) H_y = 0 \quad (4.1),$$

where k is the transversal wave factor, n is the refractive index of core and β is the longitudinal wave factor.

The magnetic field distribution of fundamental E_{11}^x can be characterized by

$$H_y = \begin{cases} A \cos(k_x x) \cos(k_y x) & (|x| < a, |y| < d) \\ A \cos(k_x a) e^{-\gamma_x(x-a)} \cos(k_y x) & (|x| > a, |y| < d) \\ A \cos(k_x x) e^{-\gamma_x(x-a)} \cos(k_y d) & (|x| < a, |y| > d) \end{cases} \quad (4.2),$$

where A is the electrical field amplitude. By applying the boundary condition where the electrical field is continuous at $x = a$ and the magnetic field is continuous at $y = d$, the following dispersion equations are obtained as

$$\begin{cases} \tan(k_x a) = \frac{n_c^2 \gamma_x}{n_s^2 k_x} \\ \tan(k_y d) = \frac{\gamma_y}{k_y} \end{cases} \quad (4.3).$$

The transversal wave numbers are expressed as

$$\begin{cases} \gamma_x^2 = k_0^2 (n_c^2 - n_s^2) - k_x^2 \\ \gamma_y^2 = k_0^2 (n_c^2 - n_s^2) - k_y^2 \end{cases} \quad (4.4),$$

where k_0 is the wave number in vacuum. By solving the equations, both transmission coefficients can be solved and the longitudinal wave factor β is therefore defined as

$$\beta^2 = k_0^2 n_c^2 - (k_x^2 + k_y^2) \quad (4.5).$$

To measure the overall delay of the light beam in the waveguide, the effective refractive index n_{eff} is related with the longitudinal wave factor β and wave number in vacuum k_0 as

$$\beta = n_{eff} \cdot k_0 \quad (4.6).$$

The effective refractive index can be simulated by MODE solver of Lumerical, and the longitudinal wave factor can therefore be simulated for any structure. The transversal wave vector k and attenuation coefficient γ can therefore be expressed as

$$k = k_0^2 n_c^2 - \beta^2 \quad (4.7)$$

and

$$\gamma = \beta^2 - k_0^2 n_s^2 \quad (4.8)$$

Both the longitudinal modes and transverse modes can be selectively supported in waveguide by varying the waveguide parameters such as width, height and the refractive indices of the core and cladding.

The evanescent wave is of particular interest for opto-mechanical coupling and energy transfer. The confinement factor Γ , which measures the energy level confined in the core, is defined as the fraction of power in the waveguide core, and can be expressed as

$$\Gamma = \frac{\gamma a + \sin^2(ka)}{\gamma a + 1} \quad (4.9)$$

The confinement is poor for narrow waveguides, which means that more energy is transmitted in the cladding as evanescent wave. High propagation losses are expected when the confinement is poor, while this is undesired for a normal waveguide, but in this case, this is useful for the optical design of waveguide based VOA and optomechanical actuator which use and benefit from an enhanced evanescent wave.

In summary, the rectangular waveguide is the basic element of nano-silicon-phonic circuits, where light is confined within the waveguide, with low loss and low dispersion. The transmission mode in the waveguide structures can be designed by changing the thickness or width. The evanescent wave at the cladding layer provides an efficient way for optomechanical coupling and energy transfer, and it can also be enhanced by waveguide design.

4.2.2 Optical directional coupler

A waveguide directional coupler is used to couple light from one waveguide to the other through evanescent wave coupling. The basic structure of the directional coupler is shown Fig. 4.7(a).

The optical direction coupler consists of two waveguides that are very close to one another, so that the optical energy can transfer via evanescent waves from one waveguide to the other and vice versa. The energy in one waveguide can be fully coupled into the other waveguide with the coupling length of L_c as shown in Fig. 4.7(a). L_c is related to the coupling coefficient κ which can be expressed as

$$L_c = \frac{\pi}{2\kappa} \quad (4.10)$$

The energy flow in the directional coupler as a function of the gap g is shown in Fig. 4.7(b). Energy is gradually transferred from the left waveguide to the right waveguide and completely coupled after a critical coupling length. The coupling coefficient κ can be characterized by either the mode equation or the mode superposition.

Fig. 4.7: (a) Schematic of waveguide the directional coupler and the energy flow along propagation direction, (b) electrical-field distribution at different propagation distances.

For a weakly coupled waveguide coupler, the mode coupling coefficient is defined as [190]

$$\kappa = \frac{\sqrt{2\Delta}}{a} \frac{(k_x a)^2 (\gamma_x a)^2}{(1 + \gamma_x a) v^3} \exp(-\gamma_x g) \quad (4.11),$$

where Δ is relative refractive index difference, defined as $\Delta = \frac{n_c^2 - n_s^2}{2n_c^2}$ and v is the normalized frequency defined as $v = kn_c a \sqrt{2\Delta}$. The calculated coupling coefficient of the waveguide directional coupler versus the gap g is shown in Fig. 4.8. The coupling coefficient decays exponentially as the gap increases due to the exponentially decaying evanescent wave. The decay rate is higher for a smaller gap g and a narrower waveguide because of stronger evanescent wave interaction. Therefore, light is coupling more efficiently (shorter critical coupling length) from one waveguide to the other when the waveguide width is narrower and the gap between waveguides is smaller.

The mode coupling of the directional coupler can also be analyzed by interference phenomena between the even and odd modes, which is also named mode

Fig. 4.8: Coupling coefficient versus the gap between signal waveguide and coupler waveguide of directional coupler.

Fig. 4.9: Transmission intensity of both original and coupler waveguide at different coupling length.

superposition. When the first mode is an even mode and the second mode is an odd mode, the electrical field can be expressed as [190]

$$E(x, z) = E_e(x) \exp(-j\beta_e z) + E_o(x) \exp(-j\beta_o z) \quad (4.12),$$

where E_e and E_o denote the electrical fields for the even and odd modes, respectively; and β_e and β_o denote the propagation constants of the even mode and odd modes, respectively.

The longitudinal wave factor of the even mode β_e , and that of the odd mode β_o can be simulated using the MODE solver of Lumerical. Thus, the coupling length and coupling coefficient can be expressed as

$$L_c = \frac{\pi}{\beta_e - \beta_o} \quad (4.13),$$

and

$$\kappa = \frac{\beta_e - \beta_o}{2} \quad (4.14).$$

Both mode equation and mode superposition methods are based on the mode properties of waveguides, which can be derived by numerical simulation. The coupling coefficient is related to the geometry of the waveguide and the gap. When the gap is constant, the coupling coefficient remains unchanged and the light intensity at original waveguide (WG) drops sinusoidally as shown in Fig. 4.9. Light is coupled from original waveguide to coupled waveguide as light transmit along the propagation direction (L). The critical coupling length is 27.5 μm when the gap is 250 nm and the waveguide width is 400 nm.

The optical power at the end of the original waveguide is

$$P_{original} = P_1 \sin^2(\kappa z) \quad (4.15),$$

where P_1 is the input power and z is the coupling length. The results of simulations down using Lumerical MODE for the light coupling between the waveguides and the energy distribution can be simulated are shown in Fig. 4.10. Two waveguide width values, 400 nm and 350 nm, and two inter-waveguide gap values, 150 nm and 200 nm, are simulated and presented. As indicated clearly in Fig. 4.10, light needs smaller critical coupling length to completely couple from one waveguide to another for narrower waveguide (Fig. 4.10 (a) & (b)) and smaller gap (Fig. 4.10 (a) & (c)).

