Chapter 2
Nanophotonics for Information Systems

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Abstract The field of photonics finds applications in information technology, health care, lighting, and sensing. This chapter explores the role of nanotechnology with focus on nanophotonics in dielectric and inhomogeneous metamaterials for optical communications, computing, and information and signal processing.

2.1 Introduction

Optics has the potential to solve some of the most exciting problems in communication and computing hardware. It promises crosstalk-free interconnects with essentially unlimited bandwidth, long-distance data transmission without skew and without power- and time-consuming regeneration, miniaturization, parallelism, and efficient implementation of important algorithms such as Fourier transforms. In the past, when the speed of digital computers was able to support only relatively small information processing throughput, the optical information processing techniques were developed and used to construct processors and systems in support of numerous applications that required high throughput for real time operation. These methods exploited the parallelism of optics supported by the richness of the modal continuum of free space and a variety of optoelectronic devices that were developed in support of these applications and systems. The constructed information processing systems and concepts were used for image processing [3–6], pattern recognition [7, 8], neural networks [9], and linear algebra calculus [10] to name a few. However with rapid advancements of the speed and, therefore, the information processing throughput of digital computers, optical signal processing systems were not able to support these applications in a broad sense due to high cost, lesser accuracy, and lack of user-friendly interfaces. Later, the optical information processing
transformed from parallelism in space domain to parallelism in optical frequency domain in support of processing information carried by ultrashort optical pulses in the femtosecond range. Such waveforms vary too rapidly for even the fastest photodetectors to resolve, leading to the need to develop optical information processing methods. Time-domain and spectral-domain processors utilized linear [11] and nonlinear [12] processes and found useful applications for ultrafast waveform synthesis, detection and processing [12–14].

It is evident that optical processing in space and time has so far failed to move out of the lab. The free-space and guided-wave devices are costly, bulky, and fragile in their alignment. They are also difficult to integrate with electronic systems, both in terms of the fabrication process and in terms of delivery and retrieval of the massive volumes of data the optical elements can process. However, with the most recent emphases on construction of chip-scale integration using advanced lithographic tools employed in surrounding electronics, things may be changing. Experts predict lithographic resolution as fine as 16 nm by 2013 [65] which is about 100 times smaller than the telecommunication wavelength of 1,550 nm. These techniques can be used to create deeply subwavelength features that act as a metamaterial with optical properties controlled by the density and geometry of the pattern and its constituent materials. In this chapter, we focus on metamaterials composed primarily of dielectric materials that are engineered on the nanometer scale so as to have emergent optical properties not otherwise present. The increased localization of the optical field as a result of these engineered materials brings about phenomena such as form-birefringence, structural dispersion, and enhanced optical nonlinear interactions. Equivalently, characteristics such as the local polarizability of the metamaterial and the dispersion may be controlled by the geometry, properties of constituent materials, and their composition. The introduction of periodicity in these engineered materials result in a modification in the dispersion relation that can be used to create an artificial bandgap [15–17]. The manipulation and modification of this periodicity allows the bandgap to shift and parts of the bandgap to be accessed by propagating modes. Photonic crystal (PhC) waveguides rely on this exact concept – a line of defects is introduced into the otherwise periodic structure so as to guide light [18–20]. The confinement of light within the PhC lattice is also used to realize devices such as super collimators, super prisms, super lenses, omnidirectional filters, modulators, and lasers through proper design and optimization of Bloch modes [21–30].

Similar to the PhC in its periodic nature is a class of metamaterials which exploits the advantages of both continuous free space and discrete guided wave modes. The simplest example involves the propagation of light in a waveguiding slab, where confinement occurs only in the vertical direction; the free space propagation occurs in the plane of the slab. This configuration, aptly termed “free space optics on a chip” (FSOC) enables interaction with discrete optical components which are located along the propagation direction. Functionalizing devices for such integrated systems would require free space implementations of focusing, beam steering, and wavelength selectivity [31]. Realization of these functionalities can exploit periodic, quasi-periodic, or even random nanostructured composites. By altering at nanometer scales, the surface morphology of a dielectric using nanolithography and
advanced etching techniques, we can realize these complex structures and control
the material’s local polarizability. As we shall see in this chapter, these structures
fall into the deeply sub-wavelength regime with spatial features $\ll \lambda/2n$ and require
metamaterials engineering with very high spatial resolution.

The engineering of composite dielectrics can continue to larger scales creat-
ing metamaterials that involve feature sizes on the sub-wavelength scale, e.g., just
$<\lambda/2n$. The common themes of periodicity/quasi-periodicity and enhanced effects
due to light confinement of guided modes will still remain. Continuing the simpli-
fication of PhC with periodicity in two dimensions that has been used for planar
confinement, an alternative system whereby light confinement in 2D is achieved
by total internal reflection and periodicity in 1D is introduced to create a bandgap
in the third dimension. One method of implementation involves using a channel
waveguide instead of a slab waveguide in the FSOC case for guiding light, and
periodically modulating the effective index of the channel waveguide along the
propagation direction. This results in a periodic photonic nano-wire akin to a 1D
PhC. Thereafter, interesting properties may be engineered by once again, introduc-
ing defects in the periodic structure to access forbidden modes or slightly changing
the periodicity to alter the effective bandgap and dispersive properties. The strong
confinement of fields in these engineered nano-wire structures will also enable ex-
ploring interaction with other overlapping fields or discrete components despite the
highly guided nature of these modes.

