Modelling and Simulation of Optical Pressure Sensors For Detection of Acoustic Signals In Sub-Micron Range

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Abstract—Micro-sized acoustic pressure sensor is designed to detect sub-micron range dimension change using the photonic crystal. The applied acoustic pressure on the hydrophone will change the dimension of the waveguide carved in the photonic crystal. As a result, this change in spacing can alter the propagation feature of electromagnetic waves that pass through them, which is changing the transmission spectrum. So, this change can directly be mapped to acoustic pressure on the observed object. In this paper, the acoustic based acoustic pressure sensor using photonic crystal has been designed, modelled and analysed. The sensitivity of the sensor is in the order of 10⁻⁶.

Keywords—FDTD, Photonic crystal, Photonic sensing technology, Acoustic Sensor

I. INTRODUCTION

The photonic crystal technology has immensely aided in exploring new ways to detect variation of physical parameters like pressure, temperature, strain, stress etc. Integrated photonics has opened a way to develop sensor systems which can replace the conventional electronic acoustic pressure sensors. The miniaturization, extreme efficiency and high sensitivity [1] has made photonic sensor most viable solution to the conventional acoustic pressure sensor with limitations like inefficiencies in harsh environment, high cost and low sensitivity. Opto-mechanical micro sensor technology can be explored to develop acoustic pressure sensor. MEMS merged with Micro-optics involves sensing or manipulating optical signals on a very small size scale using integrated mechanical, optical, and electrical systems, giving rise to a new class of MOEMS technology.

Photonic crystal is emerged as a new frontier for development of material classification and physical parameter measurement possibilities. The photonic crystal based sensor provides better sensitivity and selectivity as compared to conventional optical fiber methods [2]. The basic principle, on which the working of any optical sensor is based, is index of refractive variation with respect to change in the sensing element [3]. Capturing the change in refractive index is enhanced by using the line defect in photonic crystal structure.

This variation is refractive index can be mapped to the shift in frequency and wavelength of the light, which further is mapped into change in acoustic pressure.

The goal of this paper is to model and simulate for photonic crystal based acoustic based sensor. The model consists of a waveguide carved in two dielectric slabs surrounded by photonic crystal. The dielectric slabs are mobile. The photonic crystal is mounted on the object under observation. As such its acoustic pressure can be coupled to the movement of the dielectric slabs in the photonic crystal and acoustic pressure variation can be mapped to the separation of these slabs and thus measured. As a consequence the optical properties of the photonic crystal like the transmission spectrum change. The altered transmission spectrum act as a signature of the acoustic pressure applied. The spectral analysis has been done to detect the change in the acoustic pressure.

II. THEORY

The photonic crystal is periodic structure of refractive index which helps in controlled propagation of light. The photonic crystal has certain properties which can manipulate the light propagation by altering the refractive index profile of the crystal. Photonic crystal appears in two configurations, rods in air and holes in slab configurations. It occurs in lattice structure, mainly square lattice and hexagonal lattice. Photonic crystal exhibits band gap properties which can be explored for sensing applications. Manipulation of light propagation can be done by creating defects, point defect and line defects [4].

In this paper, the model of photonic crystal consist waveguide carved with the help of two dielectric slabs, with the upper plate mobile. As the stress or strain is applied on the photonic crystal, the dielectric slab moves and change the dimension of the waveguide. As a result the index profile of the photonic crystal [5] is altered and thus changing the spectral property. This change in optical property is directly proportional to the applied stress or strain.

The Finite difference Time Domain (FDTD) method is implemented using the simulation tool MEEP. The Finite Difference Time Domain method solves the time domain Maxwell’s equation.
The method divides the field in time and space and solves for electric and magnetic fields. MEEP is a simulation tool developed by MIT for design, model and stimulate various photonic crystal structures. It is a time domain tool and implements the FDTD method. The transmission and the reflection spectrum [6] are obtained using the MEEP tool. MEEP solves the Poynting vector (Equation 1) and computed the fluxes [8].

\[ P(\omega) = Re \int E_\omega(x)^* \times H_\omega(x) d^2x \] ............ (1)

Here, 'P' is power, 'E' and 'H' are electric and Magnetic fields, '\omega' is the frequency.