Fig. 4.10: Light intensity along propagation distance for two identical coupled waveguides, at different values of waveguide width w and inter-waveguide gap g : (a) $w = 400$ nm, $g = 200$ nm, (b) $w = 350$ nm, $g = 200$ nm, (c) $w = 400$ nm, $g = 150$ nm and (d) $w = 350$ nm, $g = 150$ nm.

In summary, the coupling coefficient is higher for the narrower waveguide because more energy is transmitted along the waveguide as evanescent wave. It is also noted that light confinement is poorer for the narrower waveguide, which may induce more losses. The directional coupler with 350-nm-wide waveguides and 200-nm gap is demonstrated, which is designed to maintain high coupling efficiency and to reduce the coupling loss.

4.2.3 Optical actuator controlled by wavelength detuning

The optical actuator can be controlled by tuning the Q-factor of the ring resonator, as it was discussed in Chapter 3. Beside the Q-factor modulation, another effective control mechanism is by means of single laser detuning, which is realized by tuning the optical energy in the ring resonator through wavelength detuning.

In the optical actuator, the doubly-clamped silicon beam is located in the immediate vicinity of the ring resonator and its movement can have effects on the optical energy in the ring resonator. The energy of the single wavelength light trapped inside the ring resonator can be expressed as

$$U = -\frac{2\gamma_e P_{optical}}{\Delta(x)^2 + \gamma^2} \quad (4.16),$$

where γ_e is the external damping due to waveguide-ring coupling, $P_{optical}$ is the input optical power, γ is the total damping coefficient and $\Delta(x)$ is the laser detuning, which is defined as

$$\Delta(x) = \omega(x) - \omega_c = 2\pi c \left(\frac{1}{\lambda(x)} - \frac{1}{\lambda_c} \right) \quad (4.17),$$

where $\omega(x)$ and ω_c are the resonance frequencies of the ring resonator and the control light, respectively; and $\lambda(x)$ is the resonance wavelength of the ring resonator, which is related to the displacement of optical force driven arc actuator through optomechanical coefficient g_{om} according to the relation

$$\lambda(x) = \lambda_0 + \int g_{om}(x) dx \quad (4.18),$$

where λ_0 is the resonance wavelength with no displacement. The wavelength detuning is defined as

$$\delta = \lambda_c - \lambda_0 \quad (4.19),$$

where λ_c is the wavelength of control light.

When a red-detuned control light ($\delta > 0$) is coupled into the ring resonator, the optical force is generated and applied over the doubly-clamped silicon beam. The optical gradient force is related not only to the control light, but also to the displacement of the arc actuator. The optical gradient force can therefore be expressed as

$$F_{optical}(x) = -\frac{2\gamma_e P_{optical}}{n_{eff}(x)} \frac{g_{om}(x)}{\Delta(x)^2 + \gamma^2} \quad (4.20),$$

where n_{eff} is the effective refractive index. The optical forces versus the actuation distance for various wavelength detuning values are shown in Fig. 4.11.

The arc actuator is influenced by the optical gradient force and the mechanical spring force. The mechanical spring force acts in the opposite direction of the optical gradient force, which pulls the actuator back to its original position. The mechanical spring force can be expressed as

$$F_{mechanical} = K\Delta g \quad (4.21)$$

Fig. 4.11: The mechanical spring force (black line) and the optical gradient force (color lines) for various wavelength detuning values.

where K is the spring constant and Δg is the displacement of the arc actuator. The mechanical spring force is also plotted in Fig. 4.11 (black line). The spring constant is simulated by COMSOL and has a value of 0.107 N/m.

The curve of the optical gradient force as a function of the actuation distance has a Lorentzian shape when the mechanical force is linear, as shown in Fig. 4.11. It can be noted that the optical gradient force increases at large actuation distances, even though the power of the control light remains constant. This is because the optical gradient force between the arc actuator and the ring resonator increases exponentially when the gap becomes smaller. The optical gradient force and mechanical spring force are balanced at multiple positions as indicated by cross points A, B, and C.

Fig. 4.12: Simulated actuation distance versus the wavelength detuning when the control light is 10 mW.

When the control light with the wavelength detuning of 0.1 nm is pumped into the ring resonator, the two forces are balanced at “A” and the actuation distance is approximately 48 nm. When the wavelength detuning is increased to 0.5 nm, the displacement of the actuator is increased to 93 nm as indicated by “B” and a new balance position is reached. When the wavelength of the control light is further increased, the actuator is pulled even closer towards the ring resonator. The maximum displacement reaches 131 nm as indicated as point “C”.

The actuation distance of the actuator at various control light wavelength detuning is simulated as shown in Fig. 4.12. When the detuning is zero, the actuator is in its initial position and the actuation distance is at 26.7 nm. The actuator is more sensitive to wavelength detuning at larger gap values. The actuation distance can reach up to 149.87 nm when the wavelength detuning is 2.5 nm.

In summary, the optomechanical actuator controlled by wavelength detuning provides a larger actuation distance than that driven by Q-factor modulation. The main reason is that in wavelength detuning, the wavelength of control light is always close to the resonance wavelength and the light energy can be pumped continuously into the ring resonator, which is helpful to construct an efficient optical attenuator.

4.2.4 Optical attenuation via waveguide directional coupler

The waveguide directional coupler consists of a coupler waveguide and a signal waveguide. The coupler waveguide is designed as part of the arc actuator. When the coupler waveguide is moving along the x direction, it changes the gap between the coupler waveguide and the signal waveguide and consequently modify the coupling coefficient κ so that the signal light is attenuated.

The attenuation of the optical power in the signal waveguide is associated with several parameters such as the gap g , the waveguide width W and the wavelength length L , as discussed in Chapter 4.2.2. Fig. 4.13 shows the simulation results of a 20- μm -long waveguide coupler, with different gaps and waveguide widths. The total light intensity in the original waveguide and the coupled waveguide remains constant in the simulation. The energy couples more efficiently for smaller gaps and narrower waveguides.

(a)

(b)

Fig. 4.13: Normalized transmission of 20- μm -long directional coupler versus gap when the waveguide widths are (a) 400 nm and (b) 350 nm.

The optical power attenuation A is defined as the power loss at the original signal waveguide, which is due to the coupled energy in the coupler waveguide:

$$\begin{aligned} A &= \frac{P_{input} - P_{original}}{P_{input}} = 1 - \sin^2(\kappa(g) \cdot L) \\ &= 1 - \sin^2(C \cdot \exp(-\gamma g) \cdot L) \end{aligned} \quad (4.22),$$

where γ is the attenuation coefficient, L is the coupling length, and C is the coupling constant given by

$$C = \frac{\sqrt{2\Delta}}{a} \frac{(k_x a)^2 (\gamma_x a)^2}{(1 + \gamma_x a) v^3} \quad (4.23),$$

where Δ is relative refractive index difference, k is the propagation constant, and v is the normalized frequency.

