Design of Silicon Photonic Crystal Integrated Optical Devices

Zhi-Yuan Li, Lin Gan, and Chen Wang

Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences
P. O. Box 603, Beijing 100190, China
Email address: lizy@aphy.iphy.ac.cn

Abstract—**Photonic crystal has attracted extensive interest in the past 25 years due to its great power to mold the flow of light in micrometer/nanometer scale and promising aspects in building all-optical integrated devices and circuits. In this talk we present our recent efforts of design, fabrication, and characterization of integrated optical elements and devices in infrared silicon two-dimensional photonic crystal slabs. These devices operate either on band gap confinement or on band dispersion control. We focus on topics such as the broad-band wide-angle self-collimation effect, on-chip optical diodes and isolators, new cavities without apparent confinement barriers, and polymer-silicon hybrid nonlinear photonic crystal.**

Keywords-silicon photonic crystal; optical integration; self-collimation; optical diodes; cavities with confinement barrier; ploymer-silicon hybrid nonlinear photonic crystal

Photonic crystal has offered a powerful means to mold the flow of light and manipulate light-matter interaction at subwavelength scale. The fundamental goal of photonic crystal is to realize ultrasmall integrated optical circuits on the basis of different defects introduced within photonic band gaps. Theoretical analysis and numerical simulation are very important to design and realize high-performance photonic crystal integrated optical devices.

Silicon has a large refraction index and low loss in infrared wavelengths, which makes it an important optical material that has been widely used for integrated photonics applications in the near infrared regime around 1550 nm [1-6]. In this talk we review some of our recent theoretical and experimental works on the design, realization, and characterization of infrared two-dimensional (2D) air-bridged silicon photonic crystal slab devices that are based on both the band gap and the band structure engineering. In particular, we will focus on several works that we have carried out in the past two years.

Firstly we discuss on-chip wavelength-scale optical diodes and isolators based on photonic crystal heterojunctions with directional bandgap mismatch [7]. Optical isolation is a long pursued object with fundamental difficulty in integrated photonics. As a step towards this goal, we demonstrate the design, fabrication, and characterization of on-chip wavelength-scale optical diodes that are made from the heterojunction between two different silicon 2D square-lattice photonic crystal slabs with directional bandgap mismatch and different mode transitions. The measured transmission spectra show considerable unidirectional transmission behavior, in good agreement with numerical simulations. The experimental realization of on-chip optical diodes with wavelength-scale size using all-dielectric, passive, and linear silicon photonic crystal structures may help to construct on-chip optical logical devices without nonlinearity or magnetism for application in on-chip optics communication and signal processing, and would open up a road towards photonic computers.

Secondly we discuss a photonic crystal that exhibits self-collimation effect in a wide angle range and with a large bandwidth [8]. We have designed, fabricated, and characterized a silicon PC structure that exhibits broadband large-angle self-collimation effect of transverse-magnetic (TE) modes at wavelengths around 1550 nm. Experimentally the collimation effect is clearly observed for TE modes with different incident angles at a broad wavelength range by recording the ray trace of light scattering off the sample. Our structure can find potential applications in many areas such as beam combiner and solar energy collector.

Thirdly we design and fabricate cavities without an apparent confinement barrier by combining two incommensurate photonic crystal superlattice waveguides in 2D photonic crystal slab [9]. A resonant mode with a high quality factor shows up in the pass band of waveguides. It has nearly no influence on the propagation of waveguide mode and can be directly coupled with the waveguide mode. The experimental measurement confirms the theoretical prediction of extraordinary coexistence of localized cavity mode and continuous waveguide mode with high coupling efficiency in the same frequency and space regime. Due to the extraordinary co-existence of localized cavity mode and continuous waveguide mode in both spatial and spectrum regions, the non-barrier cavity opens up a new avenue of cavity design and may find application in integrated optical devices and solid state lasers.

Finally we present a versatile technique based on nano-imprint lithography to fabricate high-quality semiconductor-polymer compound nonlinear photonic crystal (NPC) slabs [10]. It has been shown in our previous works that polymer materials such as polystyrene has a far larger Kerr nonlinearity and much faster optical response speed (down to several femtoseconds) compared with silicon [11-15]. So it is expected that the hybrid photonic crystal structures can incorporate both advantages of ultrafast and low power nonlinear optical effects. We have found that the approach allows one to infiltrate uniformly polystyrene materials that possess large Kerr nonlinearity and ultrafast nonlinear response into the cylindrical air holes with diameter of hundred nanometers that are perforated in silicon membranes. Both the structural characterization via the cross-sectional scanning electron microscopy images and the optical characterization via the transmission spectrum measurement undoubtedly show that the fabricated compound NPC samples have uniform and dense polymer infiltration and are of high quality in optical properties. The compound NPC samples exhibit sharp transmission band edges and nondegraded high quality factor of microcavities compared with those in the bare silicon photonic crystal. The versatile method can be expanded to make general semiconductor-polymer hybrid optical nanostructures, and thus it may pave the way for reliable and efficient fabrication of ultrafast and ultralow power all-optical tunable integrated photonic devices and circuits

Our works presented in this review show that photonic crystals have a strong power of controlling propagation of light at micrometer/nanometer scale and possess a great potential of applications in integrated photonic circuits. New concepts are very important to bring closer the fundamental goal of ultrasmall optical integration in the framework of silicon photonic crystal. Design is always the fresh blood of the science of photonic crystal.

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