Slow light engineering in the hollow-core vertical photonic crystal waveguide for gas sensing

Ali Rostamian[1], Jason Midkiff[1], Kyoung Min Yoo[1], and Ray T. Chen[1,2]
[1]*Microelectronic Research Center, Department of Electrical and Computer Engineering, University of Texas at Austin, Austin, TX, 78758, USA*
[2]*Omega Optics, Inc., 8500 Shoal Creek Blvd., Bldg. 4, Suite 200, Austin, Texas 78757, USA*
Author e-mail address: ali.rostamian@utexas.edu, chenrt@austin.utexas.edu

Abstract: In this paper, we present a hollow-core vertical photonic crystal waveguide geometry in silicon for gas detection in the mid-infrared region. The dispersion is engineered to enhance light-matter interactions inside the hollow-core defect. © 2022 The Author(s)

In a conventional optical fiber, the mode is guided by total internal reflection (TIR) through the core with a higher refractive index than its cladding. The total loss in TIR includes scattering and absorptive loss of the material that could be avoided to a large extent by guiding the light through a hollow core [1]. In a photonic bandgap fiber (PBGF), the photonic bandgap effect is used instead of index-guiding to trap the light in the low index region, and the modes are guided by Bragg reflection from the cladding layers. Along with single-mode guidance, this geometry can tailor the dispersion and support large mode area and filling factor. Photonic bandgap brings about a lot of interesting properties, including localization of light at the engineered defects and slow light effect. By tailoring the medium, it is possible to control the dispersion, slow the light down, or even bring it effectively to a complete stop [2]. Photonic crystals are well known for exhibiting slow-light propagation in line-defect waveguides [3].

In this paper, we present a vertical photonic crystal waveguide (VPCW) in silicon that can be employed for simultaneous detections of a myriad of gas species. This VPCW has perfectly periodic air holes as the cladding in a 2-dimensional photonic crystal arrangement that gives rise to bandgaps at specific optical passbands. Conventionally, PBGFs are made of low index contrast material systems like silica glass/air that do not support a complete bandgap for both polarization at small propagation constants, but silicon has the peculiar dispersion with a complete bandgap extending to very small wavevectors where large group velocity dispersion occurs. By tailoring the microstructured cladding, the light would be bandgap-guided at a specific optical wavelength corresponding to the spectroscopic absorption spectrum of a special analyte through the core of the waveguide with a small group velocity. The hollow core can confine the optical mode and the gas species simultaneously and therefore enhances light-matter interaction. Plane wave expansion (PWE) simulation was performed to extract the dispersion for two structures on silicon ($n = 3.42$) with similar dimensions: a) a photonic crystal with hexagonal lattice comprising silicon rods in air, b) a photonic crystal with hexagonal lattice comprising air holes in a silicon slab. Fig. 1(a) plots the numerical simulation results for the silicon rods structure. In this dispersion diagram, the solid red lines represent TM bands, and solid blue lines represent TE bands. Red and blue hatched regions correspond to TM and TE bandgaps, respectively. As revealed, there are two distinct TE and TM bandgaps without any overlay. Fig. 1(b) plots the dispersion diagram for the photonic crystal with hexagonal lattice comprising air holes in a silicon slab. Similarly, solid red lines represent TM bands, and solid blue lines represent TE bands, and cross-hatched regions correspond to bandgaps. The dispersion diagram exhibits significant bandgaps for both polarizations. As revealed, contrary to the silicon rods structure, this photonic crystal supports a complete and overlapping bandgap for both polarizations in two dimensions. Simulations are performed assuming that the out-of-plane propagation constant is zero. At $\beta = 0$, modes are pure TE and TM because of the symmetry, but for nonzero axial wavevectors, the reflection symmetry through the transverse x-z plane breaks, and the modes would be hybrid. In the vicinity of $\beta = 0$, index-guided modes become less confined, and eventually, at the propagation constant of zero, only bandgap-guided modes would exist. However, high group indices occur in this vicinity. Structures that possess the peculiar feature of supporting a complete bandgap for both polarizations at the propagation constant of zero are projected to have the bandgap at nonzero values of β, where there are distinct TE and TM eigenmodes. In low index-contrast geometries like conventional holey photonic crystal fibers, the so-called finger-like bandgaps appear at large values of β and pinch off before reaching $\beta = 0$ point.

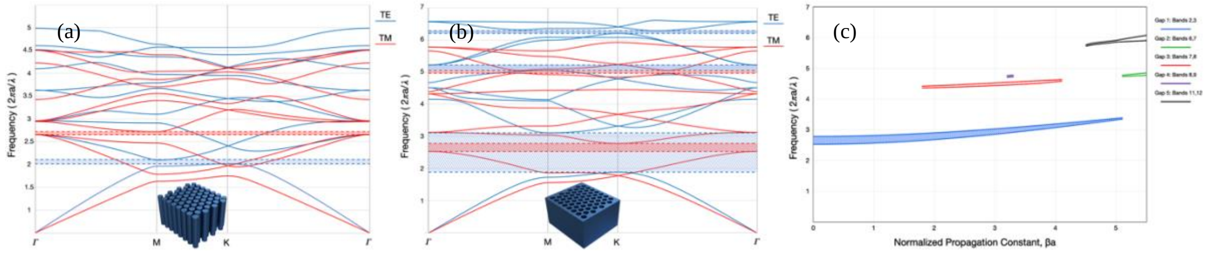

Fig. 1 Dispersion diagram of the photonic crystal with hexagonal lattice comprising (a) silicon rods in air (b) air holes in a silicon slab. Solid red lines represent TM bands, and solid blue lines represent TE bands. Hatched regions correspond to bandgaps. (c) Bandstop edges as a function of normalized propagation constant. Bandstops occurring between different bands are color-coded.