Fig. 4.14: Simulated signal attenuation versus the actuation distance.

The attenuation increases sinusoidally as the actuation distance increases, as shown in Fig. 4.14. The waveguides are 350 nm in width and the coupler waveguide is 20 μm in length. When the initial gap g is around 188 nm, the energy is fully coupled back to the original waveguide from the coupler waveguide and the power attenuation is 0. When the actuation distance is increased to 67 nm, the gap g is 255 nm, the energy is fully coupled to the coupler waveguide and the attenuation is 1.

The power of signal light is attenuated by decreasing the coupling coefficient of waveguide directional coupler. And the coupling coefficient is decreased by increasing the gap between the coupler waveguide and the signal waveguide, which is realized by optomechanical actuator.

4.2.5 Design of VOA array

A VOA array is designed to realize broadband light attenuation by using the wavelength dependency of the directional coupler. The schematic of the VOA array is shown in Fig. 4.15. It can be seen that it consists of more ring resonators, each with a slightly different resonance wavelength, and all cascaded along the signal waveguide. Broadband signal is coupled into the waveguide at the signal input port. The light with its wavelength overlapping with the resonance wavelength of one ring resonator of the VOA array is directed into the waveguide adjacent to that ring resonator. The control lights are coupled into each actuation ring resonator from the control input ports, which are controlled separately to realize separate control of each unit cell of the VOA array. By controlling the wavelength at each control input port, the attenuation of that specific wavelength in the single light can be controlled.

The actuation distance of the coupler waveguide is limited by the travel range of the nano optomechanical actuator. Furthermore, the coupling length of the directional coupler is also limited due to internal stress and stiction during the release processes. In order to improve the attenuation, one single device can be replaced by a VOA series array which integrate several VOAs to accumulate the attenuation effects. The series connected VOA array architecture is shown in Fig. 4.16 (a).

The signal light is transmitted inside the signal waveguide and attenuated as part of the signal is coupled into the coupler waveguide. The signal light is coupled multiple times in the series connected VOAs and the optical power at the output port can be expressed as

$$P_{out} = P_{in} \cos^{2 \cdot N} (\kappa(\Delta g) \cdot L) \quad (4.24),$$

Fig. 4.15: Schematic of VOA array with ring resonator based wavelength demultiplexer.

where $\kappa(\Delta g)$ is the coupling coefficient, L is the coupling length and N is the number of the cascaded VOA elements. The transmitted power of the series VOA array at various gaps are shown in Fig. 4.16 (b). It can be shown that the VOA array with more elements can have the same attenuation effects at smaller actuation distance. However, coupling losses can be high when too many unit cells are integrated.

Fig. 4.16: (a) Architecture of series VOA array, and (b) transmission of signal when the number of cascaded VOAs is 1, 4 and 20.

4.3 Fabrication of NEMS VOA

The NEMS VOA is fabricated using the nano-silicon-phonic fabrication processes detailed previously in section 3.3. The waveguides and ring resonators are fabricated by a one-time RIE process using SiO_2 as hard mask. After a 2- μm -cladding oxide deposition, the narrower trench is etched first, followed by Al_2O_3 deposition. The window is then defined by lithography followed by Al_2O_3 etch. After the second trench etch, the devices are released through HF vapor etching process.

The SEM images of the fabricated NEMS VOA are shown in Fig. 4.17, with the arc actuator and coupler waveguide highlighted in yellow. Different types of VOA were designed with different coupling lengths. The window had a size ranging from $20\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$ to $40\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$, each used in different directional couplers.

The VOA arrays were also fabricated, as shown in Fig. 4.18. Two VOAs can be optical connected serially to further enhance the attenuation. A large scale array is also possible based on the current fabrication technology.

(a)

(b)

Fig. 4.17: SEM images of two different types of VOA designs with (a) single output port and (b) dual-output ports.

Fig. 4.18: SEM image of a VOA series array consists of two unit cells of VOA.

4.4 Experimental results and discussions

4.4.1 Experimental setup

The NEMS VOAs are measured using the setup shown in Fig. 4.19. Two input fibres are aligned with the control waveguide and signal waveguide, respectively, such that both the control light and signal light can be coupled into the device. The control light from a tunable laser source (Santec TCL510) is amplified by the EDFA (Amonics EDFA-CL-27) and passes through a 98/2 splitter. 2% of light is detected by the photo detector (PD) to monitor the power level while most of the energy is

Fig. 4.19: Experimental setup for VOA characterization.

coupled into the control waveguide. The light is detected by an optical spectrum analyzer (OSA) (Yokogawa AQ6370C) for wavelength and power monitoring. The signal light from the tunable laser source is coupled into the signal waveguide through a 98/2 splitter and monitored by the PD. By tuning the wavelength of the control light, the detector at the end of the signal waveguide can measure the attenuation of the signal light

4.4.2 Actuation distance via wavelength detuning

The performance of the doubly-clamped silicon beam actuator has been characterized and this section presents the measured results and their discussions. When the wavelength detuned control light is coupled into the actuation ring resonator, the transmission spectra of the ring resonator with different control light detuning is collected and monitored by the optical spectrum analyzer. The measurement results are shown in Fig. 4.20.

Fig. 4.20: Transmission spectra of the ring resonator versus control laser wavelength.

Two resonance wavelengths of the ring resonator were used to investigate the actuation process. Two resonance wavelengths, 1580.78 nm and 1585.53 nm, are observed initially as indicated by the arrow in Fig. 4.20. The resonance wavelength at 1580.78 nm is used for control light characterization, while the resonance wavelength at 1585.53 nm is for actuation distance characterization.

The wavelength of the control light is tuned from 1585 nm to 1588 nm while the resonance wavelengths are measured. When the wavelength of the control light is 1585 nm, the control light is not coupled into the ring resonator, the actuator is at rest in its default state and the resonance wavelength is 1580.78 nm. When the wavelength of the control light is increased to 1585.5 nm, light is coupled into the ring resonator, thus the actuator is pulled towards the ring resonator and the resonance wavelength is increased to 1580.94 nm. When the wavelength of the control light is

increased to 1586 nm, the resonance wavelength increases to 1581.36 nm and the actuation distance is increased further. When the wavelength of control light is increased to 1588 nm, the resonance wavelength reaches 1583.28 nm. The optical gradient force cannot overcome the mechanical spring force when the wavelength of the control light is increased further and the actuator is pulled back to its original position.

Based on the optomechanical effects, the resonance wavelength shift is related to the mechanical displacement of the doubly-clamped silicon beam, which can be measured by the optomechanical coefficient g_{om} . By measuring the resonance wavelength shift of the ring resonator, the actuation distance of the actuator can be calculated. The actuation distance of the actuator versus the wavelength detuning of control light is summarized in Fig. 4.21.

Fig. 4.21: Actuation distance of the doubly-clamped silicon beam actuator versus wavelength detuning δ .

The actuation distance is not zero at zero wavelength detuning, because even if the control light wavelength is slightly less than the resonance wavelength of the ring resonator, the control light can still be coupled into the ring resonator and induces the mechanical deformation of the doubly-clamped silicon beam. Therefore, when the wavelength of the control light is equal to the resonance wavelength of 1585.53 nm, the actuation distance is equal to 48 nm.