Silicon on insulator (SOI) materials will be used for most of the discussion in
this chapter because SOI is compatible with the well established CMOS fabrication
process. In addition, a large index difference between silicon and its oxide exists,
which leads to highly confined modes and enables the miniaturization of on-chip
silicon based photonic circuits. Furthermore, silicon is optically transparent and has
a very low material absorption coefficient at the wavelengths region around 1.55 $\mu$m
which is also used for telecommunications. Waveguiding loss in SOI platforms has
a state of the art value of less than 1 dB/cm. In terms of the impact for future systems
applications, it is evident that next generation computing would benefit greatly from
all-optical data transfer and processing on a chip. Electrical interconnections inher-
ent in today’s computing cannot measure up in terms of both speed and bandwidth.
Researchers in the field are aware of the need to bypass any sort of electro-optic pro-
cess in order to take computing speeds to the next level. Much work is being done
in creating both passive and active devices in SOI. Discrete device components such
as filters, modulators, and resonators have been demonstrated. Active devices utiliz-
ing Raman gain and hybrid silicon lasers which achieve gain from a bonded III–V
material have been demonstrated. The momentum of research in this area is the best
evidence that silicon photonics is set to revolutionize the field of computing and
communications.

In this chapter, we will divide the analysis of the dielectric metamaterials into two
categories, namely those in the deeply sub-wavelength scale and the sub-wavelength
scale. As we shall see, interesting material emergent properties arise when the mate-
rials are engineered to sizes smaller than or comparable to the wavelength of light in
the said medium. Optical field concentrators, compact sources, polarizers, chromatic
dispersers, diffractive structures, and other optical processing devices can now be implemented on-chip using metamaterials wherever natural materials with similar properties either do not exist, or (more frequently) would not be compatible with lithographic fabrication processing. Moreover, there exists an opportunity to develop a new family of optical devices exploiting near field interactions in a much broader sense than that which has been done to date. In summary, there exists an opportunity in using advanced *lithography* and materials composition geometry to “lithographically write and assemble” optical materials and devices with novel optical functionalities into circuits and subsystems on a chip.

### 2.2 Nanophotonics Process

To advance this technology, investigations of nanostructures and their interaction with electromagnetic field are critical. Engineers also need appropriate modeling and design tools, new fabrication recipes, and test instruments capable of characterizing on-chip components (see Fig. 2.1). The nanophotonics process will help to establish near field optical systems science and underlying technologies to advance future integrated information systems.

The design of integrated photonic systems is a challenging task as it not only involves the accurate solution of electromagnetic equations, but also the need to incorporate the material and quantum physics equations to enable the investigation and analysis of near field interactions. These studies need to be integrated with device fabrication and characterization to verify device concepts and optimize device designs. In this chapter we discuss examples of the SOI metamaterials and devices that can be realized using CMOS-compatible fabrication process which we demonstrated recently in our lab. These examples include birefringent elements that utilize a combination of geometry and material properties to separate light into orthogonal polarizations, graded-index lenses, frequency-selective resonators and Bragg gratings, and metal-dielectric nanostructures that can achieve extremely tight field confinement. Some of these example devices are tested using our near field characterization tool, the heterodyne near-field scanning optical microscope (H-NSOM).

**Fig. 2.1** Nanophotonics process
This microscope uses a fiber probe tapered to about 200–500 nm diameter with an aperture of about 50–200 nm which is brought close enough to the nanostructure under test to pick up its evanescent electromagnetic fields. The idea to improve resolution of optical measurements by bringing a subwavelength aperture close to the object of interest was first introduced by Synge in 1928 and experimentally realized only in 1983 by two independently working research groups: Dieter W. Pohl and his colleagues working in IBM laboratories [32] and Aaron Lewis with colleagues in Cornell University [33]. The efficiency of light transmission through a small aperture ($d \ll \lambda$) rapidly drops as the aperture size decreases: $T \sim (d/\lambda)^4$ [33], thus for realistic aperture of 100 nm and visible wavelengths the transmission efficiency only reach $10^{-6}$ to $10^{-8}$ [34]. Such small transmission coefficients demands using powerful optical sources (often lasers), efficient detection schemes and detectors. Heterodyne detection, as one of the examples, an interferometric technique which not only improves the detection efficiency but also allows measurement of optical phase.

In addition, heterodyne setup is ideal for studying pulses propagation in the nanophotonic circuits [1], which is of particular importance for information systems. It was also shown that dynamic response (e.g., pulse propagation velocity) can be measured as well by using continuous but spectrally broad optical sources [2].

The concept of heterodyne detection is to mix the signal of interest with a coherent reference beam possessing slightly shifted optical frequency. This can be done by implementing Mach–Zehnder interferometer scheme with one arm (signal arm) including NSOM and the other arm (reference arm) providing a frequency-shifted reference. The two fields are added coherently, yielding the desired interference signal of interest oscillating at the heterodyne frequency. The coherent gain of the heterodyne detection significantly improves the sensitivity of the instrument. An example of the H-NSOM [35] arrangement is shown on the Fig. 2.2. The system is composed of the readily available telecom components.

![Fig. 2.2 Schematic diagram of the H-NSOM setup with the collection system for effect of the tip analysis [35]](image_url)
This in-fiber realization provides better interferometric stability; polarization maintaining fibers can also be used for maximizing interference term. The scanning process provides simultaneously three images: sample topography, deducted from the AFM feedback system which keeps the probe at the constant height above the sample surface; amplitude and phase distributions of the evanescent optical fields. Example of H-NSOM characterization of microring resonator with $10 \mu m$ diameter is given in Fig. 2.3. The mapping of evanescent fields has proven to be a powerful aid in understanding the performance of nano-scale optical materials, devices and circuits.

### 2.3 Dielectric Metamaterials

In this section, we will describe the analysis of the deeply sub-wavelength scale dielectric metamaterials and also their interesting emergent behavior in the sub-wavelength scale limit as well as when they are perturbed into aperiodic composites.

We investigate a class of dielectrics, characterized by feature sizes $\delta \ll \lambda/2n$, where $\lambda$ is the free-space wavelength of device operation and $n$ is the refractive index of the dielectric material. The photonic structures having periodic or quasi-periodic refractive index variation with characteristic distances much smaller than the wavelength of light can be called “metamaterials” (from the Greek word “μετάματα” = “after,” “beyond”) – materials that determine their optical properties from the structure geometry rather than only from constituent material composition. This approach, as we will discover in detail in this section, can be illustrated by the simplest example – form-birefringent materials, a one-dimensional periodic structures which have polarization-dependent index of refraction [36–38] and unusual nonlinear properties [39].

