Design Analysis and Development of Photonic Crystal Based Structures for Sensing Applications

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By

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ABSTRACT

Controlling the propagation of light on small scale using photonic band gap (PBG) effect has been a recent research area globally. Photonic crystal (PhC) technology provides strong dispersion, which facilitates low group velocity for the guided modes in the vicinity of PBG edges, hence provides strong light-matter interaction at very small scale. This property is further used to design various PhC-based optical sensors. Although conventional optical sensors possess high selectivity, stability and real time detection capability, still PhC-based sensing technique takes an edge because of its compact structure, capabilities of slowing down and confining the light. This leads to an improvement in light matter interaction, and hence, the sensitivity. Further, the integration of micro-fluidic and PhC technology, with CMOS compatible fabrication process, improves the sensing proficiency of optical sensors.

Photonic crystals are periodic dielectric structures that are designed to control the flow of photons and to affect the propagation of electromagnetic (EM) waves that would satisfy the demand for highly efficient optic devices. By introducing point and/or line-defects in periodic photonic crystals, highly efficient cavities and waveguides can be realized. The continuous and innovative works on photonic crystal based devices would depict that they contain extraordinary properties (band gap, photon confinement, and low losses) and overcomes many limitations of conventional optical devices i.e., evanescent field loss, bending losses, etc. Considering these unique properties, this work is primarily focused on design optimization and realization of PhC-based structures for sensing applications.

Initially, various PhC structures including uniform PhC structures, PhC with line-defects and multilayer PhC structures are designed and optimized to achieve the highest possible sensitivity and quality factor values. At first, the properties of photonic crystal waveguide (PhCW) structure is explored and detailed dispersion and sensitivity analysis of PhCW structure is carried out. The PhC cavity structure is formed by deliberately introducing some defect holes within PhCW. The number of PhC cavities and surrounding holes are optimized in order to attain highest possible quality factor along with significant signal strength. Finally, sensing capability of proposed optimized structure is explored by three-dimensional finite difference time domain (3D-FDTD) method. The optimized PhC cavity structure shows the quality

factor and sensitivity of about 1x 10^5 and 500nm/RIU respectively. This gives a figure of merit (FOM) of about 33920.

Two-dimensional PhC structures are promising building blocks for sensing applications. However, complex fabrication and characterization processes limit their widespread applications. Therefore, the fabrication and characterization processes are further simplified by designing a multilayer PhC structure. The proposed structure comprises alternate layers of SiO_2 and Si_3N_4 dielectric material showing the photonic band gap (PBG) in the visible region. The number of alternate layers and their thicknesses are optimized in order to achieve the highest possible reflection at preferred wavelength range. The porosity is introduced within layers to ease the analyte infiltration. Additionally, the effect of porosity on reflected wavelength is also analyzed. Finally, the detailed sensing analysis of optimized multilayer PhC structure is carried out. The proposed structure exhibits a sensitivity of about 50nm/RIU for 12 number of alternate layers (6 stack) with 20% porosity.

To demonstrate their sensing capabilities, the main challenge is to fabricate these devices. This is because they comprise sub-micron dimensions having etch-depth of about 250 nm and hole diameters of the order of 300 to 500 nm. These structures also possess various defects (of different dimensions and geometry), which are deliberately introduced to enhance structure functionality. Slight deviation in structural dimensions can drastically affect the device performance. In addition, characterization and interfacing to outside world of these nano-photonic devices of sub-microns size is another important challenge. For guided-wave applications, it is often necessary to use relatively large-sized access-waveguides that are usually defined using conventional lithography and etching methods. However, for structure like PhC, an accurate alignment with large structures is highly desirable for integrated optics. That is why, despite the extraordinary applications of PhC-based devices, present fabrication techniques keep them away from being viable commercial devices/modules. Extensive research has been carried out to simplify the fabrication and characterization process for these PhC-based structures. A number of techniques (E-beam nanolithography, Focused ion beam lithography, Dip Pen Nanolithography, and Interference lithography) have been demonstrated at laboratory level to make few numbers of devices, but still a simpler alternate method is required to fabricate PhC-based devices with long I/O waveguides of sub-micron width.

The dissertation work also deals with theses above-mentioned challenges and provide an alternate way to fabricate PhC-based devices. The planned fabrication technique comprises combination of optical lithography and focused ion beam (FIB) lithography, where input and output waveguides along with rectangular platforms are fabricated by optical lithography with the help of specially designed mask and FIB is used to fabricate PhC-based structure in selected areas on the platform. Proposed fabrication technique provides a flexible, low-cost, and highly effective method to fabricate devices of dimensions greater than 1 cm^2 having such small features in large scale. This technique also eliminates the problem of slow-writing of conventional nanolithography techniques. Similarly, the proposed multilayer PhC structure is also fabricated by PECVD deposition technique. Finally, detailed sensing analysis of fabricated multilayer PhC structure is carried out.