Compared to the Q-factor modulation based NEMS actuator, this actuator controlled by wavelength detuning has larger actuation distance because light can be continuously pumped into the ring resonator and thus displacing the actuator at different equivalent positions. The actuation distance can reach up to 150 nm when the wavelength detuning δ is close to 2 nm.

4.4.3 Characterization of VOA

The NEMS VOA was characterized and experimentally tested. Initially, the VOA was characterized by pumping lights with different wavelengths without any actuation. The normalized transmission of the signal light at different wavelength was measured and the obtained results are shown in Fig. 4.22. The sinusoidal experimental data curve agrees well with the simulation results.

By fixing the signal light wavelength, the intensity of the signal light versus different wavelength detuning is recorded, and the gap between the coupler waveguide and signal waveguide is calculated based on Fig. 4.21. Light intensity at the output port of signal waveguide for two different VOA designs are shown in Fig. 4.23 and Fig. 4.24.

Fig. 4.22: Normalized transmission of single light with different wavelengths.

Fig. 4.23: Normalized transmission of signal light versus gap in the directional coupler when the waveguide width is 400 nm and coupling length is 15 μm .

The directional coupler of the first VOA design has a coupling length of 15 μm , while the waveguide width is 400 nm. The normalized transmission of the signal light is monitored and plotted at various gaps of the directional coupler, as shown in Fig. 4.23. The red line shows the simulation results and blue dots are the experimental results. Light intensity drops from 0.75 to 0 when the gap is increased from 200 nm to 250 nm. The light intensity increases when the gap is increased beyond 250 nm. Therefore, the transmission of such VOA design is from 75% to 0% by changing the coupling coefficient.

The directional coupler of the other VOA design has a coupling length of 20 μm , while the optimized waveguide structure is 350 nm in width. The normalized

Fig. 4.24: Normalized transmission of signal light versus gap in the directional coupler when the waveguide width is 350 nm and coupling length is 20 μm .

Fig. 4.25: Measured attenuation of the signal light as a function of the actuation distance.

transmission of the signal light is shown in Fig. 4.24. Both the signal waveguide (original WG) and the coupler waveguide (coupler WG) signals are recorded. The transmission in the signal waveguide increases till the gap between waveguides reaches 220 nm. Thereafter, the light intensity drops to 20% when the gap is close to 275 nm. The attenuation of signal light is calculated and shown in Fig. 4.25.

The light intensity in the original waveguide is maximum hence the attenuation is 0 when the gap is 220 nm. As the actuation distance increases, the signal light drops and the attenuation increases. Theoretically, attenuation can reach 1 when the gap between waveguides is 300 nm. However, in practice, the attenuation can only reach a maximum value of 0.8, as shown by the experimental data because the actuation distance of the optical actuator is limited.

4.5 Summary

In conclusion, a NEMS VOA has been experimentally demonstrated. The VOA was realized via a waveguide based directional coupler. The gap between the directional coupler was controlled via an optical force driven actuator. The doubly-clamped silicon beam of the actuator was controlled by tuning the wavelength of the control light. As a results, the signal light can be attenuated to 20% of its initial value, as shown by experiments. A VOA array is also designed and characterized. It can improve the attenuation effects but will also introduce more losses. The NEMS VOAs have the merits of small dimension, low power consumption and good capability for all optical integration, making then a good candidate for future applications in silicon photonics circuits and optical communication devices.

The key original points of the proposed NEMS VOA are summarized as follow,

- a) This is for the first time a waveguide-based VOA controlled by an optical force-driven actuator is demonstrated. The optical attenuation is realized by tuning the gap between the waveguides in the directional coupler. The optical force driven actuator is integrated with the directional coupler, to realize an all-optical and high speed tuning.
- b) The nano actuator is controlled by tuning the wavelength of the control light. By means of wavelength detuning, light can be continuously pumped into the ring resonator during actuation processes. The wavelength tuning method can realize even larger actuation distances compared to the Q-factor modulation-driven actuator, and therefore provides a better signal attenuation.

- c) The VOA is realized using a waveguide based directional coupler. The optical coupling between waveguides is an effective energy coupling method compared to split waveguide coupling and traditional fibre split coupling. The coupling efficiency can theoretically reach more than 90%. Furthermore, the CMOS compatible silicon photonics fabrication technology provides more freedom in the VOA design, allowing the designer to choose different values for the waveguide width and coupling length.
- d) The VOA can be easily expended into a VOA array. Silicon photonics provides a simple design platform so that VOAs can be easily integrated together without introducing any extra fabrication complexity. A VOA array can provide better attenuation performance compared to a single VOA.

CHAPTER 5

OPTOMECHANICAL MEMORY

This chapter presents a bistable optomechanical memory, which employs a ring resonator to generate an optical gradient force over a doubly-clamped silicon beam. The doubly-clamped silicon beam shows bistability due to the nonlinearity of the optical gradient force, as it has two stable positions between which it can be switched by controlling the light power transmitted inside the ring resonator. First, the theoretical model of the optical gradient force induced bistability is analysed, followed by presenting the operation of the optical memory and the architecture of the optical memory array. The fabrication of the optomechanical memory is then detailed. Finally, the experimental setup and testing results are shown and discussed, together with the time response of the optical memory.

5.1 Design of optomechanical memory

Fig. 5.1: Schematic of optomechanical memory.

The optomechanical memory consists of a ring resonator, a doubly-clamped silicon beam and a bus waveguide, as shown in Fig. 5.1. Light can be coupled in and out of the ring resonator through the bus waveguide. An optical gradient force is generated between the ring resonator and the doubly-clamped silicon beam. The ring resonator is supported by a rib structure and released from the substrate to reduce loss. The doubly-clamped silicon beam can have two stable positions generated by the nonlinearity of the optical gradient force, which are therefore identified as memory states.

The schematic of the 200-nm-wide doubly-clamped silicon beam is shown in Fig. 5.2. The outer radius R is $20.4\ \mu\text{m}$. The silicon beam is clamped by two anchors, so that it can move along the x -direction but remains stable in the z - and y -directions. The gap between the silicon beam and the ring resonator is 200 nm.

Fig. 5.2: Schematic illustration of the ring resonator and the mechanical arc actuator.

The diameter Φ of the ring resonator is 40 μm . The waveguide of the ring resonator is 450 nm wide and supported by the rib structure. The rib structure is only 80 nm in thickness, such that it has negligible influence over the electrical field distribution in the ring resonator. With the support of the rib, the ring resonator can therefore be totally released, such that the whole ring resonator is exposed to air and minimizes the loss due to partial release.

The operation of memory requires two light beams to realize write and read processes. A red-detuned control light, known as ‘write’ light, is coupled from the bus waveguide into the ring resonator. Thereafter, the optical gradient force is conducted between the ring resonator and the silicon beam, which pulls the silicon beam towards the ring resonator. The signal light, known as ‘read’ light, is also coupled into the ring resonator and sensed at the output port. The wavelength of the

‘read’ light overlaps with the resonance wavelength of the ring resonator. For the ‘write’ beam, the power of the light injected through the waveguide is increased 1 mW to 3 mW. Consequently, the optical gradient force is increased and the mechanical arc moves towards the ring resonator along the x direction. The displacement Δx of the silicon beam results in the change in the effective refractive index Δn_{eff} of the ring resonator, causing a red shift of the ring resonance wavelength $\Delta \lambda_r$. The ‘read’ light can be transmitted through the waveguide since its wavelength is no longer overlapped with the resonance wavelength now. The displacement of the silicon beam can affect the transmission of the ‘read’ light by altering the resonance wavelength of the ring resonator. Therefore, by pumping a red-detuned write light with different power level, the transmission of the ‘read’ light can be controlled and the doubly-clamped silicon beam can be switched between an on- and off-state.

