Sensors and Actuators B 238 (2017) 1–8

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Theoretical modeling and investigations of AZO coated LMR based fiber optic tapered tip sensor utilizing an additional TiO_2 layer for sensitivity enhancement

Nidhi Paliwal*, Joseph John

Department of Electrical Engineering, Indian Institute of Technology-Bombay, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form 2 July 2016
Accepted 7 July 2016
Available online 11 July 2016

Keywords:
Lossy mode resonance
Fiber optic sensors
Thin films
Tapered tip
Refractive index

ABSTRACT

This article presents a theoretical model for lossy mode resonance (LMR) based fiber optic (FO) tapered tip sensor coated with aluminum doped zinc oxide (AZO) and titanium dioxide (TiO_2) layer. In LMR based FO tapered tip sensor, sensing signal is measured in terms of retro-reflecting spectra whereas in conventional LMR sensors it is measured in terms of the transmittance. A major advantage of the proposed sensor is that it requires small sample volume. Also its compact tapered tip design makes it more suitable for point sensing. In this work, for the first time, a detailed analysis of AZO coated LMR based FO tapered tip sensor has been carried out. Additionally, the combined effect of AZO and TiO_2 thickness ratio along with the fiber parameters such as fiber tip radius, tip length and numerical aperture on the reflectance spectrum has been investigated. The proposed geometry along with appropriate combination of various fiber parameters and the thin films thickness ratio provides approximately sixfold increase in the sensitivity compared to the conventional tapered LMR sensors. Sensitivity of the proposed sensor has also been compared with straight fiber geometry. Refractive index (RI) sensitivity of the proposed sensor is in the range of 1500–9000 nm/RIU.

1. Introduction

In the past few years lossy mode resonance (LMR) phenomenon has been an emerging field of research due to its several advantages over surface plasmon resonance (SPR) [1–5]. The various advantages of LMR phenomenon such as freedom to use any specific light polarization for its generation and multiple LMRs make these sensors very popular and efficient in physical, chemical and biological sensing [6,7]. LMR can be easily generated by an unpolarized light source provided that the fiber cladding material has positive real part of its dielectric constant and the magnitude of real part is higher than both its imaginary part and the dielectric constant of the sensing medium. LMR arises due to the coupling between waveguide modes and the thin film lossy modes at specific conditions [1]. LMR based FO sensors are miniaturized and also capable of remote sensing due to the ability of optical fibers to transmit optical power over long distances. In the transmission based LMR sensors, light is coupled into one end of the fiber and after passing through the sensing region transmitted power is detected at the other end. Another possible technique in LMR sensors is to detect the retro-reflection spectra instead of the transmission spectra [8,9]. Various SPR sensors incorporating retro-reflection spectra have been reported where the fiber tip coated with a metal layer is used as the sensing element [10–12]. These sensors work on the principle of first coupling the light into one end of the fiber sensing element and detecting the reflected light after reflection from the tip at other end of the fiber. This results in the retro reflection spectra of the sensor which can be detected by a spectrometer. These retro-reflecting sensors have several advantages such as cost effectiveness, less sample volume requirement and simple sensor illumination [12]. In this view, we propose an AZO coated LMR FO tapered tip sensor based on retro-reflection spectra with an additional TiO_2 film to enhance its sensitivity. Structure of the proposed LMR based FO tapered tip sensor was formed by decladding and tapering the fiber end and then depositing an AZO layer followed by a TiO_2 thin film on the tapered portion.

Various studies on LMR fiber optic sensors based on clad-removed multimode tapered, monomode tapered and reflection geometries have been reported [13,9,8,14]. However to the best of our knowledge a detailed theoretical analysis of thin film coated

* Corresponding author at: EE-206 Fiber Optics Lab, Electrical Engineering Dept., Indian Institute of Technology-Bombay, Mumbai 400076, India.
E-mail addresses: nidhi83paliwal@gmail.com (N. Paliwal), jjohn@ee.iitb.ac.in (J. John).

http://dx.doi.org/10.1016/j.snb.2016.07.032
0925-4005/

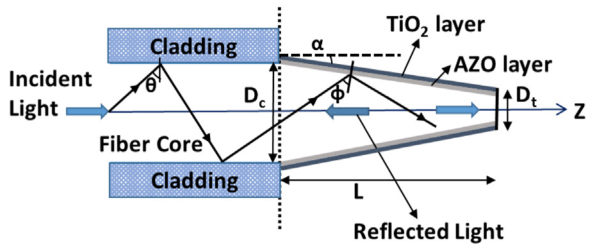

Fig. 1. Schematic of AZO/TiO_2 coated LMR based fiber optic tapered tip sensor.