Form birefringence occurs in structures which have deeply subwavelength periodicity [20]. The altered surface morphology of the dielectric used to construct such structures results in a large difference between the effective indices of the TE and TM polarized optical fields, since they need to satisfy different boundary conditions.
Form-birefringent nanostructures (FBN) are advantageous to naturally birefringent materials in that (1) the strength of birefringence, $\Delta n / n$ (where $\Delta n$ and $n$ are the difference and average refractive indices for the two orthogonal polarizations) is larger in the former; (2) the extent of form birefringence, $\Delta n$ may be adjusted by varying the duty ratio as well as the shape of the microstructures; and (3) FBNs may be used to modify the reflection properties of the dielectric boundaries [40]. These features are useful for constructing polarization-selective beam splitters and general-purpose polarization-selective diffractive optical elements such as birefringent computer-generated holograms (BCGHs) [38]. Extending this concept to the 2D geometry or implementing aperiodicity enables other useful functionalities such as converting a linear polarization state to radial or azimuthal polarization [40, 41] and creating graded-index medium [41, 42]. It was also shown that the metamaterial approach can help to overcome fabrication difficulties and create Fresnel lens analogue using binary lithographic fabrication with deeply sub-wavelength feature size of less than 60 nm [31].

2.3.1 Inhomogeneous Dielectric Metamaterials with Space-Variant Polarizability

It is also possible to mold the light flow in the planar configuration using the metamaterial approach. Bringing functionality of the table-top optical information processing components to a chip will create compact devices, which can benefit from fast data transfer, small form-factor, parallel processing, and low power consumption. Implementing free-space-like propagation for planar optics means that while the light is confined by index difference in the vertical direction (chip plane), the horizontal beam size is regulated by the phenomena similar to that in 3D free-space optics such as diffraction, reflection and refraction. This can be seen as a direct and more natural transition of the conventional free space bulk optical components and devices to chip-scale photonic integrated circuits.

To create a dielectric metamaterial we use a subwavelength structure that can be fabricated in the high refractive index slab (see Fig. 2.4a). The slab has an index of refraction, $n_1$ and the gaps in the etched subwavelength structure can be filled with a material possessing a low index of refraction $n_2$ such as for example air with $n_2 = 1$. This slab structure is constructed on the cladding with an overall lower index of refraction $n_c < n_1$, to ensure confinement in the vertical direction. For some material systems such as SOI, the cladding with the guiding slab is located on the top of a thick substrate with the refractive index $n_s$. Consider a grating with a period, $\Lambda$ with $F \Lambda$ being a fraction of the unit cell filled with high-index material. It can be shown that the second-order effective medium theory approximation [43, 44] is accurate for small grating periods $\Lambda < \lambda / n$ [20] and for grating thickness larger than $\lambda / 3$ [45]. Other approaches in design and analysis of these subwavelength grating metamaterial structures include numerical methods such as RCWA, finite element method (FEM), and the finite-difference time-domain (FDTD) approach.
This concept can be used for example in creating new materials with refractive indices different from those of the constituent materials. For example, the SOI material system includes silicon with index of refraction of $n_{Si} = 3.48$ and silicon dioxide with $n_{SiO_2} = 1.46$ as the only materials available for structure design. In the table-top free-space optics we, on the other hand, have a variety of materials such as different glasses, crystals, polymers, etc. This fact makes it difficult to directly transfer table-top optical setups for on-chip implementations. Metamaterials can provide a solution to overcome this difficulty. For example, by implementing the scheme of subwavelength gratings, the index achievable for SOI material system varies from 1.5 to 3.4, thus covering almost fully the range between high-index silicon and low-index oxide. This range was estimated for TE-polarized fields in structures with a period of $\Lambda = 400 \text{ nm}$ satisfying $\Lambda < \lambda/n = 1,500 \text{ nm}/3.5 \approx 400 \text{ nm}$ condition, with filling factors varying from 0.1 to 0.9 to comply with the state of the art nanofabrication capabilities (e.g., feature size $\sim 40 \text{ nm}$). We examine subwavelength structures with a linearly varying filling factor, corresponding to introducing a linear spatial chirp. Such a slab will equivalently act as a graded index metamaterial media, where the effective index of refraction in the transverse direction decreases or increases linearly. It is well known that in such a “graded” index material, the incident beam of light will bend towards a higher index of refraction. We performed numerical simulations of light propagation in such spatially chirped subwavelength grating structures with initial periods of $\Lambda = 150 \text{ nm}$. The numeric simulation result for SOI material platform is shown in Fig. 2.4b.

2.3.2 Graded Index Structures

The simplest example of non-resonant metamaterials is a subwavelength periodic nanostructure that can dramatically affect the polarization of propagating light due to anisotropic polarizability of the medium, an effect known as form-birefringence.
where the effective properties can be engineered through the choice of constituent materials and their geometry. For a specific eigen polarization, a mode matching device can be realized using the nonresonant metamaterial with space-variant polarizability to guide and manipulate the modes of light propagating on a chip. The device is realized by lithographically defining and etching subwavelength features into a high refractive index slab waveguide [31], thus modifying its local effective index of refraction. We use a sub-wavelength periodic structure and locally modulate its duty cycle in the transverse direction \( x \), to achieve modulation of the index of refraction, i.e., \( n(x) = n_0 \left[ 1 - (1/2)\alpha x^2 \right] \), where \( n_0 \) and \( \alpha \) are constants representing the maximal effective index and the gradient strength, respectively. To validate our approach, we designed and fabricated a graded index slab element that focuses light into a 2-\( \mu \)m wide Si ridge waveguide. We used a SOI geometry with a Si slab thickness of 250 nm and an oxide thickness of 3\( \mu \)m. The fabricated element in Fig. 2.5a shows the layout of the device. A grating period of 400 nm is chosen to assure the validity of the effective medium approximation on one hand, and to avoid the need for fabricating ultra small features. For compatibility with CMOS fabrication, the minimal air gap is chosen to be 100 nm, imposing a maximal duty cycle of 75%.