The deformation of the doubly-clamped silicon beam is the result of two balanced forces: the optical gradient force and the mechanical restoring force. The nonlinear optical gradient force interacts with the linear mechanical spring force and

Fig. 5.3: Schematic illustration of memory states versus write light power.

results in the bistability of the doubly-clamped beam. The two stable positions of the silicon beam can be switched by increasing or decreasing the write light power, as shown in Fig. 5.3. A short pulse of write light at power of P_I can switch the memory state to “1” while maintains this status at the power P_m . Meanwhile, dropping the write light power to P_0 can switch the memory state to “0”.

5.2 Theoretical analysis and numerical simulation

5.2.1 Optical gradient force induced bistability

Optical force enabled actuator has been realized through the control of either Q-factor modulation or wavelength detuning. The optical gradient force shows high nonlinearity due to the exponentially decaying evanescent wave, as discussed in Chapters 3 and 4. In this chapter, the doubly-clamped silicon beam actuated by the optical gradient force shows bistability by controlling the power of a red detuned control laser.

The deformation of the doubly-clamped silicon beam is determined by two forces: the optical gradient force and the mechanical spring force, as shown in Fig. 5.4. The green line is the mechanical spring force, which increases linearly as the deformation of the silicon beam increases. The optical gradient force is generated by light with a single wavelength light and exhibits Lorentzian-shaped curves for

Fig. 5.4: Mechanical spring force and optical gradient force over the doubly-clamped silicon beam.

different deformations of the doubly-clamped silicon beam, while the maximum force happens when the resonance wavelength coincides with the wavelength of the input light. The Lorentzian curves show the optical gradient force at different power levels when the wavelength detuning is $\delta = 0.15$ nm. The wavelength detuning is defined as

$$\delta = \lambda_w - \lambda(0) \quad (5.1),$$

where λ_w is the wavelength of the ‘write’ light and $\lambda(0)$ is the resonance wavelength of the ring resonator at zero deformation. The generated optical force by the single wavelength laser λ_w can be expressed as

$$F_{optical}(x) = -\frac{2\gamma_e P_{optical}}{n_{eff}(x)} \frac{g_{om}(x)}{\Delta(x)^2 + \gamma^2} \quad (5.2),$$

where γ_e is the external damping due to waveguide-ring coupling, $P_{optical}$ is the light power, n_{eff} is the effective refractive index, g_{om} is the optomechanical coupling coefficient, γ is the total damping coefficient and $\Delta(x)$ is the laser detuning which is defined as

$$\Delta(x) = \omega(x) - \omega_w = 2\pi c \left[\frac{1}{\lambda(x)} - \frac{1}{\lambda_w} \right] \quad (5.3),$$

where $\lambda(x)$ is the resonance wavelength of the ring resonator, which is related to the effective refractive index and therefore the deformation of the doubly-clamped silicon beam.

The optical gradient force and mechanical spring force has multiple cross points, which means that the optical gradient force is equal to the mechanical spring force. When the light power is 1 mW, there is only one cross-point (named “A”) close to the origin, which is the only stable position and the deformation is approximately 2.48 nm. When the light power is 3 mW, there is one cross-point (named “D”) far from origin, which is also the only stable position with 30.9-nm deformation. When the light power is 2 mW, there are three cross-points, and two of them (named “B” and “C”) are in a stable position. The “E” is not stable because a small disturbance can induce a net force whose direction is towards either B” or “C”. Therefore, the doubly-clamped beam can rest at either position when the ‘write’ light is at 2 mW. In one position, the beam one has a 6.9 nm deformation, while in the other position is has a 25.3 nm deformation.

Fig. 5.5: Simulated deformation of doubly-clamped silicon beam versus light power when the wavelength detuning $\delta = 0.15$ nm.

By tuning the light power, the silicon beam can be transferred between the two stable deformations. The bistable hysteresis curve is shown in Fig. 5.5. When the wavelength detuning is 0.15 nm, the deformation increases from 0 to 10.7 nm while the optical power increases from 0 mW to 2.25mW. When the optical power increases further, the deformation of the silicon beam “jumps” to 27.5 nm and increases further as power increases. When the power decreases from 3 mW, the deformation decreases continuously until 23.1 nm when the power is 1.9 mW. Further decreasing the power induces another abrupt change in the deformation, which is from 23.1 nm to 6.3 nm. The hysteresis curve shows that the deformation of the silicon beam can be controlled by tuning the light power.

Fig. 5.6: Simulated deformation of doubly-clamped silicon beam versus optical power with different wavelength detuning.

However, the doubly-clamped silicon beam may lose bistability under different wavelength detuning conditions. The doubly-clamped silicon deforms in different paths at different wavelength detuning, as shown in Fig. 5.6. When the wavelength detuning is 0.1 nm, the doubly-clamped silicon beam shows only one stable position at all times. Therefore, the doubly-clamped silicon beam shows no bistability. When increase the wavelength detuning is increased to 0.125 nm, there is only a very narrow region that the doubly-clamped silicon beam shows two stable positions, and the transition curve is close to a vertical line. This is the critical condition where the doubly-clamped silicon beam starts to show bistability. When the wavelength detuning is increased to 0.175 nm, the bistable region is further broadened. Therefore, besides the write light power, the wavelength is critical to control the bistability of the doubly-clamped beam.

The doubly-clamped silicon beam shows bistability when it is deformed by the optical gradient force. But such bistability is not due to the mechanical properties of the doubly-clamped silicon beam, but caused by the non-linear properties of the optical gradient force. The bistability of the doubly-clamped silicon beam can therefore be manipulated by controlling the light wavelength and power, providing more freedom in the operation of the optomechanical memory.

5.2.2 Optical memory via opto-mechanical effects

The deformation of the doubly-clamped silicon beam has a “feedback action” over the ring resonator’s resonance wavelength due to optomechanical effects. The transmission of the read light is therefore different at the two stable positions of the doubly-clamped silicon beam.

Fig. 5.7: Schematic illustration of optical force induced bistability.

At different ‘write’ light power, the optical gradient force is balanced by the mechanical spring force, as shown in Fig. 5.7. There are two stable positions (“A” and “B”). When the deformation is close to zero, the difference between “A” and “B” is quite small, and the deformation for both positions is around Δx_0 , while the resonance wavelength of the ring resonator is around $\Delta \lambda_0$. The other two stable positions are at “C” and “D”. When the deformation is around Δx_1 , the resonance wavelength of the ring resonator is around $\Delta \lambda_1$. Therefore, in the optical domain, two resonance conditions are associated with different stable positions, named memory state of “0” and “1”, respectively.