By introducing a central defect, the light would be confined and defect-guided thanks to the complete bandgap of the hexagonal photonic crystal, as shown in Fig. 1(b) and Fig. 1(c). A top-view schematic representation of the hexagonal photonic crystal with the hollow-core defect is depicted in Fig. 2(a), where D=2r is the diameter of holes and α is the lattice constant of the photonic crystal.

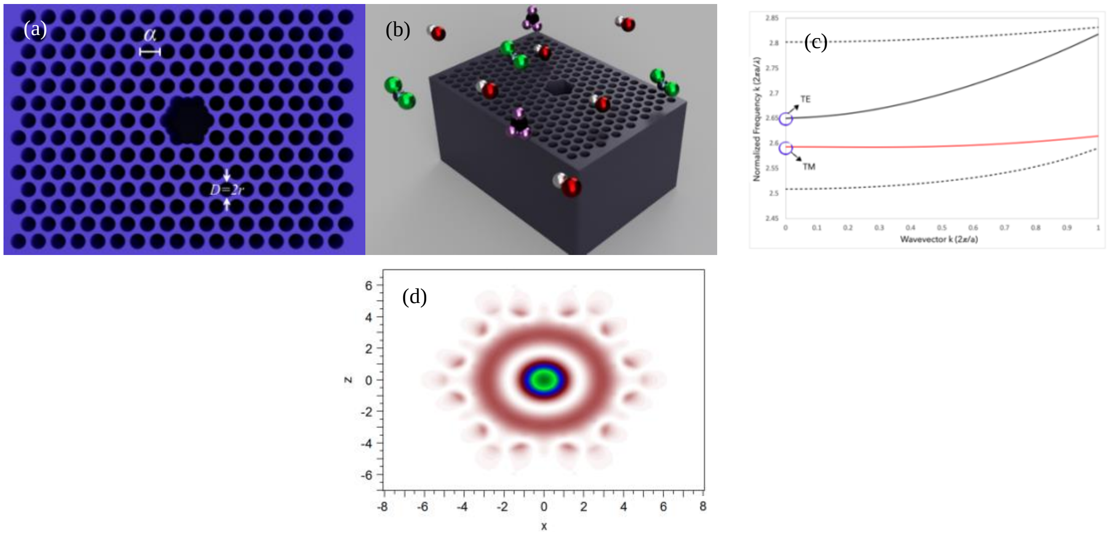

Fig. 2 (a) Top-view schematic of the hexagonal photonic crystal with a hollow-core defect. (b) Schematic illustration of the sensor structure (c) Projected band diagram, normalized frequency as a function of out of plane wavevector (d) Profile of the bound mode inside the bandgap

In order to investigate the defect states and the bound modes residing inside the bandgap, eigenvalues for every band and every value of β are calculated. Fig. 2(c) plots the projected band diagram or normalized frequency as a function of the out-of-plane wavevector for the hexagonal lattice photonic crystal with the central defect as depicted in Fig. 2(a). At k=0, there are two distinct TE and TM modes within the gap. The group velocity in a dispersive medium is defined as the derivative of the angular frequency with respect to wavenumber: $v_g = \frac{\partial\omega}{\partial\kappa} . n_g$, the group index, regarded as a slow-down factor, is the reciprocal of group velocity : $v_g = c/n_g$. The bandgap-guided modes indicated by the solid red and black lines, have peculiar flattened dispersion close to zero, leading to extremely large group indices. The modes are examined to find the ones that fall inside the bandgap. Confined modes are guided through the hollow-core. Fig. 2(d) shows the profile for the defect-guided mode. This is a bound mode that falls within the bandgap with minimal leakage out of the core. The dimensions of the photonic crystal structure are optimized to operate at the mid-IR wavelength range. By changing the dimensions, this structure can be tuned to have high group indices at any wavelength of interest and hence enhance light-analyte interaction. This device, if used as an array, can be used for on-chip absorption spectroscopy to identify a myriad of different gas species. Experimental results will be presented along with different designs to demonstrate multi-wavelength operation.

[1] R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. S. J. Russell, P. J. Roberts, and D. C. Allan, "Single-mode photonic band gap guidance of light in air," Science (80-.). **285**, 1537–1539 (1999).

[2] C. Liu, Z. Dutton, C. H. Behroozi, and L. V. Hau, "Observation of coherent optical information storage in an atomic medium using halted light pulses," Nature **409**, 490–493 (2001).

[3] T. Baba, "Slow light in photonic crystals," Nat. Photonics **2**, 465–473 (2008).