Optics and Laser Technology 102 (2018) 254–261

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

[INVITED] Design of turn around point long period fiber grating sensor with Au-nanoparticle self monolayer ☆

Sankhyabrata Bandyopadhyay, Nandini Basumallick, Sandip Bysakh, Tanoy Kumar Dey, Palas Biswas, Somnath Bandyopadhyay *

Fibre Optics and Photonics Division, CSIR-Central Glass and Ceramic Research Institute, Council of Scientific and Industrial Research (CSIR), 196, S.C. Mullick Road, Kolkata, India

ARTICLE INFO

Article history:
Received 30 September 2017
Received in revised form 8 December 2017
Accepted 13 December 2017

Keywords:
Fiper optic sensor
Long period fiber grating
Refractive index sensing
Coupled mode analysis
Chemical and biosensor

ABSTRACT

In this paper studies on the design and fabrication of a long period fiber grating (LPFG) with a self mono layer of gold nanoparticle (AuNP) has been presented. Refractive index (RI) sensitivity of a dispersed cladding mode (DCM) near turn around point (TAP) of its phase matching curve (PMC) has been investigated with and also without AuNP coated LPFG. The typical role played by the intermediate layer of AuNP on the effective index and thus on the sensitivity of the cladding mode to the surrounding RI has also been explored by carrying out coupled mode analysis of the requisite multilayer waveguide. Deposition of AuNP enhanced the sensitivity by more than a factor of 2. Measured sensitivity was found to be ~3928 nm/refractive index unit (RIU) in the range of 1.3333–1.3428.

1. Introduction

Optical fiber long period grating (LPFG) is nowadays playing a major role in the field of chemical and biological sensing [1]. These sensors are compatible to standard components used in the fiber optic telecommunication. Secondly, the sensor signal is wavelength encoded and can be conveniently located anywhere in the C and L band of the telecommunication window. Wavelength encoded sensor signal is immensely useful because the readout is never affected by changes in the optical intensity caused by either fiber bending or source fluctuations. Also the availability of a wide operating wavelength helps many sensors be multiplexed for specific applications. These sensors are nowadays designed with significantly enhanced RI sensitivity either by operating the cladding modes of the LPFG near the turn-around-point (TAP) or by designing the cladding mode near mode transition (MT) [2–4]. The most interesting approach seems to be the design where a combined effect of working around DTP and MT is used [5,6]. These highly sensitive LPFG sensors, if suitably designed are able to provide ample information about the dynamic interactions taking place around the surface of the optical fiber during bio-molecular interactions [7].

New developments in nanotechnology and nanomaterial have allowed researchers to expand chemical and biological sensing approach with improved sensitivity and selectivity [8,9]. Among them gold nanoparticle (AuNP) is found to become an important constituent for the fabrication of novel chemical and biological sensors. AuNPs with tuneable nanostructures improve the optical and electronic properties, increase the effective surface of the transducer and thus offers high sensitivity [10,11]. Secondly, there are several options to effectively functionalize AuNPs with well engineered biorecognition components and organic or biological ligands to promote surface based binding events with target analyte and recognition element. The process subsequently alter the optical and electrical properties of AuNPs and produces a detectable response signal for the transducer which provides a variety of inventive approaches for the detection of metal ions, proteins, DNA, mRNA and many more microorganisms. Almost all of the established sensor signal interrogation techniques, such as electromechanical sensors, spectroscopic or chromatographic measurement platforms or excitation of localized surface plasmon resonance have been in use for signalling the binding event or the attachment of analyte with AuNP.

In the case of LPFG sensors, evanescent filed of the propagating cladding modes interacts with the medium surrounding the optical fiber. Thus deposition of a self organized monolayer of AuNP or a layer of AuNP-Polymer or AuNP-glass composites around on the fiber grating will influence the resonance condition of the cladding modes of LPFG. The resonant wavelength of the cladding modes

☆ Invited article by the Guest Editor: Orlando Frazão.

* Corresponding author.
E-mail address: somnath@cgcri.res.in (S. Bandyopadhyay).

https://doi.org/10.1016/j.optlastec.2017.12.025
0030-3992/

then become a function of the shape, size, inter particle distance and refractive index of the medium surrounding the layer of AuNP as well as the analyte molecules those subsequently bind with the AuNPs. However though in recent past, the number of articles published on the use of AuNP in chemical and biosensing is countless, the research efforts devoted to the integration of AuNPs to highly sensitive LPFGs with an aim to develop biosensors are scanty. Enhancement of sensitivity of cladding modes of LPFG in presence of AuNPs on the surface of the fiber has been demonstrated earlier [12]. Recently, the sensitivity of $LP_{0,10}$ cladding mode with AuNP having average diameter of 50 nm was shown to be ~759 nm/RIU in the RI range from 1.333 to 1.4 [13]. Detection of streptavidin with a detection limit of ~19 pg/mm^2 was demonstrated successfully using TAP-LPFG with a coating of silica core gold shell (SiO_2: Au) nanoparticles [14].

It is important to mention at this point that the shift of the resonant wavelength of a cladding mode measured during the binding of chemical or biological analytes with the AuNPs is in fact influenced by two processes. The variation of average RI of the AuNP layer which arises due to attachment of chemical or biological species at specially functionalized AuNP sites must alter the effective index of a cladding mode and subsequently its resonant wavelength. This is actually the signal that reflects the binding events. The second contributing factor is the change of average RI of the AuNP layer due to filling up of its interstitial space by the fluid medium in the surrounding. The fluid, that may either be water, a buffer solutions, serum or plasma, acts as the matrix in which the chemical or biological assays are generally performed. The shift of the resonant wavelength in the second case depends solely on the nature of the AuNPs and their distribution on the surface and also on the RI of the matrix material but does not anyway depend on the binding mechanism. In the case of LPFG has never been addressed or studied in the literatures reported so far. Moreover, as there are no theoretical studies carried out to understand the influence of nanoparticles on the behaviour of the cladding modes of LPFG, eventually it was not possible to come up with sensor designs where the best of the LPFGs and the fascinating properties of the available nanostructured material could be amalgamated.