The memory states are therefore related to the ‘write’ light power as shown in Fig. 5.8. When the power of the ‘write’ light is changed from the low level (P_0) to the high level (P_1), the stable position is shifted from point “A” to “D”, the wavelength shift is increased from $\Delta \lambda_0$ to $\Delta \lambda_1$ and the memory state is switched from “0” to “1”. When the power is increased from P_0 to P_m , the silicon beam changes from “A” to “B”, while maintaining the resonance wavelength and therefore the memory state. The memory state remains the same when the power is decreased from

Fig. 5.8: Schematic illustration of memory state versus optical power.

Fig. 5.9: Operation demonstration of optomechanical memory

P_1 to P_m while the silicon beam changes from “D” to “C”. The status can either be switched into “0” or “1” by changing the optical power between P_0 and P_1 . The status is maintained if the power is switched to P_m .

The operation of the memory is summarized in Fig. 5.9. The ‘write’ light can switch the memory to “1” with a high power pulse (P_1), and the transmission of the ‘read’ light is high (P_H). The ‘write’ light can switch the memory to “0” with the notch in power (P_0), while the transmission of the ‘read’ light is low (P_L).

The optomechanical memory can realize all optical operations through the optical force actuated doubly-clamped silicon beam. The deformation of the doubly-clamped silicon beam shows bistability, which is induced by the nonlinear optical gradient force.

5.2.3 Architecture of optomechanical memory array

The element of the optical memory design can be easily expanded to a memory array. In optical communications, multiplexing and demultiplexing can combine or split light with different wavelengths into or out of one fibre/waveguide without interference. The proposed architecture of the memory array is shown in Figs. 5.10 and 5.11. With the resonance properties of the ring resonator, the resonance wavelength can be well controlled by redesigning the ring resonator. In the memory shown in Fig. 5.10 (a), four elements show four different resonance wavelengths by

Fig. 5.10: Schematic illustration of: (a) architecture of a memory array which consists of 4 elements, and (b) spectra of ‘write’/‘read’ light and the resonance wavelength.

varying the radius. For each single element, there are two types of the light, write and read light, paired with the resonance wavelengths of the ring resonator as shown in Fig. 5.10 (b). One of the advantages of ring resonator based all-optical memory is its wavelength-dependency, such that each unit cell can be controlled by different wavelengths. Since the spacing of adjacent resonance wavelength of ring resonator can be as small as 0.2 nm, 100 memory unit cells can be integrated in a row within one free space spectral range (20 nm).

Beside the series array design, a matrix type of memory array are also designed, as shown in Fig. 5.11. The 3×3 memory array has two input ports, one is a ‘write’ light port and the other is a ‘read’ light port. The ring resonators are identical in each column, but different in radius for those in the same row. In such case, the

Fig. 5.11: Schematic illustration of the 3×3 memory array with separated ‘write’ and ‘read’ input/output ports.

‘write’ light’s spectra is exactly the same as shown in Fig. 5.10, meaning that 100 channels can be integrated in a row

The memory array can be fabricated with the same fabrication processes used for single element, without adding any complexity. A large scale memory array, such as 128×128 , can also be easily designed and fabricated, which is not easily realized in traditional MEMS mechanical memory.

5.3 Fabrication of optomechanical memory

The optical memory is fabricated by the same previously detailed nano-silicon-photonics fabrication processes using a standard silicon-on-insulator wafer. The waveguide structures have a width of 450 nm and a height of 220 nm. The doubly-clamped silicon beam is designed to be 200 nm wide while the coupling gap between the ring resonator and the silicon beam is 200 nm. The waveguides and ring resonators are patterned by a two-step deep UV lithography and RIE process. The rib structure has a 70-nm silicon slab layer to support the ring resonator. After etching, a 2- μm SiO_2 layer is deposited on the structure layers. A 40-nm Al_2O_3 is deposited and patterned, which is used as the protection film to protect the fixed structures and leave the window area opened for suspended structures. Finally, HF vapour etching selectively undercuts the buried oxide layer in the window area to release the movable structures. The SEM image of the optomechanical memory is shown in Fig. 5.12(a) and the zoomed view of the doubly-clamped silicon beam is shown in Fig. 5.12 (b).

(a)

(b)

Fig. 5.12: SEM images of (a) optomechanical memory element and (b) zoomed view of the doubly-clamped silicon beam.

Fig. 5.13: SEM images of optomechanical memory array.

Besides the single unit cell memory, memory arrays with both series and matrix structure were designed and fabricated, as shown in Fig. 5.13. The radius of the ring resonator varies a little to have different resonance wavelength so that each element has separate control light with no interruption. The foot print of each element is limited to $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$.

5.4 Experimental results and discussions

5.4.1 Experimental setup

Fig. 5.14: Experimental setup for optomechanical memory characterization.

The optomechanical memories were tested using the setup shown in **Fig. 5.14**. Both the ‘write’ and ‘read’ light are coupled into and out of the bus waveguide.

The ‘write’ light from a tunable laser source (Santec TCL510) is amplified by the EDFA (Amonics EDFA-CL-27), followed by a 98/2 splitter. 2% of light is detected by the photo detector (PD) to monitor the ‘write’ light power. 98% of the ‘write’ light is combined with the ‘read’ light from another tunable laser source through the optical coupler. The coupled light is coupled to the bus waveguide through the tapered fibre. After passing through the device, the light is detected by the optical spectrum analyser (Yokogawa AQ6370C) to monitor the transmission spectra.

The power of the ‘write’ light is modulated by tuning the pumping current of the EDFA. At different pumping levels, the transmission of the ‘read’ light is recorded.

Fig. 5.15: Experimental setup for time response measurement of optical mechanical memory.

The time response of the optomechanical memory, the experimental setup is shown in Fig. 5.15. A modulator is connected between the ‘write’ light laser source and the EDFA, which can modulate the power level of the ‘write’ light at high speed. The ‘read’ light is pumped from the other side of the bus waveguide and detected by the PD after passing through the circulator. The power of the ‘read’ light is converted to an electrical signal using the PD and received by the oscilloscope for time domain measurement.

5.4.2 Optical force induced bistability

The bistability of the optical force-actuated doubly-clamped beam was experimentally verified by changing the power of the ‘write’ light. The resonance

wavelength of the ring resonator is related to the deformation of the doubly-clamped silicon beam due to the optomechanical effects, which is simulated by Lumerical and shown in Fig. 5.16. The wavelength shift increases exponentially as the deformation increases because the effective refractive index of the ring resonator is more sensitive at smaller gap. By measuring the resonance wavelength shift of the ring resonator, the deformation of the silicon beam can therefore be calculated.

The high power ‘write’ light is pumped into the bus waveguide and the resonance wavelength shift is measured through the optical spectrum analyzer as shown in Fig. 5.17. The wavelength detuning for the ‘write’ light is 0.25 nm. When the power increases from 1 mW to 6 mW, the wavelength shift is less than 0.05 nm. The turning point is close to 6 mW, where the wavelength shift jumps from 0.05 nm to 0.38 nm. The wavelength shift reduces to 0.275 nm when the power is decreased

Fig. 5.16: Resonance wavelength shift of the ring resonator versus the deformation of the doubly-clamped silicon beam.

Fig. 5.17: Simulation and experimental demonstration of optical force induced bistability when the wavelength detuning is 0.25 nm.

to 2.1 mW. Then, the wavelength shift jumps back to 0.02 nm only when the power is further reduced.

