Photonic Bandgap Microcavities and Waveguides

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Introduction

Microfabricated optical cavities provide us with the geometries needed to guide and concentrate light into extremely small volumes and to obtain very high field intensities. Fabrication of such optical structures has now evolved to a precision which allows us to control light within such etched nanostructures. Sub-wavelength nano-optic cavities can be used for efficient and flexible control over both emission wavelength and frequency, and nanofabricated optical waveguides can be used for efficient coupling of light between devices. The reduction of the size of optical components leads to their integration in large numbers and the possibility to combine different functionalities on a single chip, much in the same way as electronic components have been integrated for improved functionality in microchips. The past rapid emergence of optical microcavity devices, such as Vertical Cavity Surface Emitting Lasers (VCSELs, Figure 1) can be largely attributed to the high precision over the layer thickness control available during semiconductor crystal growth. High reflectivity mirrors can thus be grown with sub-nanometer accuracy to define high-Q cavities in the vertical dimension. Recently, it has also become possible to microfabricate high reflectivity mirrors by creating two- and three-dimensional periodic structures. These periodic "photonic crystals" can be designed to open up frequency bands within which the propagation of electromagnetic waves is forbidden irrespective of the propagation direction in space and define photonic bandgaps. When combined with high index contrast slabs in which light can be efficiently guided, microfabricated two-dimensional photonic bandgap mirrors provide us with the geometries needed to confine and concentrate light into extremely small volumes and to obtain very high field intensities. Here we show how to use photonic crystals in functional nonlinear optical devices, such as lasers, modulators, add/drop filters, polarizers and detectors. These components can now be combined into very compact nanophotonic integrated circuits.

Fig.1: 1-D Resonator Cavity

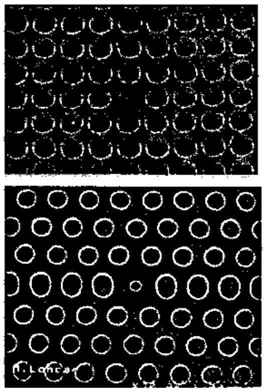

Figure 2. Two different photonic crystal laser designs

Silicon on Insulator Photonics

The primary and most obvious advantage of defining nanophotonic circuits on silicon substrates is the possibility of integrating microelectronics with nano-optics. Through such integration on the same platform, it is possible to trade off the complexity fo the electronics with that of optics. Silicon on silicon dioxide, formed by Smartcut or Simox methods, however, also offers some other important technologically important advantages over more conventional semiconductor materials systems. One of these is the maturity of the processing technology, which has been refined by the microelectronics industry. Reproducibility, alignment accuracy, and minimum feature sizes on large wafers are at or beyond the specifications needed for optical nanophotonic integrated circuits. Silicon on insulator material also provides a thin waveguide material with high vertical index confinement. This high contrast in the refractive index permits the use of rather shallow etch depths

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to define optical structures, with a corresponding advantage in the minimum feature sizes. Optoelectronic materials systems with more modest vertical confinement, such as the GaAs/AlGaAs or InGaAs/InP waveguide materials systems provide a much more formidable process challenge to the fabricator, since optical nanostructures in these materials systems have to be etched through the cladding as well as the core of the waveguides, requiring etch depths above 1 micron. Of course, if such structures are chemically undercut by wet etching, these etch depths are relaxed, but heat-sinking becomes a significant problem in the resulting free-standing membrane slabs. An even more insidious problem in weakly confined waveguide systems results from the excitation of cladding modes, which represent potential loss mechanisms for high-Q photonic crystal nanoresonators. We have predicted that these losses limit the quality factors of optical cavities made in such materials systems. It should be noted, however, that the GaAs/AlAs heterostructures, when combined with steam oxidation, do offer an alternative with similar vertical confinement, but do not provide gain in the telecommunication wavelengths of interest.