Typically, characterization of nanophotonic devices is performed by analyzing the light intensity measured at the output of the device. Unfortunately, this approach lacks the ability to probe the amplitude and, even more importantly, the phase profile of the optical beam as it propagates within the structure. To overcome this deficiency, the fabricated samples are characterized using our H-NSOM [35], capable of measuring both amplitude and phase of the propagating optical field with a resolution of about 100 nm. Figure 2.5b, c shows the measured amplitude and phase of the optical field propagating through the device at a wavelength of \( \lambda = 1.550 \) nm. Figure 2.5b shows the amplitude of the optical field in the region that includes the input waveguide, the non-patterned slab (“S”) and large portion of the slab lens section (“L”). The dashed vertical white lines mark the boundaries between the various sections of the device. Light propagates from left to right. Figure 2.5c shows the
measured phase in the same region. The obtained results clearly show the expanding of the optical beam in the region of the slab. As expected, the phase front is diverging in this section. As the beam enters the metamaterial, the curvature of the phase front is gradually decreasing and becomes planar after about $5 \mu m$ propagation in the slab. Then, the phase front begins to converge towards the focus. As the beam continues to propagate, the phase front starts to diverge again, and the optical beam expands.

The investigated metamaterial based graded index slab “lens” device is the first step towards the realization of the FSOC concept. Our H-NSOM measurements clearly demonstrate the focusing effect. This experimental demonstration opens new possibilities in the field of on chip integrated photonic devices, as the demonstrated component can be integrated with other building blocks (some of these yet to be developed) to create future devices and systems based on the concept of FSOC. We believe that this new concept may become essential for applications such as optical interconnections, information processing, spectroscopy and sensing on a chip.

2.4 Photonic Nano-wires: Sub-Wavelength Inhomogeneous Dielectrics

We refer to sub-wavelength structures as structures with features that are smaller but comparable to the wavelength of light. An example of such periodic structures is a general family of resonant structured materials such as Photonic Crystal (PhC) lattices and the whole family of devices that can be implemented in the PhC lattice. In this section we explore a novel practical approach that we call photonic nano-wire metamaterials which can be used to implement both sub-wavelength as well as deeply sub-wavelength nanostructures. It should be noted that sub-wavelength scale devices are characterized by feature sizes $\Lambda < \lambda/2n$, where $\lambda$ is the vacuum wavelength of operation of the device, and $n$ is the effective index of the specific mode in the device. The effective index of the mode in the material, $n_{\text{eff}} = \beta/k$, where $\beta$ is the propagation constant of the waveguide mode and $k$ is the wave number in vacuum. For example, for SOI materials system with silicon refractive index, $n_{\text{Si}} = 3.48$ and silicon oxide refractive index, $n_{\text{SiO}_2} = 1.46$, we can construct a typical single-mode silicon waveguide with $n_{\text{eff}}$ of around 2.5 for operation at the telecommunications wavelength of 1.55 $\mu m$. In the following we will mainly focus on the sub-wavelength regime to demonstrate the unique capabilities of this approach and demonstrate experimentally example devices. We first investigate a periodic 1D PhC nano-wire, and extend the investigation to a quasi-periodic nano-wire. Finally, we study the characteristics of a filter created by coupling two such photonic nano-wires together.
2.4.1 Photonic Crystal-Based Resonant Device

Photonic crystal (PhC) lattice [15–17] is a well-known resonant inhomogeneous material, which found a number of realizations during the past decade [21, 22, 37, 47]. Photonic crystal lattice may play a unique role as an integration platform of nanophotonic devices. Numerous devices with various functionalities have been utilized in a PhC lattice including modulators, detectors, filters, lasers, superprisms, and elements with negative refraction. However, fabrication of 3D resonant inhomogeneous materials and devices remains challenging, and frequently, 1D and 2D topologies are used due to ease in their design, fabrication, and integration.

A simple example of a 1D resonant structure is a distributed Bragg reflector (DBR) used in planar waveguide technology to perform and enhance various functionalities of optical elements such as a single-mode selector in semiconductor lasers, optical filters, switches, modulators, couplers, detectors, and sensors. The DBRs conventionally fabricated on the surface of the waveguide involves an additional fabrication procedure separate from the waveguide. Recently, in contrast to traditional approaches, we exploit single step fabrication method to define the DBRs and other nanostructured resonant devices using corrugation of waveguide sidewalls. In this approach, both the period and the modulation strength of the DBRs are lithographically assigned on the waveguide sidewalls [48, 49]. We term this class of devices as “vertical gratings” to distinguish them from conventional surface DBRs.

The designed devices are Fabry–Perot (FP) type filters made of a pair of identical Bragg reflectors each having reflection \( r \) and transmission \( t \) amplitude coefficients, and separated by a spacer of length \( d = \lambda / 2 \) causing a phase shift \( \phi = \pi / 2 \), as shown in Fig. 2.6a. The transmission amplitude of the resonant filter \( t_{RF} \) as a function of \( \lambda \) is given by \( t_{RF} = [t^2 \exp(i\phi)]/1 - r^2 \exp(2i\phi) \), where \( t \) is transmittance of the Bragg structure. These filters are fabricated on a piece \((\sim 1 \times 0.5 \text{ cm}^2)\) of 6-inch SOI wafer consisting of a silicon top layer with a mean thickness of 252.2 nm with distribution of \( \pm 18.3 \text{ nm} \) on a \( \sim 3-\mu \text{m} \)-thick silicon dioxide layer. Figure 2.6b, c shows SEM micrographs of the fabricated device. For the testing process of the device, a linearly polarized tunable laser source is coupled into a polarization maintaining (PM) tapered fiber with an output mode field diameter of \( \sim 2.5 \mu \text{m} \), producing \( \sim 20 \text{ dB} \) polarization extinction. Another PM tapered fiber is used to collect light from the fabricated devices and its relative power transmission over the wavelength is analyzed. All measurements are performed using TE polarization. Figure 2.7 shows the measured transmission spectrum. The measured transmission spectrum of the fabricated device shows a wide stopband of \( \sim 19 \text{ nm} \) bandwidth with a narrow transmission band with linewidth \( (\Delta \lambda) \) of \( \sim 0.5 \text{ nm} \) in the center of the stop band. The developed fabrication procedures show very good surface quality which is also indicated by the measured cavity \( Q \sim \lambda_B / \Delta \lambda \) of about 3,000.

