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Design optimization of long period waveguide grating devices for refractive index sensing using adaptive particle swarm optimization

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A B S T R A C T

Grating assisted surface plasmon resonance waveguide grating has been designed and optimized for the sensing application. Adaptive particle swarm optimization in conjunction with derivative free method for mode computation has been used for design optimization of LPWG sensor. Effect of metal thickness and cladding layer thickness on the core mode and surface plasmon mode has been analyzed in detail. Results have been utilized as benchmarks for deciding the bounds of these variables in the optimization process. Two waveguides structures have been demonstrated for the grating assisted surface plasmon resonance refractive index sensor. The sensitivity of the designed sensors has been achieved 3.5×10^4 nm/RIU and 5.0×10^4 nm/RIU with optimized waveguide and grating parameters.

1. Introduction

Fiber Bragg grating (FBG) and long period fiber grating (LPFG) are widely used for strain, temperature and chemical sensing applications [1–3]. LPFGs are more popular in the sensing technologies because these gratings are easier to fabricate, robust and cost effective. The LPFG based sensors can be coupled easily to source and monitoring device through optical fiber cable. Hence, the source and monitoring devices can be installed at different location from the sensors. This feature facilitates the monitoring of parameters at hazardous place. The devices based on multilayer planar waveguides can also be utilized in sensing technology. Metal clad leaky waveguide (MCLW) and surface plasmon resonance (SPR) waveguide sensors have been reported for the biological and chemical warfare agents' detection [4–10]. Extensive study has been carried out to develop the SPR based sensors for biochemistry and microbiological spectroscopy [11–16]. The SPR sensors are excellent as these are compact, robust and have potential of integration with other components on single substrate.

In planar waveguide technology, long period waveguide grating (LPWG) based sensors also attracted attention because of flexibility of material and geometry selection as compared to LPFG. The grating assisted SPR structure has also been demonstrated as the refractive index sensors [17–19]. Similar device has been demonstrated for mid-infrared spectroscopy also [20]. The work carried out in Ref. [18] revealed that device performance is affected by two waveguide parameters namely the metal layer thickness and the cladding thickness. Hence optimization of these parameters is required to enhance the performance of SPR based sensor in conjunction with grating parameters. The sensor with optimized parameters gives the optimum sensitivity with optimum resolution.

In the present study, we have proposed the design optimization of LPWG assisted SPR based refractive index sensor in a five layer planar waveguide structure. Two waveguide structures proposed in Ref. [18] have been taken for the study and analysis. We have analyzed the surface plasmon waveguide using the derivative free method for computing the modes of complex waveguide [21]. The waveguide and grating parameters have been optimized using APSO for the design optimization of LPWG assisted surface plasmon waveguide devices for refractive index sensing.

2. Surface plasmon and surface plasmon resonance

The analysis of Maxwell's equations with suitable boundary conditions shows that plasmon waveguides support only the TM modes. The TM modes closely confined around the metal film are known as surface plasmon (SP) modes. The maximum intensity of SP-modes is observed at the metal–dielectric interface and decays exponentially on either side of metal layer. The analysis of the

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plasmon waveguide has been carried out in the similar manner as given for the multilayer structure in Ref. [21]. The simple structure of plasmon waveguide is a two-layer structure which consists of metal as substrate and dielectric as superstrate. The propagation constant of TM modes of two-layer structure is given as [13]

$$\beta = k\sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}} \quad (1)$$

where, quantities ε_d and ε_m are the permittivity of dielectric and metal respectively and k_0 is the free space wave number. Permittivity is, in general, a complex quantity. For the lossless metal and dielectric, permittivity is a real quantity and the modes supported by the structure are guided modes provided that $\varepsilon_m < -\varepsilon_d$. The permittivity of dielectric material is usually positive hence, permittivity of the real part of metal must be negative for guided mode. Above description shows that β is real for the guided modes. The permittivity of metal is given as

$$\varepsilon_m = \varepsilon_0\left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\nu}\right) \quad (2)$$

here, ε_0 is the permittivity of free space, ν is collision frequency and ω_p is plasma frequency. Plasma frequency is given as

$$\omega_p = \left(\sqrt{\frac{Ne^2}{\varepsilon_0 m_e}}\right) \quad (3)$$

where, N is electron concentration in metal, e is charge of electron, m_e mass of electron. In case of the complex permittivity of metal, the supported modes have the real and imaginary parts for $\varepsilon_m > -\varepsilon_d$. Such modes have propagation loss due to imaginary part but these modes propagate through certain distance before being extinguishing and are designated as SP-modes. The propagation constant of SP-mode is given by Eq. (1) and is a complex quantity.