Higher power is needed in order to switch the memory states when the wavelength detuning of the ‘write’ light is larger. But the resonance wavelength shift of the ring resonator is larger compared to the smaller wavelength detuning and the power difference of the ‘read’ light can be further enhanced.

5.4.3 Characterization of optomechanical memory

The optomechanical memory was experimentally tested by modulating the ‘write’ light power. The resonance wavelength that coincides with that of the ‘read’ light was measured such that the power difference can be verified.

Fig. 5.18: Transmission spectrum of the ring resonator versus write light when the wavelength detuning 0.36 nm.

The power of the ‘write’ light is modulated among P_I , P_m and P_0 . The transmission spectra of the optical memory at various power of the red detuned (0.36 nm) ‘write’ light is shown in Fig. 5.18. Initially, the power level is P_m (-8 dBm, the black line), the resonance wavelength is close to 1593 nm, which is the wavelength of the ‘read’ light, the transmission of the ‘read’ light is low, and the memory is in its “0” state. When the power level is increased to P_I (-6 dBm, the red line), the resonance wavelength shifts to 1591.6 nm, the transmission of the ‘read’ light is high and the memory is in its “1” state. After the power level is decreased to P_m again (the blue line), the resonance wavelength maintains its current position with negligible blue shift, and the memory remain at “1”. When the power is further reduced to P_0 (-10 dBm, the pink line), the resonance wavelength reduces to the original position, and the memory state is switched to “0”. The memory state remains at “0” when the

power is changed to P_m (the green line) again. Therefore, the intensity difference of the ‘read’ light between “0” and “1” is approximately 4.7 dB.

The transmission spectrum of the ring resonator when the wavelength detuning of the write light is 0.43 nm is shown in Fig. 5.19. The ‘read’ light wavelength is 1587.87 nm and its modulation depth is 3.5 dB. The memory state can be switched to “1” by increasing the power to 3 dBm and to “0” by decreasing the power to -10 dBm. The memory state can be maintained when the power is -5 dBm.

In summary, the optomechanical memory was experimentally tested with different detuned write light, and the memory states are switched between “0” and “1” by tuning the power of the ‘write’ light. The modulation depth of the ‘read’ light

Fig. 5.19: Transmission spectrum of the ring resonator when the ‘write’ light wavelength detuning 0.43 nm.

can reach up to 4.7 dB, which is also the power level difference between memory states “0” and “1”.

5.4.4 Time response of optical memory

Switching time is an important parameter to characterize the optical memory. The time domain measurement of the optomechanical memory is conducted using the experimental setup shown in Fig. 5.15 and the measured results are shown in Fig. 5.20.

The time response of the optomechanical memory can be defined as

$$I(t) = I_0(1 - e^{-t/\tau}) \quad (5.4),$$

where I is the light intensity and τ is the time constant, which is also defined as the response time. Therefore, the falling/rising time of the optomechanical memory is when the intensity of the read light reaches 63% of its final value. The switching time is restricted by the mechanical movement of the doubly-clamped silicon beam. During measurement, the rising time is 122 ns while the falling time is 111 ns.

Owing to the small dimension, the optomechanical memory has faster response as compared with MEMS mechanical memory, which is normally in microsecond level [175]. To further increase the switching speed of the optical memory, the most direct way is to reduce the size the doubly-clamped beam. However, a smaller size of the doubly-clamped beam means a shorter interaction length for the optical gradient force and therefore smaller force. On the other hand, a

Fig. 5.20: Time response of optomechanical memory.

smaller ring resonator increases the bending loss of light circulating, which can further reduce the Q-factor and the optical force.

5.5 Summary

In summary, an optomechanical memory was designed, simulated and experimentally demonstrated. The optical memory is driven by the evanescent wave coupled optical gradient force. Two stable positions of a doubly-clamped silicon beam, named as “0” and “1”, can be switched by pumping light with different power levels due to the optical force-induced bistability. The proposed optomechanical

memory has the advantages of small dimensions, low power consumption, easy integration and fast response time, and therefore offers great potential for an on-chip all optical light storage in telecommunications.

The novelties of the optomechanical memory are summarized as follows:

- a) This is the first time an optomechanical memory based on optical force induced bistability is demonstrated. Normally, the doubly-clamped beam shows bistability due to the mechanical properties. However, owing to the nonlinearity of the optical gradient force, the optical force actuated doubly-clamped beam exhibits bistability and it can be switched between its two stable positions via light power control. The memory based on such bistability can be well controlled by simply changing the light power.
- b) The optomechanical memory has a simple design with compact size. Compared to the traditional optical memory, the optomechanical memory do not require complex control system or special non-linear materials. The memory can be fabricated using CMOS compatible process, the footprint is less than $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ and silicon is the only structural materials.
- c) The optomechanical memory is an all-optical device. The write and read processes are realized by modulating the optical signals only. The memory states can be switched by altering the power of the red-detuned laser.
- d) The optomechanical memory can be easily expanded to a memory array. Ring resonators with different resonance wavelengths can operate separately without interfering each other. The element of the memory can therefore be easily integrated and aligned to form the memory array.

- e) The optomechanical memory has a fast response time. Due to microcavity and nano scale doubly-clamped beam design, the optomechanical memory states can be switched within 150 ns, which is faster than the traditional mechanical switch.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Different optical NEMS devices, which are fabricated by nano-silicon-phonic processes on a SOI platform have been theoretically and experimentally investigated. They are a NEMS actuator, a NEMS VOA and an optomechanical memory. Theoretical studies, system designs, fabrication technologies and experimental characterizations are presented. The contents cover mainly the innovation of the optical NEMS devices based on optical gradient force, and the exploration of the optical manipulation through nano machining. The major conclusions drawn regarding the NEMS actuator are:

- a) This is for the first time a nanoactuator controlled by Q-factor modulation is demonstrated. Normally, the optical power is controlled by an optical attenuator or directly from a laser source. The ring resonator's Q-factor is modulated via the injection current in a *p-i-n* junction. The relationship between the Q-factor and optical power is developed.
- b) The actuator is driven by the optical gradient force. Compared to the traditional electrostatic actuators, the optical gradient force is efficient in nanoscale devices and sub-nanometer displacement has been realized. All-

optical actuation via optical gradient force enables the devices to work in noisy electromagnetic environment.

- c) The actuator is integrated with a nano scale displacement sensor, which can be easily integrated with silicon photonics devices using CMOS-compatible fabrication processes. Through the wavelength shift of the optical ring resonator, the actuation distance of the nano actuator can be measured efficiently and accurately.
- d) The NEMS actuator shows a sensitivity of 0.875 nm/mA while the resolution is 0.78 nm.