The described resonant photonic crystal based devices and components implemented using photonic nano-wires are essential for future integration of various information systems on a chip. A resonant nanophotonic device utilizing vertical gratings has been realized on SOI wafer, demonstrating fabrication procedures that
Fig. 2.6 (a) Top view of resonant transmission filter in sidewall modulated nano-wire, where $W_S$ is the average width of the waveguide, and $\Delta W_S$ is the full depth of a single sidewall of the waveguide. $L$ and $\Lambda_B$ are the total length and the period of a single Bragg reflector, respectively. For SOI realization we use $d = \Lambda_B / 2$, $\Lambda_B = 305 \text{ nm}$, $W = 500 \text{ nm}$ and $\Delta W_S = 50 \text{ nm}$; scanning electron micrographs of a dry etched silicon nano-wire filter device: (b) top view; (c) tilted view

Fig. 2.7 Measured spectra from the fabricated devices with $W_S = 500 \text{ nm}$ and $\Lambda = 305 \text{ nm}$ for $\Delta W_S = 50 \text{ nm}$, $2 \times L = 70 \mu m$ [48, 50]

show very good surface quality. These experimental demonstrations open new possibilities in the field of on-chip integrated photonic devices, as the demonstrated component can be integrated with other building blocks to create future devices and systems based on the concept of FSOC. Finally, the introduced approach on
using lithography for side wall modulation opens up numerous opportunities in constructing various resonant devices for detection, modulation, generation, and manipulation of light on a chip.

### 2.4.2 Aperiodic Chirped Photonic Nano-Wires

The sidewall modulated photonic nano-wire gratings can be extended to engineer dispersion for chip-scale integration by introducing a chirp into its period. The device is similar to chirped fiber Bragg gratings (CFBG), used to compensate for group velocity dispersion (GVD) in fiber-optic applications. In this device, the sidewall modulating gratings are quasi-periodic, in contrast to the previous section where they had a fixed period [49]. Our GVD device uses the same SOI technology that was demonstrated in the previous section. A schematic diagram of the device is shown in Fig. 2.8. The refractive indices of Si and SiO$_2$ are assumed to be 3.48 and 1.46 respectively for the purposes of this study. The mean width, $W = 500$ nm and height, $H = 250$ nm of the waveguide result in an effective mode index, $n_{\text{eff}} = 2.63$ and the chosen Bragg wavelength, $\lambda_o = 1.55$ $\mu$m. The corresponding mean Bragg grating period, $\Lambda_o = \lambda_o/(2n_{\text{eff}}) = 295$ nm. Next, a linear chirp is applied to the Bragg grating to introduce a quadratic phase across the optical spectrum centered at the resonant Bragg frequency. Consequently, a linear group delay will appear across the reflection band – this leads to the term, chirped Bragg grating (CBG). The CBG period at any point, $z$ is given by $\Lambda(z) = \Lambda_o + (F/2\pi) (\Lambda_o^2/L)(2z/L)$, where $F$ is the chirp parameter and $L$ is the device length [51]. The total chirp in period for a fixed $F$ is $\Delta \Lambda = (F/\pi) (\Lambda_o^2/L)$.

The large sidewall modulation of 50 nm on our CBG devices implies that in contrast to weakly coupled CFBGs in silica, they are operating in a strong coupling regime. Moreover, the relatively short length of strongly chirped device may not meet the slowly varying envelope approximation inherent in coupled mode theory (CMT). Therefore, we perform FDTD simulations to study their characteristics. The effective index of a slab of height, $H$ infinite in the $y$-direction was used in place of the material refractive index of silicon to reduce the problem to two dimensions (2D). Although the reduction of the 3D problem to a 2D one is approximate, this

![Fig. 2.8](image) (a) A bird’s eye view of chirped Bragg grating (CBG) device geometry realized with a sidewall modulated photonic nano-wire and (b) SEM micrographs of apodized section of CBG and (c) unapodized section before SiO$_2$ cladding deposition [49]
method retains the salient spectral characteristics [52] and has shown good experimental agreement for similar structures [53].

A well known phenomenon which occurs in Bragg filters is the spectral ripple which arises from the abrupt start and end of the periodic structures in the filter. The windowing effect which leads to the degradation in the filter response may be alleviated by gradually increasing the amplitude of index modulation, and equivalently $\kappa$, from 0 at the edge to its maximum value at the center of the grating. Therefore, the effectiveness of different apodization filters [54,55] in achieving a flat-top response and in-band ripple suppression is first investigated. While our study shows that various apodization filters are effective in suppressing group delay ripple, asymmetric Blackman apodization [54] is the most effective in maximizing the CBG bandwidth while maintaining a flat response. The apodization applied is asymmetric in that the coupling strength of the input half of the CBG increases from 0 at the CBG edge to its maximum value at the center of the CBG. The rear half of the CBG has a constant $\kappa$. We adopt asymmetric Blackman apodization for our CBGs for further studies of the effect of $\Delta \lambda$ on the CBG devices. We expect that the group delay scales with the device length, and the group velocity dispersion (GVD), which is the derivative of the group delay with respect to wavelength relates inversely to $\Delta \lambda$. Increasing $\Delta \lambda$ leads to a larger range of periods and hence, larger bandwidth over which a fixed group delay is distributed. Therefore, the GVD decreases for increasing $\Delta \lambda$. Referring to Fig. 2.9a, we observe an increase in bandwidth from 38 to 88 nm for $L = 100 \mu \text{m}$ as $\Delta \lambda$ increases from 4 to 12 nm, and a corresponding drop in the GVD (Fig. 2.9b) from $7.0 \times 10^5$ to $2.1 \times 10^5 \text{ps/nm/km}$. In addition, longer device lengths are desirable to achieve reflectivities close to 100% even for