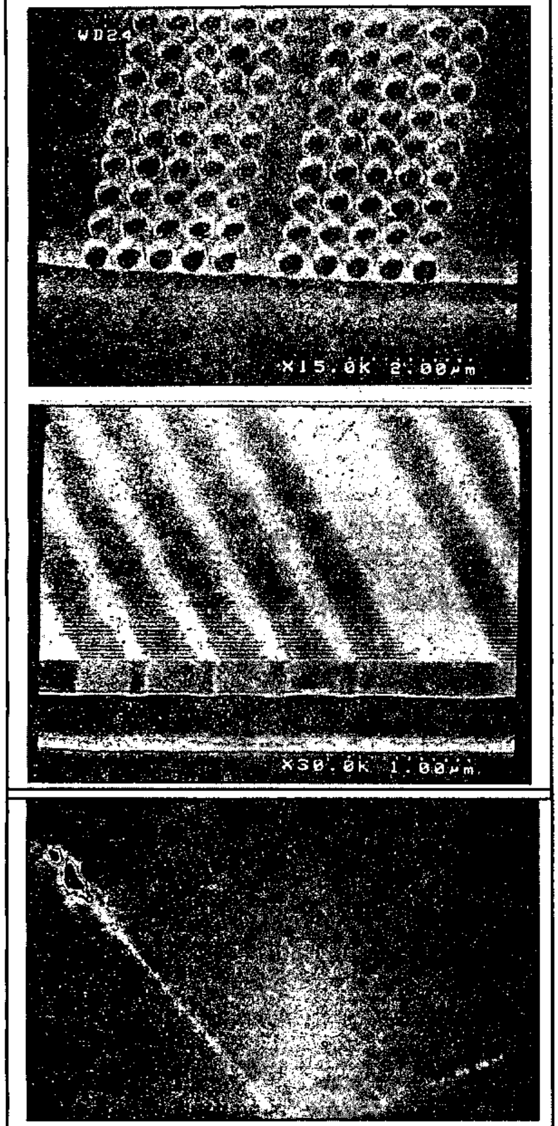

Fig. 3. SOI waveguide defined by lithography.

Detectors and Diagnostic electronics

One of the major limitations of present optical systems is the lack of diagnostic abilities with which to monitor and optimize the functioning of the system during operation. Simple devices, such as WDM (wavelength division multiplexing) demultiplexers, based on arrayed waveguide gratings are extremely bulky and quite difficult to package. We can significantly reduce the size of such devices, and demonstrate new devices which include photonic crystal superprisms, collimators, and resonators on silicon on insulator wafers. Unfortunately, silicon does not have a direct bandgap and is expected to only find limited applications for the construction of light sources. However, when germanium or Si-Ge is grown on the silicon waveguiding membrane, it is possible to construct ultra-small and very sensistive detector arrays which make use of both photon recycling and field concentration available from the photonic crystal nanocavities. In these photonic crystal structures, both spectral and polarization response can be controlled through the design of the geometry and field distribution. Simple processing, available in both Si and Ge through the use of previously optimized Freon etches, readily allows integration of Si-Ge nanophotonic detector arrays with silicon slab waveguides and silicon electronic amplification circuitry. The detectors can be spectrally filtered and their response can be accurately tuned through the introduction of nonlinear optical polymers. These devices can also be electrically contacted and further integrated with fast and sensitive electronic amplification circuitry, possibly leveraging experience from modern microelectronic fabrication technology.

Switching of light in resonators

It is widely known that crystalline silicon is a excellent transparent medium for the telecommunications wavelength range. Although it is very difficult to include gain into the silicon, it is possible to use the optical properties of silicon to switch light. For example, by changing the carrier density of silicon, it is possible to alter the absorption coefficient as well as the refractive index. This change in optical properties is relatively subtle. However, appropriate optically nonlinear polymers offer the opportunity of obtaining much higher contrast and switching speed. Since the optical response time of a resonator-based switch depends on the quality factor of the optical cavity used, this value may ultimately limit the switching speed to significantly above 100 GHz. Miniaturization offers the opportunity to reduce the capacitance of optical switch while increasing the free spectral range, and at the same time allows the spectral filtering of light..

By combining two emerging technologies, i.e., photonic bandgap crystals with nonlinear organic polymers, it will become possible to spectrally tune and modulate ultra-small optical cavities with low threshold powers. The very porous structure of photonic crystals is very well suited for the incorporation of nonlinear materials, as are the high optical fields and high Qs, which can be developed within photonic crystal nanocavities. One of the simplest approaches for using the nonlinearities of organic molecules within photonic crystals consists of filling the voids in the holes which define the photonic crystals. Altering the refractive index of the polymer either optically or electrostatically then indirectly tunes the effective cavity length, an effect that can be used to modulate an incident laser beam. Even more efficient nonlinear switching is expected if the nanocavity design is optimized to include a void at the center of the cavity to place the back-filled nonlinear polymer within the field maximum of the optical standing wave. We have already designed cavities in which this is possible, and calculate Qs in excess of 15,000 for these nanocavities from finite difference time domain models.

Both of the examples described above rely on the relatively robust nature of the photonic bandgap as well as the porosity of typical photonic crystals, and describe the operation of discrete tuneable devices. It is clear, however, that the most important advantage of using photonic crystals lies in providing a robust platform for efficiently guiding light between many nanophotonic devices which can be integrated into dense arrays. For example, dense multi-wavelength sources can be developed, in which the precise wavelengths of each device can be coarsely tuned lithographically, whereas the precise wavelength operation can be retroactively adjusted by introducing electrostatic or optical changes in nonlinear materials close to each optical nanocavity. Indeed, if photonic crystal circuits are to be used as wavelength-dispersive optical routers, it is necessary to control the precise resonance wavelength to better than what fabrication tolerances presently permit if full use of the high Qs available in such cavities is to be made.

Figure 4. Method for tuning of the photonic crystal with electro-optic or liquid crystal polymer