Optical Fiber Technology 33 (2017) 83–88

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

SPR optimization using metamaterials in a D-type PCF refractive index sensor

D.F. Santos [a,c,*], A. Guerreiro [b,c], J.M. Baptista [a,c]

[a] Faculdade de Ciências Exatas e da Engenharia, Universidade da Madeira, Funchal 9000, Portugal
[b] Faculdade de Ciências da Universidade do Porto, 4169, Portugal
[c] INESC TEC, Porto 4200, Portugal

A R T I C L E I N F O

Article history:
Received 25 August 2016
Accepted 6 November 2016
Available online 18 November 2016

Keywords:
Optical fiber sensor
Refractive index sensor
D-type photonic crystal fiber
Surface plasmon resonance
Metamaterials
COMSOL multiphysics

A B S T R A C T

Using the finite element method (FEM), this paper presents a numerical investigation of the performance analysis of a D-type photonic crystal fiber (D-type PCF) for refractive index sensing, based on surface plasmon resonance (SPR) with a planar structure made out of a metamaterial. COMSOL Multiphysics was used to evaluate the design of the referred refractive index optical fiber sensor, with higher accuracy and considerable economy of time and resources. A study of different metamaterials concentrations conformed by aluminum oxide (Al_2O_3) and silver (Ag) is carried out. Another structural parameters, which influences the refractive index sensor performance, the thickness of the metamaterial, is also investigated. The results indicate that the use of metamaterials provides a way of improving the performance of SPR sensors on optical fibers and allows to tailor the working parameters of the sensor.

1. Introduction

In the past decade, resonant interaction between surface plasmons and light in metal films have introduced a revolution in high sensitivity optical sensing. Nowadays, with the development of improved fabrication techniques of metal-dielectric nanostructures it is possible to develop new artificial materials, such as optical metamaterials. These materials combine the properties of their constituent materials, and open new ways to explore the interaction between light and matter [1], and in particular between light and surface plasmons. In this paper, we address the use of metamaterial films as an alternative to metal films in SPR optical fiber sensors.

Surface plasmons generate exceptionally robust and spectrally narrowed optical fields far beyond the diffraction limit, which are strongly dependent on geometric parameters of the films [2] (such as thickness) as well as the refractive index of the media surrounding the metal [3]. These fields can couple the optical fields guided inside a waveguide with the exterior, thus imprinting their spectral features and dependencies in the optical losses of the fiber. This can be used to strongly improve the performance of optical fiber sensors. Indeed, many configurations of fiber optic sensors are based on SPR by removing the cladding (partial or totally) to allow the deposition of a thin metallic layer (usually gold or silver) [1]. This film supports the excitation of SPR and their interaction with the electromagnetic modes of the core.

There is an abundant work in literature that study different metallic layers to optimize SPR sensors (from controlling losses, to increasing sensor endurance, among others) [4–6]. The possible combinations of the material layers used are not restricted to metals. Also materials with high refractive index (HRI) can be used to control optical losses and the sensor operation range [7]. The main problem with these materials or this combination of the materials is the difficult control in the fabrication of the material films (including their thickness and roughness) and consequently in the control of their optical properties [8].

More recent works on SPR sensors, that combine different materials, have begun to explore the use of optical metamaterials. These artificial materials combine two or more materials to create a new artificial material which exhibits optical properties that cannot be found in naturally occurring materials and which can be designed to attain predefined performances [9]. These properties depend both on the optical properties of their constituent materials, their relative abundance and the geometry of the nanostructures used to combine them. This wide freedom available during fabrication allows to develop metamaterials with almost customized optical properties that can be used to optimize the performance of the sensor (e.g. loss, the light wavelength range,

* Corresponding author at: Faculdade de Ciências Exatas e da Engenharia, Universidade da Madeira, Funchal 9000, Portugal.

E-mail address: diegonobregasantos@gmail.com (D.F. Santos).

http://dx.doi.org/10.1016/j.yofte.2016.11.010

the refractive index range detection, among others) to values beyond that of conventional SPR sensors [10].

In this paper, we pursue this approach and present a sensor based on SPR that combines a D-type PCF fiber with a metamaterial (Al_2O_3 – Ag). The performance of the sensor is investigated through simulations based on FEM using COMSOL Multiphysics [7]. The sensor analysis is focused on the percentage of each constituent of the metamaterials and the layer thickness, which are the main parameters in determining their optical properties. The numerical simulation of new sensing concepts and configurations allows to select the ones with best performance to be fabricated, thus leading to a considerable economy of time and resources when compared to an exhaustive fabrication and test of all possible designs.

2. Design and model

We consider the design of an optical sensor of refractive index composed of a PCF fiber with D-type profile, as described in Fig. 1. The fiber is composed by a glass core with refractive index n_g, surrounded by an array of dielectric structures (corresponding to the holes in the PCF fiber) with refractive index equal to 1. The refractive index n_g is calculated using the Sellmeier equation [7]. It is assumed that the space outside the fiber is filled with the analytic medium to be studied, and having an external refractive index n_{ext}. The distance between the center of the fiber and the metamaterial layer is denoted by d – residual cladding, the thickness of metamaterial layer by d_m, the diameter of the holes by d_{hole}, and the separation of the holes by Λ – pitch.