**Fig. 2.9** 2D FDTD modeling results for (a) reflection and (b) group delay spectra for CBGs with different values of $\Delta \lambda$. All devices have asymmetric Blackman apodization applied. **Solid lines** denote $L = 100 \mu \text{m}$; **dotted lines** denote $L = 200 \mu \text{m}$. **Black** $- \Delta \lambda = 4 \text{ nm}$, **red** $- \Delta \lambda = 7.5 \text{ nm}$, **blue** $- \Delta \lambda = 12 \text{ nm}$
large values $\Delta \Lambda$. Referring to Fig. 2.9, doubling the CBG length to 200 $\mu$m results in higher reflectivity and significant ripple reduction in both the reflection and group delay spectra.

The designed CBG device was fabricated on a SOI wafer with a 250 nm layer of silicon on top of a 3 $\mu$m buried oxide layer on a silicon wafer. We use e-beam lithography followed by reactive ion etching. SiO$_2$ cladding was deposited over the fabricated Si structure using plasma-enhanced chemical vapor deposition (PECVD). SEM micrographs of fabricated structures before PECVD deposition of SiO$_2$ are shown in Fig. 2.8b, c.

We fabricated test samples with an access waveguide around 200 $\mu$m in length in front of the CBG structure. For the dispersion characterization, we use Fabry–Perot (FP) resonance oscillations in the measured reflection spectrum of the device. The resonator is defined by two reflectors, the cleaved input facet of the Si waveguide and the start of the CBG. We use a method similar to that reported in [56]. The length traversed by each wavelength component from the cleaved input facet to the point of reflection in the CBG may be experimentally determined using the relation, $l_c = \lambda^2 / [2n_g(\Delta \lambda_{FP})]$, where $\Delta \lambda_{FP}$ is the free spectral range of the FP resonator and the value of $n_g$ is fixed at 4.2. The total group delay is subsequently found using $(2l_c \times n_g)/c = \lambda^2 /[c(\Delta \lambda)]$, which is independent of the value of $n_g$. Finally, the GVD is obtained using the derivative of the group delay with respect to wavelength. Since the GVD of the access waveguide is two orders of magnitude lower than that of our device [57], the measured dispersion properties are dominated by those of our CBG devices. Typical experimental data of the reflection spectrum is compared with the numeric modeling result obtained for the same CBG geometry. The modeled result shows good agreement with the envelope and bandwidth of the measured spectrum.

Three fabricated CBG devices with $L = 100 \mu$m and $\Delta \Lambda = -4$, -7.5 and 12 nm were characterized in terms of their group delay (Fig. 2.10). The GVD is extracted from the slope of a linear fit applied to the experimental data. The expected

![Fig. 2.10](image)

(a) Measured reflection spectrum showing FP oscillations (blue) and 2D FDTD modeling result for $L = 100 \mu$m and $\Delta \Lambda = 7.5$ nm. (b) Measured group delay for CBGs with $L = 100 \mu$m for different values of $\Delta \Lambda$. Solid lines denote linear fit to measured data [49]
GVD values for $L = 100 \, \mu m$, $\Delta \Lambda = -4, -7.5$ and $12 \, nm$ from the simulations are $-0.070, -0.033$ and $0.021 \, ps/nm$, respectively; the measured GVD values are $-0.067, -0.032$ and $0.020 \, ps/nm$, respectively, showing good agreement between the numeric and experimental results. Note that as expected, changing the sign of the chirp changes the sign of the dispersion (Fig. 2.10).

The CBG device provides a platform to engineer normal or anomalous dispersion for photonic systems applications including GVD compensation in silicon photonic structures on a chip. Asymmetric Blackman apodization was found to be most effective in suppressing group delay ripple while maximizing the usable bandwidth. The experiments demonstrated a dispersion value of $7.0 \times 10^5 \, ps/nm/km$ in a wide spectral range of about $40 \, nm$ in the near infrared spectral range of $1.55 \, \mu m$. Both normal and anomalous dispersion has been demonstrated. The operating bandwidth may be adjusted and arbitrary amounts of dispersion achieved by adjusting the sign and magnitude of the chirp. The tunability of the CBG bandwidth makes it highly suitable for accommodating ultrashort pulses with high spectral content.

### 2.4.3 Cladding-Modulated Photonic Nano-wires

Periodic and aperiodic structures are fundamental in implementing various optical devices for switching, wavelength division multiplexing (WDM) and sensing applications [54, 58]. We have previously demonstrated on-chip sidewall modulated Bragg gratings (SMBG) realized by single-step lithography [49, 59], in which the strength of the coupling coefficient is determined by the modulation amplitude which in turn is limited by the resolution of electron beams used to pattern these structures. Narrow bandwidth WDM components require Bragg gratings which have weak coefficients and which can be easily controlled. To this end, we introduce a cladding-modulated Bragg grating (CMBG) on SOI which overcomes the limitations inherent in SMBGs in fabricating devices with weak coupling (see Fig. 2.11) [60].

