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Photonic crystal ring resonator structure for temperature measurement

C.S. Mallika[a], Indira Bahaddur[a], P.C. Srikanth[a,*], Preeta Sharan[b]

[a] Department of ECE, Malnad College of Engineering, Hassan, India
[b] Department of ECE, The Oxford College of Engineering, VTU, Bangalore, India

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ABSTRACT

Photonic sensing technology has extended physical parameter like temperature sensing for vast range of applications. The basic principle of the photonic sensing technology is to observe the change of refractive index. The photonic crystal ring resonator structure aid in increasing the sensitivity of the designed sensor. In this paper, we propose a design of a photonic crystal ring resonator based sensor for the detection of temperature change at micron level. As the temperature change there is change in the refractive index profile of photonic crystal. This causes the central frequency, wavelength to change with respect to change in temperature. By capturing the change in the wavelength and frequency, the temperature change can be detected. The transmission and reflection spectrum are analyzed with the help of simulation tool MIT Electromagnetic Equation Propagation (MEEP). It is observed that the wavelength and frequency is shifted as the temperature is varied.

1. Introduction

The photonic crystal technology has immensely aided in exploring new ways to detect variation of physical parameters like temperature, pressure, humidity, etc. [1]. The structure health of equipment is very critical in some of the applications like civil, aerospace, defense and other. The temperature monitoring helps find any unanticipated change in the structural health of the device. The fiber optic cable based sensor for temperature variation monitoring are being used in different applications like civil, chemical and cement industries, metal production, semiconductor industry and other [2]. The fiber optical cable based temperature sensor provided better stability over the conventional non-optical methods.

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. 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 ring resonator 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 temperature.

The goal of this paper is to model and simulate a ring resonator, two dimensional photonic crystal based sensor for the detection of temperature variation.

2. 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 [4]. 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.

In this paper, we are creating a ring resonator structure which is nothing but the combination of line defect and a circular waveguide carved in the photonic crystal. The source is placed at the one end of straight waveguide and the spectrum analyzer at the other end. Due to interference the light moves in the circular waveguide and again back in the straight waveguide before coming out of the crystal. The ring resonator structure is all-pass structure which provides high sensitivity.

* Corresponding author. Tel.: +91 9449612666.

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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 [5,6]. 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 are obtained using the MEEP tool [7]. MEEP solves the Poynting vector (Eq. (1)) and computed the fluxes.

$$P(\omega) = Re \quad \hat{n} \cdot \int E_{\omega}(\dot{x})H_{\omega}(x)d^2x \tag{1}$$

Here, 'P' is power, 'E' and 'H' are electric and magnetic fields, 'ω' is the frequency.

The temperature range from 1 °C to 100 °C is observed in the steps of 10 °C. Water is used in background of the crystal since water increases to temperature sensitivity as the refractive index variation is more in water as the temperature changes. The input refractive index is calculated using Cauchy equation for given the temperature range.

3. Design

The design of the sensor consists of the two dimensional square lattice ring resonator photonic crystal structure in rods (silicon) in air configuration. A straight and circular waveguide is carved out making a ring resonator structure. The designed model is illustrated in Fig. 1.

The design and simulation is done with the help of MEEP tool [8,9]. The design parameters are given below:

(1) Rods in air configuration
(2) Square lattice structure
(3) Lattice constant 'a' = 1 μm
(4) Radius of rods 'r' = 0.19 μm
(5) Dielectric constant of silicon rods = 12
(6) Dielectric constant of back ground is changed with respect to temperature range
(7) The wavelength of light 1350 nm.

As the temperature increase the refractive index profile of the photonic crystal changes, as a result the transmitted and reflected flux values changes. The change in the transmitted flux, reflected flux is observed for the slight change in the temperature.

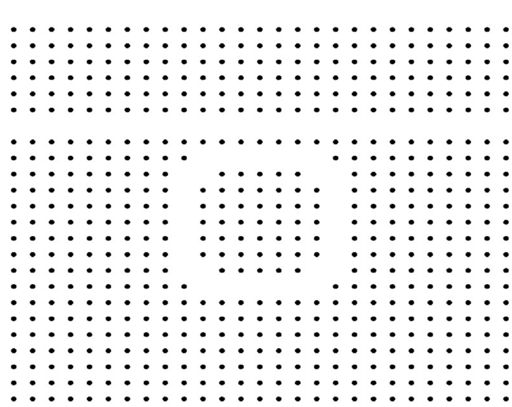

Fig. 1. Design of PCRR structure.

Table 1
Temperature vs. refractive index of silica.

T	N
1	1.756488118
10	1.756463761
20	1.756436629
30	1.756409425
40	1.75638215
50	1.756354803
60	1.756327384
70	1.756299894
80	1.756272331
90	1.756244696
100	1.756216989

The refractive index formula for pure silica has been considered as below,

$$n^2 = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E} \tag{2}$$

where the Cauchy coefficients A, B, C, D and E are linearly dependent on temperature T (in °C) in the following manner (Table 1):

$$A = M_A T + Y_A; \quad M_A = 3.1463 \times 10^{-8}; \quad Y_A = 1.3855 \tag{3}$$

$$B = M_B T + Y_B; \quad M_B = 2.0427 \times 10^{-5}; \quad Y_B = 0.7844 \tag{4}$$

$$C = M_C T + Y_C; \quad M_C = 2.8155 \times 10^{-6}; \quad Y_C = 0.011029 \tag{5}$$

$$D = M_D T + Y_D; \quad M_D = -6.7886 \times 10^{-5}; \quad Y_D = 0.91136 \tag{6}$$

4. Results

The transmission spectrum plot is illustrated in Fig. 2. The reflection spectrum plot is illustrated in Fig. 3. From the graph Fig. 2, it can be observed that as the temperature is increasing the transmitted power is also decreased. Even though the change in the refractive index is slight, the change in the transmission spectrum is visibly distinct, proving the sensor to be very sensitive to the change in the temperature. From the graph Fig. 3, it can be observed that as the temperature is increasing the reflected power is also increased (opposite to that in transmission spectrum). Even though the change in the refractive index is slight, the change in the reflection spectrum is also visibly distinct, proving the sensor to be very sensitive to the change in the temperature.

The plot in Fig. 4 shows the variation of the transmission amplitude as the temperature varies. It can be observed that the

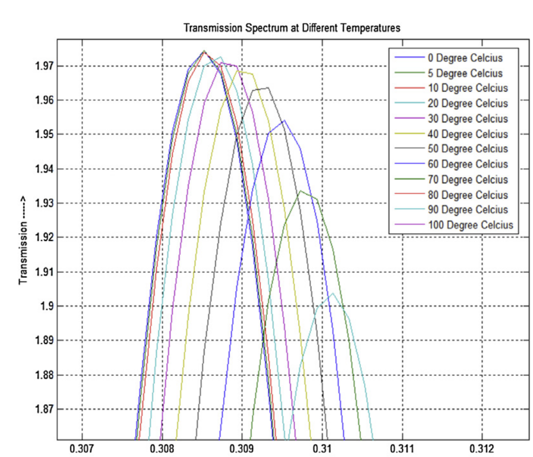

Fig. 2. Transmission spectrum for different temperatures.