Transverse 2D Photonic Crystal Inside a Fiber Optic For Picometer-scale Measurements

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***Abstract*—In this paper we analyze a sensor based on a transverse triangular 2D photonic crystal (PC) embedded inside a fiber optic (FO). The sensor modulates the transmitted light in order to estimate small mechanical deformations. The proposed sensing system measures mechanical deformations using a particular PC geometry, comparable to light wavelengths. This allows for light-matter interactions, which reveal accurate information about dimensional changes.**

***Keywords*—photonic crystal, sensor, elongation**

I. Introduction

Precise measurements of small deformations have a plethora of applications, from smart structures [1] to biomedical fields [2]. As such, they are used in intelligent devices, aiming to measure changes in shape or to monitor structural health, as well as for damage detection of composite laminates or complex-shaped composite structures [3]. Relying on light to sense various parameters (e.g., interference, variations of phase, and/or amplitude of electromagnetic field) [4], one can infer information regarding different variables to be measured – such as temperature, deformation, or chemical concentration. Out of the numerous optical systems used in various sensorial devices, fiber optics (FOs) is most promising, not only for carrying information, but also as sensing devices. Besides FOs, quite promising optical (or better said "photonic") systems are those having particular dimensions and which are specifically designed to interact with light as exhibiting photonic band gaps (PBG) [5, 6]. Smart combinations of FOs and photonic crystals (PCs) have led to a new class of lightwave guides: photonic crystal fibers (PCFs). PCFs transmit light based on two physical phenomena: one is total internal reflection (called index-guiding PCF), while the other one is the formation of photonic band gap (called photonic band gap fibers (PBGF)). The PBGF are highly sensitive, and that is the reason why they are used as sensor devices, for example for mechanical motion detection, for biomedical applications, or as refractive index sensors [7-9].

The PBGF sensors developed so far have been limited to 2D PCs along the FO axis (i.e., longitudinal structures). The aim of this paper is to present our current work that we carry on in order to propose, study and optimize sensor structures with transversal bi-dimensional (2D) PCs lattices configured inside a FO (see Fig. 1).

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II. Proposed Sensor

It is well know that PC structures exhibit strong interactions with light. Based on such interactions, a large variety of sensors have been developed over the last decades.

We have proposed [10] a rectangular lattice PC embedded transversally into a single mode FO in order to measure small mechanical elongations (Fig. 1(a)). In this paper we use the same concept but the transverse 2D PC embedded inside the FO is designed using a triangular lattice.

The sensor modulates the transmitted light, allowing for the estimation of small mechanical deformations. The proposed sensing system measures such deformations using a particular PC geometry which is comparable to the light wavelength. This allows for light-matter interactions, which reveal accurate information about the dimensional changes that occur. To develop the sensor, we simulate and analyze the sensitivity of such a structure with regard to changes in the components of the electromagnetic field of the light.

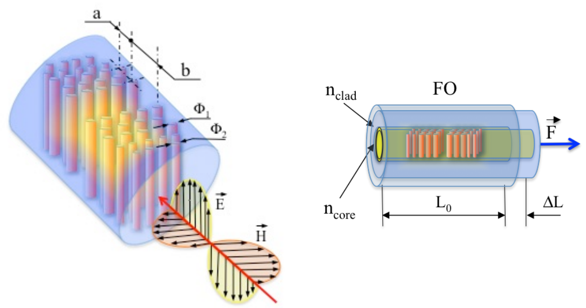


Fig. 1. Schematic 3D view of the sensor: (a) geometrical parameteres and electromagnetic (EM) components; (b) behavior under an applied force F - showing the elongation, ΔL.

III. Simulations and Discussions

The deformation of any object under an external force obeys Hook's law depending on its material (Young modulus, *Y*) and geometry, as well as on the applied force (F). As this force is applied along the FO, it will pull apart the PC, modifying its geometry (Fig. 1). This process has been repeated in our simulations for all forces in the range of 0 to 10 N (with a step of 1 N), and has been used to calculate 11 different 2D PC lattice geometries, characterized by the parameters (a, b, φ_1, φ_2). More precisely, φ_1 and φ_2 have kept constant, while a and b have been affected by F. These 11 sets of geometric parameters represent the input for the next step.

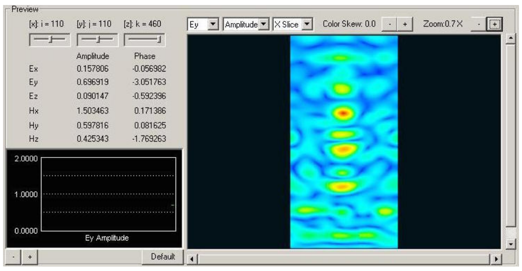
EMExplorer (a program based on the Finite Difference Time Domain method to solve Maxwell equations) has been used for analyzing all the different PCs. The simulations were performed on a layout having air as background (n/k = 1/0), a band gap wavelength λ = 1500 nm, a mesh size ($\Delta x \times \Delta y \times \Delta z$) of 5 nm×5 nm×5 nm, and a perfectly matched layer (PML) was used as an absorbing border condition.

TABLE I. SENSOR GEOMETRY AT F = 0 N AND SIMULATIONS PARAMETERS

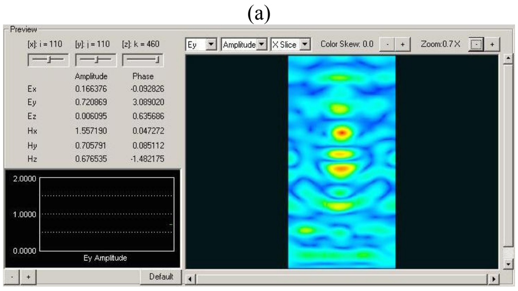
Geometry [nm]				Simulations		
a	***b***	ϕ_1	ϕ_2	***n/k***	***Boundary conditions***	***Mesh size* [nm]**
215	620	120	134	1/0	PML	5 x 5 x 5

The simulation results for each PC under test are the EM amplitude and phase components, on each of the three axes. Therefore six electrical and six magnetic components are obtained for each PC. For a variation ΔF = 1 N (between F = 1 N and F = 2 N), the phase of E_y varies from 3.051 to –3.089 radians. This means that the FO mechanical sensor embedding the triangular-lattice PC exhibits a phase variation of $\Delta\phi$ = 3.089 – (–3.058) = 6.14 radians = 351.8° (on E_y) for a mechanical deformation of ΔL = 3.34 nm (corresponding to ΔF = 1 N). Hence, the sensitivity of the sensor can be calculated:

$$\Delta L|_{\Delta F=1N}/\Delta\phi = 3.43/351.8° = 9.75\,\text{pm}/°$$



(a)



(b)

Fig. 2. Screenshots of the EMExplorer windows showing the electrical components variations: (a) F = 1N, (b) F = 2N.

IV. CONCLUSIONS

This paper has presented and analyzed a nanometer scale mechanical sensor based on transversally embedding triangular PC structures into a monomode FO.

The mechanical deformations produced for the structure have been evaluated. Our simulations have shown that measuring the output phase variations of the EM components can provide precise data on small mechanical deformations of the sensor (from F = 1 N to F = 2 N).

The next steps in exploring such sensors are to choose a different lattice of the 2D PC, alter their geometrical parameters, and/or change the materials (Y); for the latter direction, some tuning of the sensitivity may be possible by filling the PC's holes with materials having different refractive indices.

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