The CMBG consists of a single mode waveguide at $1.55 \, \mu m$ with the Bragg effect arising from placements of silicon cylinders with period, $\Lambda_B$, a distance, $d$, away from the waveguide. The cylinder radius, $R$, is chosen to be $100 \, nm$ to avoid supporting any resonant modes. Since the field amplitude of the propagating mode decays exponentially outside the waveguide boundaries, the extent of the evanescent tails residing in the silicon cylinders and hence the strength of mode coupling can be varied by adjusting the distance $d$. We first calculate the CMBG coupling coefficient, $\kappa$ of the CMBG as a function of $d$ using coupled mode theory (CMT) [61]:

$$
\kappa = \frac{k_o}{4n_{eff}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Delta n^2 E^2 dx dy
$$

(2.1)
The spatial distribution of the E-field and effective index is found using a fully vectorial beam propagation method. For small values of $d$, the coupling is large and CMT is no longer valid. The inverse logarithmic relationship between $\kappa$ and $d$ is apparent in Fig. 2.12 and is a direct result of the exponential nature of the decay in modal amplitude away from the core-cladding interface. From CMT, we expect that the bandwidth (defined here as the width between zeros of the central lobe) of the device increases as the coupling strength increases [62, 63]:
\[
\Delta \lambda = \frac{\lambda^2}{n_g L} \left[ 1 + \left( \frac{\kappa L}{\pi} \right)^2 \right]^{1/2}
\]  

(2.2)

where the group index, \( n_g \) is estimated to be 3.8 and \( L \) is the device length. Using (2.2) and the values of \( \kappa \) calculated earlier, a plot of \( \Delta \lambda \) as a function of \( d \) is shown in Fig. 2.12. The CMT results are compared with 2D FDTD simulations marked with circles on Fig. 2.12. As expected, the discrepancy between CMT and FDTD increases as \( d \) decreases. We also observe in both the CMT and FDTD plots, that \( \Delta \lambda \) approaches a limit of \( \sim 5 \) nm as \( d \) increases. For \( \kappa L \ll \pi \), \( \Delta \lambda \) becomes increasingly dependent on \( L \) explaining the limiting behavior for weak coupling. For \( \kappa L \gg \pi \), \( \kappa \) becomes the dominant factor on the value of \( \Delta \lambda \).

The device is fabricated using electron-beam lithography followed by reactive ion etching and plasma enhanced chemical vapor deposition of the SiO\(_2\) overcladding. The spectral response of two fabricated devices (A and B) measured using an optical spectrum analyzer is shown in Fig. 2.13b, c. The values of \( \Delta \lambda \) and \( \kappa \) obtained experimentally are marked on Fig. 2.12. Even though \( L = 70 \) \( \mu \)m for device B, \( \kappa L \gg \pi \) and therefore \( \kappa \) is the dominant factor on \( \Delta \lambda \). \( \kappa \) calculated from (2.2) should therefore be similar to that for \( L = 100 \) \( \mu \)m. \( \Delta \lambda \) measured for devices A

---

**Fig. 2.13**  (a) SEM micrographs of fabricated devices. Measured transmission spectra of (b) device A \((L = 100 \mu m, d = 200 nm)\) and (c) device B \((L = 70 \mu m, d = 50 nm)\)
and B are 8 and 16 nm respectively, close to the expected values of 7 and 13 nm respectively from 2D FDTD. The slightly higher value of $\Delta \lambda$ measured for device B may be attributed to the proximity effect during e-beam writing resulting in a value of $d$ smaller than the target. For small values of $d$, small changes in $d$ result in large changes in $\kappa$ owing to the inverse exponential relation between $\kappa$ and $d$ observed in Fig. 2.12.

The demonstrated CMBG device may be useful for on-chip switching and add-drop filtering applications. By integrating several CMBGs with slightly different values of $\Lambda_B$, the device could be used to route data at different carrier frequencies (i.e., wavelengths). For example, smaller values of $\kappa$ with sufficiently long $L$ to achieve $\sim$100% efficiency/extinction will allow more narrow band data channels to be accommodated for in dense WDM applications, whereas a large value of $\kappa$ accommodates fewer channels but with much higher bandwidth. To circumvent the limiting behavior of the bandwidth, devices with small values of $\kappa$ can be made longer such that $\kappa L \gg \pi$. For example, for $d = 200$ nm and $L = 2.3$ mm, $\kappa L = 10$ and $\Delta \lambda = 0.9$ nm from (2.2).

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The designed, fabricated and experimentally validated novel CMBG using SOI material platform allows large dynamic range, resolution and precise control of the coupling strengths of the device. Devices with weak and strong coupling strengths differing by an order of magnitude were demonstrated experimentally confirming the numeric predictions. This method of creating Bragg gratings enables weak coupling coefficients to be realized to meet narrow bandwidth requirements in switching and add-drop filtering applications.

2.5 Nanophotonic Devices and Circuits: Wavelength Selective Add Drop Filter with Vertical Gratings on a Silicon Chip

As a further application of the sidewall modulated photonic nano-wire demonstrated in previous sections, we developed a wavelength selective add/drop filter. The device provides a viable platform for realizing next generation integrated WDM functionalities in order to bypass the aforementioned limitations in electro-optic conversions. The wavelength selective add/drop filter is ideally suited to optical interconnects, and will be implemented using two coupled vertical gratings on the same SOI platform used to study the other vertical grating devices.

