Nanophotonics for information systems

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Abstract. The field of photonics finds applications in information technology, health care, lighting, and sensing. This paper explores the role of nanotechnology with focus on nanophotonics in dielectric and inhomogeneous metamaterials.

1. Introduction
Optics has the potential to solve some of the most exciting problems in 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. Numerous information processing systems and concepts in space and time have been studied during the past decades. Yet, optical computing and 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. Our most recent work emphasizes the construction of optical subsystems directly on-chip, with the same lithographic tools as the surrounding electronics. This has been made possible by the advances in these tools, which can now create features significantly smaller than the optical wavelength; experts predict lithographic resolution as fine as 16nm by year 2020. Arranged in a regular pattern, subwavelength features act as a metamaterial whose optical properties are controlled by the density and geometry of the pattern and its constituents. Lenses, polarizers, chromatic dispersers, diffraction gratings, 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.

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. 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 talk, we discuss some of the CMOS-compatible Silicon-on-insulator metamaterials and devices recently demonstrated in our lab. These include graded-index lenses, birefringent elements that utilize a combination of geometry and material properties to separate light into orthogonal polarizations, frequency-selective resonators.
and Bragg gratings, and metal-dielectric nanostructures that can achieve extremely tight field confinement. Characterization tools, including our Heterodyne Near Field Optical Microscope, will also be discussed. This microscope uses a fiber probe tapered to 200nm diameter and brought close enough to the nanostructure under test to pick up its evanescent electromagnetic fields. Subsequent heterodyne detection permits simultaneous measurement of both amplitude and phase of the evanescent fields, while also providing an amplification to boost the weak signal. The mapping of evanescent fields has proven to be a powerful aid in understanding the performance of nano-optical elements.

3. Example: Cladding modulation
Bragg structures are fundamental in implementing various optical devices for switching, wavelength division multiplexing (WDM) and sensing applications. We have previously demonstrated on-chip sidewall modulated Bragg grating (SMBG) realized using single-step lithography. The strength of the coupling coefficient in SMBG 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 coupling coefficients and which can be easily controlled. To address these issues, we introduce a novel cladding-modulated Bragg grating (CMBG) implemented with silicon on insulator (SOI) material platform. The proposed CMBG is shown to overcome the limitations inherent to SMBG in fabricating devices that require high resolution, wide dynamic range and high precision control of the coupling strength.

Our CMBG consists of a single mode waveguide at 1.55μm with the Bragg effect arising from placements of silicon cylinders with period, \( \Lambda_B \) a distance, \( d \) away from the silicon waveguide (see Fig. 1). The cylinder radius, \( R \) is chosen to be 100nm 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).

![CMBG schematic](image1)

**Figure 1.** CMBG schematic.
Waveguide radius, \( R=100\text{nm} \)

![SEM Micrographs of fabricated devices](image2)

**Figure 2.** (a) SEM Micrographs of fabricated devices. Measured transmission spectra of (b) device A (\( L=100\mu m, d=200\text{nm} \)) and (c) device B (\( L=70\mu m, d=50\text{nm} \))

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 & B) measured using an optical spectrum analyzer is shown in Fig. 2. Even though the length of the device B was \( L=70\mu m \), the value of \( \kappa.L \gg \pi \) indicating that \( \kappa \) is the dominant in contributing to \( \Delta\lambda \). The values of \( \Delta\lambda \) measured for devices A and B are 8nm and 16nm respectively, close to the expected values of 7nm and 13nm respectively from our 2D FDTD results.
4. Conclusions
It is evident that nanophotonics and metamaterials are important technologies for future information processing systems. The research exploiting near field optical phenomena will be key in achieving new functionalities in materials properties (birefringence, dispersion, nonlinearities) as well as unique device functionalities such as adaptation, generation, modulation, transport and detection of light. This work was supported by the NSF, DARPA, and the NSF CIAN ERC.