III. DESIGN

The design of the acoustic pressure sensor consists of two dimensional, square lattice photonic crystal with a line defect in rods in air configuration. The model consists of waveguide carved with the help of two dielectric slabs. The upper dielectric slab is mobile with respect to the acoustic pressure applied. The lower dielectric slab is static. The structure of the model is illustrated in the Figure I with minimum separation and figure II with maximum separation between dielectric slabs.

Following points explain the design parameters of the modelled acoustic pressure sensor.

The design and simulation is done with the help of MEEP tool. The design parameters are given below:

i. Rods in air configuration
ii. Square lattice structure
iii. Lattice constant 'a'=1µm
iv. Radius of rods 'r'=0.19µm
v. Dielectric constant of silicon rods =11.56
vi. Wavelength of light 1350nm.

The modeling and simulation has been done with the help of MEEP simulation tool. MEEP tool works in time domain and provides implementation of Finite Difference Time Domain Method. MEEP is MIT Electromagnetic Equation Propagation. MEEP is 'dimensionless' tool where \mu_0, \epsilon_0, c are unity. The output of MEEP is the transmitted power; the transmission spectrum [9] is obtained using output from MEEP.

Operation: The Gaussian light pulse [7] is passed through one end of the photonic crystal while the spectrum analyser is placed in the other end. The applied acoustic pressure [2] moves the mobile plate reducing or increasing the distance between two dielectric slabs. The movement of the plate is considered in 10 steps, each step of 0.1µm. The changed dimension of the waveguide alters the light propagation and thus changing transmission spectrum.

The transmission spectrum is observed at each step of 0.1µm increase or decrease in distance between the two dielectric slabs. The fig III shows different model of acoustic sensor for zero micron displacement to maximum of two micron meter displacement in steps of 0.1 micro meters.

IV. RESULTS

The variation of distance between the slabs is as shown in fig III. The transmission spectrums with respect to frequency of all the displacements ranging from zero micron displacement to two micro meter displacement are shown in fig IV.

Fig IV is plotted in Matlab with frequency as discrete input and transmission flux values at finite intervals as corresponding outputs.
The transmission spectrums with respect to wavelength of all the displacements ranging from zero micron displacement to two micro meter displacement are shown in fig V.

Fig V is plotted in Matlab with wavelength as discrete input and transmission flux values at finite intervals as corresponding outputs.

The acoustic pressure for a depth of 200 meters was calculated with the help of the formulae $P = A \omega p_o C$, where $P$= acoustic pressure, $\omega$= angular frequency, $p_o$=specific density of the medium through which sound propagates, $C$=speed of light under water.

The results were calculated for temperatures varying for 32°F, 40°F, 50°F, 60°F, 70°F, 80°F, 90°F, 100°F, 120°F, 140°F, 160°F, 180°F, 200°F and 212°F temperatures. The tabulated results are shown in table I.
V. CONCLUSION

In this paper, we are successful in modeling and analyzing acoustic pressure sensor using photonic crystal in sub-micron range. The varying spectrum of the waveguide can suitably and efficiently represent and measure the acoustic pressure applied on the object.

The sensor design consisting of a two dimensional square lattice photonic crystal structure and it is simulated and analyzed for detecting the change in the pressure for corresponding displacement level in sub-micron range. Visibly distinct shift in both wavelength and frequency are observed, proving the sensor to be sensitive to even a smallest change in the input displacement and corresponding acoustic pressure can be observed. This sensor will be very useful in different applications like aerospace, defense and pressure sensitive applications. Further, it can be designed and fabricated to measure expansion or compression or both.
REFERENCES