The SP-modes also exist at the dielectric–metal–dielectric waveguide. In this case, the SP-modes exist at each interface of the metal–dielectric. Two independent SP-modes are supported at two opposite sides of metal–dielectric interfaces for the sufficiently thick metal layer. The coupling occurs between these SP-modes when the metal thickness becomes sufficiently small. The SP-modes are highly sensitive to the properties of dielectric surfaces at either side of the metal layer. The excitation of an SP-mode occurs when the component of wave vector of coupled light parallel to the metal–dielectric interface matches with the propagation constant of SP-mode. This is a resonant excitation and is termed as surface plasmon resonance (SPR). The SPR can be obtained by prism coupling, grating coupling or waveguide coupling.

The changes in the properties of superstrate can alter the propagation constant of SP-mode. This, in term, affects the SPR condition and results in a change in the wavelength, intensity, phase or polarization state. Measurement of change in these properties can be utilized to develop the sensors which are known as SPR based sensors.

The coupling of two SP-modes generated at the opposite interfaces of dielectric–metal–dielectric structure results in symmetric and antisymmetric SP-mode. The antisymmetric SP-modes have high attenuation coefficients, attenuate in a very short distance in the waveguide. Such SP-modes are called short range surface plasmon (SRSP) modes. On the other hand the symmetric SP-modes have low attenuation coefficient and travel longer distance before being completely attenuated. These are known as long range surface plasmon (LRSP) mode. LRSP modes are attractive in the sensing technology because these modes can be sustained over longer distance in the waveguide.

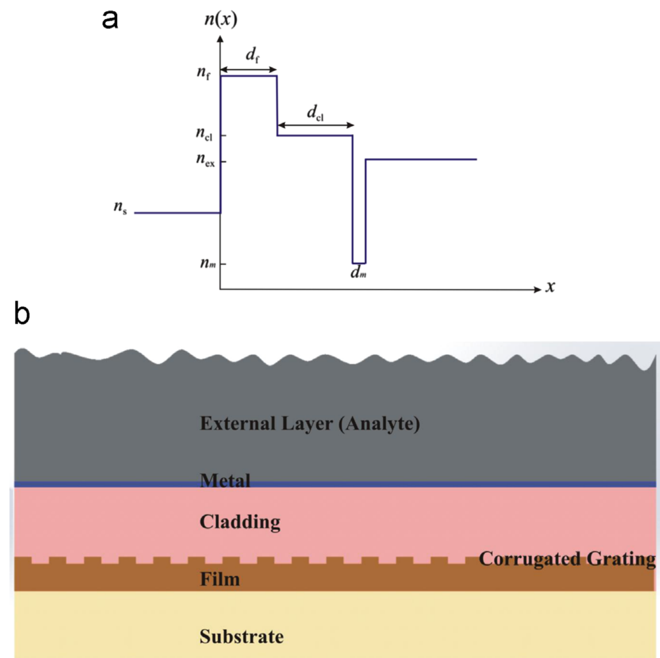

Fig. 1. LPWG structure (a) refractive index profile of plasmon waveguide (b) cross-section view of waveguide structure with embedded corrugated grating in the film of waveguide.

3. Waveguide structure and LPWG analysis

The refractive index profile of surface plasmon waveguide is shown in Fig. 1(a). It is a five-layer structure consisting of infinitely extended substrate of refractive index n_s, guiding film of refractive index n_f and thickness d_f, cladding layer of refractive index n_{cl} and thickness of d_{cl}, a metallic layer of refractive index n_m and thickness d_m and external layer of refractive index n_{ex}. The structure consists of a thin metal layer sandwiched between two dielectric layers. Hence, it works as the SPR waveguide. The film thickness is selected in such a way that it supports only one mode. A long period grating is embedded in the film of the waveguide. Transverse cross section of the grating embedded waveguide structure is shown in Fig. 1(b). Suitable combination of grating parameters of LPG couples the guided mode and the SP-mode. The coupling of these modes generates a resonance rejection band in the transmission spectrum of the waveguide. The SPR is affected by the properties of superstrate such as the refractive index of analyte (external layer). Any change in the refractive index of the analyte alters the propagation constant. The change in the propagation constant appears as the shift in resonance wavelength. This can be used in the development of refractive index sensor. The coupled mode equations are modified in the present study by including the propagation loss in each equation. The propagation loss arises due to the imaginary part of propagation constant. The modified coupled mode equations for coupling of core mode and SP-mode are given as follows.

$$\frac{dA_0}{dz} = \kappa_{TM} A_m e^{i\Gamma z} + A_0 \alpha_0 z/2 \quad (4)$$

$$\frac{dA_m}{dz} = -\kappa_{TM} A_0 e^{-i\Gamma z} + A_m \alpha_m z/2 \quad (5)$$

where $A_0(z)$ and $A_m(z)$ are the z dependent amplitude coefficients for core mode and mth mode (surface plasmon), Γ is phase mismatch and κ_{TM} is the coupling coefficient for guided mode and co-propagating cladding mode due to grating of period Λ. α_i is the