Additionally, the NEMS VOAs have also been experimentally demonstrated. They were realized through a waveguide-based directional coupler, in which the gap between the signal and coupler waveguides of the directional coupler is controlled by an optical force-driven actuator. The doubly-clamped silicon beam actuator used in the structure of the VOA is controlled by tuning the wavelength of the control light. A VOA array was also designed and characterized, as its usage instead of a single device can improve the useful signal's attenuation without introducing more losses. The major conclusions regarding the NEMS VOAs are:

- a) This is for the first time a waveguide based VOA controlled by an optical force driven actuator is introduced. The optical attenuation is obtained and controlled by tuning the gap between waveguides in the directional coupler. The optical force-driven actuator is integrated with the directional coupler, to realize an all-optical device with high speed tuning.
- b) The nano-actuator is controlled by the wavelength tuning of the control light. By means of wavelength detuning, light can be continuously pumped into the

ring resonator during the actuation processes. The wavelength tuning method can provide even larger actuation distances compared to the Q-factor modulation- driven actuator, and therefore provides a better signal attenuation.

- c) The VOA is realized through a waveguide-based directional coupler. The optical coupling between waveguides is a more effective energy coupling method compared to split waveguide coupling and traditional fibre split coupling. The coupling efficiency is more than 90% theoretically. Furthermore, the CMOS compatible silicon photonics fabrication technology provides more freedom in the VOA design in terms of different width and coupling length.
- d) The VOA can be easily expanded into a VOA array. Silicon photonics provides a simple design and fabrication platform, and VOAs can be easily integrated together without significantly increasing the fabrication complexity. A VOA array can provide better attenuation performance compared to a single VOA.

Lastly, a NEMS-based memory has been designed, simulated and experimentally demonstrated. The optical memory is driven by the evanescent wave-coupled optical gradient force. A doubly-clamped silicon beam can be switched between two stable positions, named as “0” and “1”, by pumping light with different power levels due to the optical force induced bistability. The key original points of the NEMS based memory are:

- a) This is for the first time an opto-mechanical memory based on optical force induced bistability is demonstrated. Normally, a doubly-clamped beam exhibits bistability due to its mechanical properties. However, owing to the

nonlinearity of the optical gradient force, the optical force-actuated doubly-clamped beam' stable positions can be controlled via light power level. The memory based on such a bistability can be well controlled by simply changing the light power.

- b) The optomechanical memory has a simple design and a compact size. Compared to traditional optical memories, it does not require a complex control system or special non-linear materials, and can be fabricated using CMOS compatible process. The footprint of the bit memory cell is less than $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ and silicon is the only structural material.
- c) The optomechanical memory is an all-optical device. The write and read processes are realized by modulating the optical signals only. The memory states can be switched by altering the power of the red-detuned laser.
- d) The optomechanical memory can be easily expanded to a memory array. Ring resonators with different resonance wavelengths can operate separately without interfering each other. The elements of the memory can therefore be easily integrated and aligned to form the memory array.
- e) The optomechanical memory has fast response time. Due to the microcavity and nano scale doubly-clamped beam design, the optomechanical memory states can be switched within 150 ns, which is faster than the traditional mechanical switch.

Many opportunities exist if functional MEMS services can be demonstrated and realized in NEMS, while utilizing the nano-silicon-photonic technology. Optical NEMS with standard nanofabrication can provide a new platform for various applications, with low cost, compact size and good integrability. As one of the most important components of optical NEMS devices, the NEMS actuator, which utilizes

optical gradient force, is studied. Therefore, a nano-actuator based on optical force is possible and desired, and can provide the starting point in the design and realization of various mechanical devices, such as VOAs and memories. Two important components in telecommunication, VOAs and optomechanical memories, have been demonstrated in this thesis.

6.2 Recommendations

In this PhD project, several optical NEMS devices have been developed based on optical gradient force by nano-silicon-phonic fabrication processes. The recommendations for future research are summarized as follows:

- a) In the development of the NEMS actuator, a 14 nm actuation distance has been achieved by Q-factor modulation of the actuation ring resonator. Several structural drawbacks inhibit/prevent any further increase of the actuation distance which can be achieved. First, the released length of the doubly-clamped beam is limited to less than 30 μm because a longer beam would likely be affected by stiction (cleaving) and buckling after release, both of which can make the devices unstable. Second, the Q-factor modulation via *p-i-n* junction bias current control suffers from thermal losses due to the ohm heating, causing unnecessary energy loss. To overcome the limitations of current NEMS actuator, a longer doubly-clamped silicon beam should have a

modified anchor design and must undergo a thermal treatment before release to reduce the internal stress and therefore minimize post-release buckling and achieve good mechanical stability. Better optical attenuation can also be developed with more complex optical designed, e.g. a waveguide-based VOA combined with a Mach–Zehnder interferometer.

- b) The Q-factor of the ring resonator can be further enhanced. Although the side wall roughness control is good after the RIE processes, an etchless process has been proposed and initially demonstrated to further enhance the smoothness of the side wall of waveguide structures, which is also CMOS compatible. The WGM ring resonator can theoretically reach ultra-high value for the Q-factor ($>100,000$), and etchless technology can be very helpful to achieve such values. A high Q-factor can provide better light confinement and therefore reduce the power consumption of the proposed optical NEMS devices.
- c) In both the NEMS VOA and memory devices, the control light is modulated by external devices. However, with the help of silicon photonics technology, both functions, include wavelength detuning and power control, can be integrated in the fabricated devices. Various WGM ring resonator based light modulators and even tunable lasers have been studied, and if such devices could be integrated together with the proposed devices, then they can be extremely helpful in providing the control light used in both VOAs and memories.

Author's Publications

Journal papers

1. B. Dong, H. Cai, G. I. Ng, P. Kropelnicki, J. M. Tsai, A. B. Randles, M. Tang, Y. D. Gu, Z. G. Suo and A. Q. Liu, "A nanoelectromechanical systems actuator driven and controlled by Q-factor attenuation of ring resonator", *Applied Physics Letters*, 103, 181105 (2013).
2. H. Cai, B. Dong, J. F. Tao, L. Ding, J. M. Tsai, G. Q. Lo, A. Q. Liu and D. L. Kwong, "A nanoelectromechanical systems optical switch driven by optical gradient force", *Applied Physics Letters*, 102, 023103 (2013).
3. B Dong, H. Cai, Y. D. Gu, and A. Q. Liu, "A nanoelectromechanical systems variable optical attenuator driven by optical gradient force", *Applied Physics Letters* (submitted).
4. B Dong, H. Cai, Y. D. Gu, and A. Q. Liu, "A nanoelectromechanical systems optical memory based on optical gradient force induced bistability", *Nano Letters* (in preparation).

Conference papers

1. B. Dong, J. G. Huang, H. Cai, P. Kropelnicki, A. B. Randles, Y. D. Gu and A. Q. Liu, "Nano-opto-electro-mechanical (NOEM) oscillator with controllable non-linear dynamics", MEMS 2014, San Francisco.
2. B. Dong, H. Cai, J. M. Tsai, D. L. Kwong and A. Q. Liu, "An on-chip opto-mechanical accelerometer", MEMS 2013, Taipei.
3. B. Dong, H. Cai, J. M. Tsai, P. Kropelnicki, A. B. Randles, M. Tang, D. L. Kwong and A. Q. Liu, (Oral) "NEMS actuator driven by optical gradient force", Transducers 2013, Barcelona.
4. B. Dong, W. M. Zhu, Y. H. Fu, J. M. Tsai, H. Cai, D. L. Kwong, E. P. Li, E. Rius and A. Q. Liu, "An absorptive filter using microfluidic switchable metamaterials", Transducers 2011, Beijing.

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