In this paper we present our studies on the design and fabrication of an LPFG with a self mono layer of AuNP. Refractive index (RI) sensitivity of a dispersed cladding mode (DCM) near turn around point (TAP) of its phase matching curve (PMC) has been investigated with and also without AuNPs on the surface of LPFG. The influence of the intermediate layer of AuNP on the effective index and thus on the sensitivity of the cladding mode to the surrounding RI (SRI) has also been explored by carrying out coupled mode analysis of a multilayer waveguide structure.

The paper is organized as follow, in Section 2, a brief theory of LPFG has been discussed which forms the basis of our numerical computations. Materials and experimental methods are presented in Section 3. Interpretation of results and discussions are given in Section 4 with a conclusion in Section 5.

2. Basic theory

In this section we briefly describe the mathematical equations used and the basic methodology of coupled mode analysis pursued to model AuNP coated LPFG subsequently to analyze the influence of the layer of AuNP on the sensitivity of a cladding mode to SRI. The geometry of the fiber considered in the modeling comprises a five layer (core-clad-polymeric layer-AuNP layer-Surrounding medium) cylindrical waveguide structure and is shown in Fig. 1.

We considered the transverse electric field components propagating along the z-axis as [15]

$$\Psi(r,\theta,\Phi) = e^{-j\beta_{vj}z}\Psi(r)\Theta(\theta)\varphi(\phi)$$

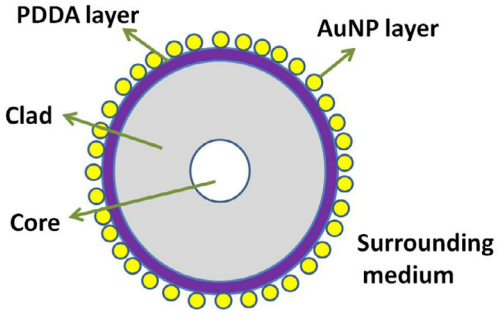

Fig. 1. Five layered waveguide structure that represents the cross section of an LPFG with a layer of AuNP.

where the radial function $\Psi(r)$ of the individual layer may be expressed as

$$\psi(r) = A_{vj}J_v(r\gamma_{vj}) + B_{vj}Y_v(r\gamma_{vj})\beta_{vj} < k_0 n \quad (1a)$$

and

$$\psi(r) = A_{vj}I_v(r\gamma_{vj}) + B_{vj}K_v(r\gamma_{vj})\beta_{vj} > k_0 n. \quad (1b)$$

$k_0 = 2\pi/\lambda$ is the free space wavelength, n is the refractive index of the layer, β_{vj} is the longitudinal propagation constant of the $LP_{v,j}$ mode and $\gamma_{v,j} = \sqrt{[k_0^2 n^2 - \beta_{v,j}^2]}$ is the magnitude of the transverse wave number. $A_{v,j}$ and $B_{v,j}$ are the field expansion coefficients determined by the boundary condition of the cylindrical layers. $J_v(r\gamma_{v,j})$ and $Y_v(r\gamma_{v,j})$ are the ordinary Bessel function of the first and second kind, while $I_v(r\gamma_{v,j})$ and $K_v(r\gamma_{v,j})$ are the modified Bessel function of first and second kind of order v. Standard transfer matrix method [16] was applied to find out the effective indices of the modes and field expansion coefficients of multi-layer LPFG waveguide structure. Field expansion coefficients of each layer were normalized so that each mode carries the same power P_0.

$$P_0 = \frac{\beta_{0j}}{2\omega\mu_0}\int_0^{2\pi} d\phi \int_0^{\infty} \psi(r)\psi^*(r) r dr \quad (2)$$

2.1. Coupled mode formation for the waveguide structure

Once the field expansion coefficients for each layer was derived, coupled mode differential equations were formed assuming each of the forward propagating modes have complex amplitude $A(z)$. We neglected backward propagating scattered waves. The generalized coupled mode equations may be expressed as

$$\sum_v \frac{dA_{\mu k}}{dz} = -j\sum_{vj=01}^{M}[K^t_{vj,\mu k} + K^z_{vj,\mu k}]A_{vj}(z)\exp(-j(\beta_{vj} - \beta_{\mu k})z) \quad (3)$$

for $\mu k = 01, \ldots M$. The parameters $K^t_{vj,\mu k}$ and $K^z_{vj,\mu k}$ are the transverse coupling and longitudinal coupling coefficients between $LP_{v,j}$ and $LP_{\mu,k}$ modes. It was assumed that $K^t_{vj,\mu k} \gg K^z_{vj,\mu k}$ so only transverse coupling coefficients were considered to compute the coupling of the modes. Transverse coupling coefficients was computed using the formula as prescribed in [15] and which may be represented as

$$K^t_{vj,\mu k} = \int_{\Phi=0}^{2\pi} d\Phi \int_{r=0}^{\infty} \Delta\varepsilon\psi_{vj}(r)\psi_{\mu k}(r) r dr. \quad (4)$$

where $\Psi_{vj}(r)$ and $\Psi_{\mu k}(r)$ are the transverse field components of $LP_{v,j}$ and $LP_{\mu,k}$ modes respectively. $\Delta\varepsilon$ is the change of permittivity. It is defined as $2n\Delta n$, where Δn is the change in refractive index of the core during grating inscription.