Figure 2.14a shows a schematic diagram of the add/drop filter. Two vertical gratings with different widths, $W_1$ and $W_2$ are placed in parallel such that three Bragg conditions arise [64]: $2\beta_1 = 2\pi/\Lambda$ (backward coupling in waveguide 1 (WG1)), $2\beta_2 = 2\pi/\Lambda$ (backward coupling in WG2) and $\beta_1 + \beta_2 = 2\pi/\Lambda$ (cross coupling), where $\beta_1$ and $\beta_2$ are the propagation constants of WG1 and WG2 respectively, $L$ is the device length and $\Lambda$ is the grating period. A raised cosine apodization filter is applied to both gratings to minimize out of band ripple. Here, we allocate the cross coupling wavelength to $\lambda_B = 1.55 \mu$m by setting the period as $\Lambda_B = 2\pi/\left[\beta_1(\lambda_B) + \beta_2(\lambda_B)\right]$, and backward coupling wavelengths in WG1 and
WG2 to be outside the C-band by setting $2\beta_1(\lambda > 1.57 \mu m) = 2\pi/\Lambda_B$ and $2\beta_2(\lambda < 1.53 \mu m) = 2\pi/\Lambda_B$. Figure 2.14b shows the dispersion plots of $2\beta_1$, $2\beta_2$, and $\beta_1 + \beta_2$, calculated using a fully vectorial beam propagation method for the quasi-TE mode. Based on the calculated propagation constants, we obtain $\Lambda_B = 316$ nm for $\lambda_B = 1.55 \mu m$. An approximation to the full 3D problem is obtained by performing 2D FDTD simulations using the effective index method for $L = 400 \mu m$ and $G = 160$ nm, as shown in Fig. 2.14a. The obtained transmission and drop port spectra is summarized in Fig. 2.14c. The stop band centered close to 1.57 $\mu m$ in the transmission plot arises from the self coupling in WG1 whereas the stop band centered at 1.535 $\mu m$ is the cross coupling band which brings about the device’s add/drop functionality. Another important feature of the device is the tunability of the cross coupling bandwidth, $\Delta \lambda_c$ using $G$. A larger $G$ implies a smaller overlap integral between the forward mode in WG1 and the backward mode in WG2, and therefore a lower cross coupling coefficient, $\kappa_c$. According to coupled mode theory [59, 64] and (2.2), the coupling coefficient is inversely related to the
stop-band of the resonant device. $\Delta \lambda_c$ obtained using 2D FDTD for several values of $G$ is plotted in Fig. 2.14d, and confirms the inverse relation between $\Delta \lambda_c$ and $G$.

For device characterization, we fabricated several add/drop filters using an SOI wafer with 250 nm of Si on a 3 μm buried oxide layer on a Si substrate. E-beam lithography was performed followed by reactive ion etching and plasma-enhanced chemical vapor deposition of the top layer of SiO$_2$ cladding. Four add/drop filters with varying $G$ from 60 to 200 nm were fabricated. The length of the fabricated add/drop filters was fixed at 400 μm for the three smallest values of $G$. All access waveguides are terminated in inverse tapers to improve coupling and to minimize Fabry–Perot oscillations. For the filter with the weakest coupling ($G = 200$ nm), the length had to be increased to 1 mm in order to obtain a sufficiently large extinction at the drop port. Figure 2.15a shows SEM micrographs at the center of the add/drop filter, where the sidewall modulation amplitude is at its maximum. The measured transmission spectra for the transmission and drop ports are shown in Fig. 2.15b. The drop port’s bandwidth is also observed to decrease as $G$ is increased from 60 to 200 nm. The inverse relation is shown in Fig. 2.15c, and shows that $\Delta \lambda_c$ decreases

![Fig. 2.15](image-url) (a) Optical and SEM images of the fabricated device and (b) measured transmission spectrum for the transmission (red) and drop (blue) ports. (c) The experimentally measured values of $\Delta \lambda_c$ for several fabricated add/drop filters with different values of $G$
from 3 nm in the most strongly coupled case of $G = 60$ and 1.2 nm in the device with weakest coupling ($G = 200$ nm).

To incorporate the add/drop filter as a building block of a WDM system, several such coupled vertical grating add/drop filters may be combined to multiplex different wavelengths on a chip. Several additional vertical gratings, each with a slightly different width and hence, different propagation constant and dispersion relation, may be coupled with WG1 in order to multiplex/drop a different cross coupling wavelength. Consequently, the device will be able to serve as a WDM system to be integrated with next generation on-chip computing and communication networks.

2.6 Discussions and Future Perspectives

This chapter has given an introductory view on the emerging field of nanophotonics and its potential for chip-scale integration of information systems. The main points include our ability to use standard and novel nanofabrication tools to create complex geometries of composite materials varying the spatial distributions periodically, quasi-periodically or even at random. The feature sizes of these nanocomposites can be deeply subwavelength, which enables creation of materials and devices with unique functionalities that is not possible to achieve with existing technologies. These structures can also be created on a sub-wavelength scale where the individual features are coupled and can be operated in spatial as well as spectral resonance. We have described the localized effects and alterations in optical behavior such dielectric metamaterials with space variant polarizability (form birefringence and metamaterials lens), as well as various functionalities achieved by single and spatially coupled resonant photonic nano-wires.

The current trend of using SOI material platform will continue due to its ability to utilize well established CMOS compatible fabrication processes in the future as the microelectronics is projected to reach resolutions on the order of 10–16 nm. Another major reason is that future computing systems complexity will increasingly rely on optical interconnections that may reach out scales of intra-chip communications, where silicon photonics will enable efficient manipulation, transformation, filtering and detection of light meeting the needs of the future information systems. It should be noted that efficient generation of light on a silicon chip is still in its infancy and may not be able to overcome the fundamental issues prohibiting efficient generation of light in indirect bandgap semiconductors; however, alternative solutions similar to delivery of electrical power from off the chip sources will bring optical fields into Si chips. Introduction of heterogeneous metamaterials is certainly another valid alternative, but it may require major technological and manufacturing advancements. It is evident that the fundamental limits of scale and composition in the present technology will continue to improve, reaching out to smaller and smaller features in multitudes of materials compositions. It is possible that current trends in engineering electronic bandgaps are not merely a pipe dream, and may one day merge with engineering nanophotonic metamaterials, leading to new device
concepts that will serve as the backbone of future information systems technologies. Engineering the polarizability of dielectric nanostructures is still in its nascent stages and numerous novel functionalities are still to come.

References


Information Optics and Photonics
Algorithms, Systems, and Applications
Fournel, T.; Javidi, B. (Eds.)
2010, XV, 281 p., Hardcover