PCF favors the confinement of light in the core, whereas the D-type profile of the fiber promotes the interaction of the core modes with the external medium. The interaction of the electromagnetic modes with the external media is mediated by a metallic film that supports surface plasmons, which improves the sensitivity of the sensor [11]. In this paper we replace the metal with a metamaterial film composed of thin layers (sub-wavelength) of silver and alumina (see the inset of Fig. 1).

The optical properties of the metamaterial depend on the relative thickness of the silver and alumina layers. The effective refractive index of the metamaterial film can be calculated using an effective medium approach, of which the Maxwell- Garnett Theory (MGT) and the Bruggeman effective medium theory (BEMT) are the most commonly used models [9]. In our case, we adopt the BEMT since it is more adequate when the two material have quite distinct permittivity, rather than the MGT, which considers only materials with similar permittivity,

$$f_1 \frac{\epsilon_1 - \epsilon_m}{\epsilon_1 + \nu\epsilon_m} + f_2\epsilon_2 - \epsilon_m\epsilon_2 + \nu\epsilon_m = 0 \quad (1)$$

where ε_m is the dielectric constant of the metamaterial, ε_i (i = 1, 2) is the refractive index of each of the two types of inclusions (Ag and Al_2O_3, respectively), with volume filling-ratios of f_1 and $f_2 = 1 - f_1$, respectively, and η is the form factor (η = 2 for this geometry). Other nanostructures of Al_2O_3 – Ag can also be used, including silver nanowires or nanorods immersed in an alumina matrix. In these cases, the same homogenization model can be used by replacing the form factor η with the appropriate value according to the geometry of the nanostructures. The general optical properties obtained for other metamaterials are alike and therefore we focus here on the simplest form to fabricate [10].

The complex dielectric of the metamaterial results from the combination of properties from its metal and dielectric components. As a result, the metamaterial layer can be considered as an artificial metal layer capable of supporting effective plasmonic modes. Using Eq. (1) we can calculate the complex dielectric of the metamaterial as shown in Fig. 2, for different concentrations of Ag.

Fig. 2 shows the real (Fig. 2a) and imaginary (Fig. 2b) parts of the dielectric for the different concentrations or fill ratios of the Ag and Al_2O_3 calculated using the BEMT model. Like in the case of a pure silver film, the metamaterial films with fill ratios up to 50% have a negative dielectric constant for the large majority of the spectral range considered, which is a necessary condition to support surface plasmons. In the case of a fill ration of 50%, the metamaterial is close to a epsilon-near-zero regime, situation where the effective medium approach may have a limited validity.

The study is based on the calculation of the guided modes taking into account both the PCF D-type fiber and the metamaterial layer. These modes are referred as supermodes (SMs) since they correspond to the hybridization of the individual modes of each of the structures that compose the device taken isolated, which in our case are the fundamental guided mode of the fiber and the plasmon modes in the metal or metamaterial layer. All these modes can be calculated numerically by solving the wave equation for the Fourier components of the electric field [12]

$$\nabla \times [\nabla \times E(\gamma, \omega) - k_0^2 \tilde{\epsilon}_\gamma(\gamma, \omega)]E(\gamma, \omega) \quad (2)$$

where ω is the frequency, $E(r, \omega)$ is the electric field, $k_0 = \omega/c$ is the wave-number of the field mode and c is the speed of light. The term $\tilde{\varepsilon}_r$ represents the complex relative dielectric function written in terms of the real part (n_r') and imaginary part (n_r'') of the refractive index. The computer model is based on FEM implemented in COMSOL Multiphysics, following the method described in a previous work [13].

The optical power flow of the guided mode is given by the real part of the time-averaged Poynting vector

$$S = (1/2)Re(exh^*)e^{-oz} \quad (3)$$

whereas the sensor resolution (R) is calculated from the sensitivity according to [14]

$$R(\lambda) = \frac{\Delta n_{ext}\Delta\lambda_{min}}{\Delta\lambda_{peak}} \quad (4)$$

where $\alpha = 2n_{ef}''k_0$ is known as the power absorption coefficient, λ_{min} is the minimum value associated with an experimental accurately

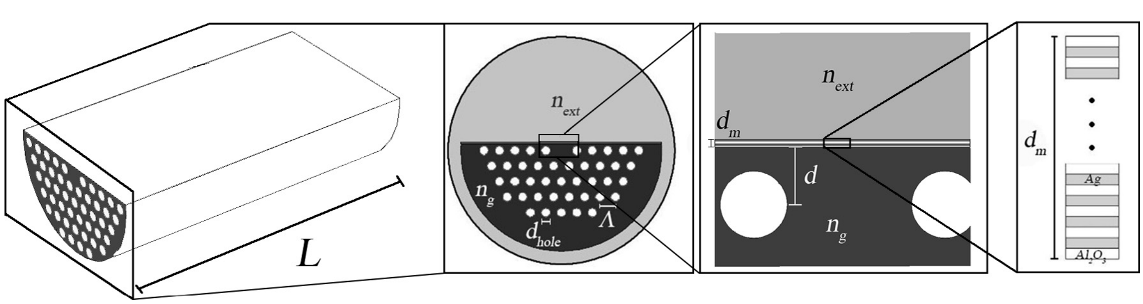

Fig. 1. From left to right: three dimensional representation of a section of the fiber sensor, transverse cross-section of the fiber sensor, detail of the structure of the surface of the sensor indicating the position metamaterial film and a scheme of the thin metal-dielectric layers that compose the metamaterial.