multimode tapered tip sensors based on retro-reflection method has not been done so far. In this article we provide a detailed theoretical modeling of a reflection based LMR FO tapered tip sensor utilizing AZO thin film. Additionally, we analyze sensitivity of the proposed reflection based tip sensor, utilizing additional TiO_2 thin film of higher RI on top of the AZO film of lesser RI. In our theoretical studies, we have chosen AZO for various reasons. First, it comes under the category of transparent conducting oxides (TCO) which showed potential as a substitute for plasmonic materials required in SPR based sensors [15]. ITO also belongs to TCO and is the most popular material for solar cells, liquid crystal displays, etc.; however the devices produced with ITO are costly and at the same time indium is also scarce in nature [16]. Therefore the various advantages of AZO over ITO, viz. low cost, non-toxic and easy availability, makes it an ideal substitute for ITO in applications such as flat panel displays, transparent solar cell electrodes, etc. Second, AZO film can be deposited by various deposition methods such as ALD, sol–gel, dip coating, sputtering, CVD. Its optical properties can also be easily tuned by choosing the appropriate deposition technique depending on the application [16–19]. Various studies utilizing AZO thin films have been reported for ultra-violet (UV) detectors, solar cells and gas sensing applications [17,19,20]. Above all, the most important characteristic of AZO is that LMR can be generated in the visible spectral range (400–700 nm). Hence with AZO coating it is possible to fabricate cost effective LMR-based refractometers operating in the visible region due to the availability of low cost sources and detectors. Additionally, AZO is a relatively new material for LMR generation [21,22] whereas, indium tin oxide (ITO) coated optical fiber refractometers operating in the infrared (IR) region have been extensively studied [1,2,23–25,4]. We study the effect of various fiber parameters, viz. taper radius, taper length and numerical aperture on the reflection spectra. Also the combined effect of tapering and thin film thicknesses on the sensitivity has been studied extensively by considering all possible combinations of thin film ratios. Sensitivities of LMR tapered tip sensor coated with single AZO film and AZO/TiO_2 thin film combination have also been compared with the untapered (straight) reflection based LMR FO sensors.

2. Model and methods

We used attenuated total reflection (ATR) method along with the most commonly used Kretschmann configuration for analyzing the AZO/TiO_2 coated LMR based FO tapered tip sensor. In order to design a tip sensor, polymer cladding was removed from a small portion at the one end of a step index multimode fiber and the unclad region was conically shaped with a linear profile. This conical portion of the fiber was coated with AZO thin film and subsequently with the TiO_2 thin film. This structure was further surrounded by different sensing media. A schematic of AZO/TiO_2 coated LMR based FO tapered tip sensor structure is illustrated in Fig. 1. In this proposed LMR sensing structure, the inner thin film comprises AZO and the outer one is of TiO_2. All the guided light rays from a broadband source were launched onto one end of the fiber and detected at the same end after reflection from the end face. We used the transfer matrix method for simulating the ATR.

2.1. Dispersion relations

For theoretical simulations, dispersion relation of optical fiber core is given by the Sellmeier relation [4]

$$n_1(\lambda) = \sqrt{1 + \frac{a_1\lambda^2}{\lambda^2 - b_1^2} + \frac{a_2\lambda^2}{\lambda^2 - b_2^2} + \frac{a_3\lambda^2}{\lambda^2 - b_3^2}} \quad (1)$$

where λ is the wavelength (μm), $a_1 = 0.6961663$, $a_2 = 0.4079426$, $a_3 = 0.8774794$, $b_1 = 0.0684043$, $b_2 = 0.1162414$ and $b_3 = 9.896161$ are the Sellmeier coefficients.

For the dispersion of AZO, the following Drude model is used [26]

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 + \gamma^2} + \frac{i\gamma\omega_p^2}{\omega(\omega^2 + \gamma^2)} \quad (2)$$

where ϵ_∞ is the background permittivity, ω_p is the plasma frequency, and γ is the damping frequency, $\epsilon_\infty = 3.5$, $\omega_p = 5.22 \times 10^{14}$ Hz and $\gamma = 4.86 \times 10^{13}$ Hz. Here $\omega = c/\lambda$ where λ and c are the wavelength and the speed of light respectively.

For TiO_2, dispersion relation is defined by the Lorentz model [3]

$$n^2(E) = \epsilon_\infty + \sum_k \frac{A_k}{E_k^2 - E^2 - iB_kE} \quad (3)$$

For our simulations we have used the following parameters: high frequency dielectric constant $(\epsilon_\infty) = 1$, center energy $(B_k) = 1.2$ eV, amplitude $(A_k) = 101$ eV^2 and $E_k = 6.2$ eV. Photon energy is given by $E = hc/\lambda$ where h and c are the Planck's constant and speed of light in vacuum respectively.

2.2. Reflected power

The expression for optical power (dP) at the fiber-end is given by [1]

$$dP \propto \quad n_1^2 \sin\theta \cos\theta d\theta \quad (4)$$

Since all guided rays are launched into the fiber tip sensor structure, the generalized expression for the normalized reflected power P_{ref}, can be written as [11]

$$P_{ref} = \frac{\int_0^L \int_{\phi_1}^{\phi_2} R^{2N_{ref}(\theta,z)} k_0^2 n_1^2 \sin\theta \cos\theta d\theta dz}{\int_0^L \int_{\phi_1}^{\phi_2} k_0^2 n_1^2 \sin\theta \cos\theta d\theta dz} \quad (5)$$

where $N_{ref}(\theta, z) = (L/(2\rho(z)\tan(\theta + \alpha)))$ is the number of reflections in the sensing region.

Here L is the sensing region (taper) length, θ is the angle of the ray with the normal to core-cladding interface, $\alpha = \tan^{-1}((\rho_c - \rho_t)/L)$ is the taper angle and $\rho(z)$ is the variation of tip radius with the length of propagation given by the expression

$$\rho(z) = \rho_c - \frac{z}{L}(\rho_c - \rho_t) \quad (6)$$

where ρ_c, ρ_t are the radius of optical fiber core and tip respectively. The range of angles in the tapered region becomes ϕ_1 and ϕ_2 due to variations in the fiber core diameter. Therefore, numerical expression for ϕ_1 and ϕ_2 is given by

$$\phi_1(z) = \cos^{-1}\left(\frac{\rho_c \cos\theta_{cr}}{\rho(z)}\right) - \alpha \quad (7)$$

$$\phi_2(z) = \frac{\pi}{2} - \alpha \quad (8)$$