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Enhancement of refractive index sensitivity of Bragg-gratings based optical waveguide sensors using a metal under-cladding

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ABSTRACT

We theoretically analyze, a compact Bragg grating inscribed metal clad leaky ridge waveguide (MCLRW) as a refractive index sensor which can be integrated with other elements on a single chip. The grating is considered to be written in the photosensitive core. Using the quasi-TE mode of the structure, it is shown that a metal layer underneath the core enhances the evanescent field in the ambient region resulting in a significant increase in the ambient refractive index sensitivity. The obtained sensitivity and the figure of merit of the considered sensor structure are found to be almost 13–14 times higher than that of a ridge waveguide without any metal layer. Further, due to the higher modal loss of the quasi-TM mode, no in-line polarizer is required to assemble with the device. Effect of the loss due to metal layer on the peak reflectivity as well as bandwidth of the spectrum is also discussed.

1. Introduction

Fiber and integrated optical waveguide sensors have several advantages, due to which several such devices are proposed and developed in the last three decades or so. Fiber Bragg gratings (FBG) and long period fiber gratings (LPFG) based devices are the most popular one amongst them as such devices are wavelength interrogated and hence are free from source intensity fluctuations. Initially, for ambient refractive index (ARI) sensing, LPFGs were preferred over FBGs [1,2], as the former one are much more sensitive due to higher evanescent field in the ambient region. However, narrow bandwidth response of the FBG makes it more suitable for detection of spectrum shift with the change in ARI. To enhance the evanescent field in the ambient region, in the case of FBG, the fiber has been etched or side polished [3–5]. Though it increases the sensitivity, etching of the fiber makes it fragile and greatly impacts the durability and strength of the fiber. In contrast, an integrated optical waveguide is definitely a better choice in terms of these; it is much more flexible in terms of fabrication, can have higher evanescent field within the ambient medium and is also suitable for lab on chip applications. In view of the above, an open top ridge waveguide Bragg grating with GeO_2 doped SiO_2 core has been proposed [6], with a relatively lower sensitivity of 12 nm/RIU around ARI 1.33. Later a corrugated grating in silicon on insulator (SOI) rib waveguide has been proposed by Passaro *et. al.* [7] with a sensitivity of 33.6 nm/RIU. However, the grating formation through corrugation in photo-insensitive silicon core is a difficult task as compared to grating formation in photo sensitive core with UV writing. To overcome this problem Tripathi *et. al.* proposed an SOI ridge waveguide with the grating written in the photosensitive upper cladding made of GeO_2 doped SiO_2 with a sensitivity 239 nm/RIU at ARI 1.33 [8].

In this paper we examine the refractive index (RI) sensing characteristics of Bragg gratings written in a ridge waveguide with a metal layer incorporated in between the substrate and the core. The grating is considered to be written in the photosensitive GeO_2 doped SiO_2 core. Introduction of the metal layer enhances the evanescent field in the ambient medium as well as its RI sensitivity significantly. We exploit the quasi-TE mode instead of quasi-TM mode as the later one is highly lossy compared to the quasi-TE mode. As a result of the higher attenuation, the quasi TM mode dies out after propagating a small distance and hence no in-line polarizer is required to be used with the device to separate out the two polarized modes at the output as in the case of [8]. Though in the literature metal clad leaky waveguides (MCLW) are used to sense the change in ARI [9,10], however all are planar in nature and operated in the reflection mode. To the best of our knowledge no guided wave optic device using Bragg grating in MCLRW, has been explored till date.

This paper is organized as follows: in Section 2 we describe the modal analysis of MCLRW and in Section 3 we discuss the effect of metal layer in enhancing the fractional modal power (FMP) in the

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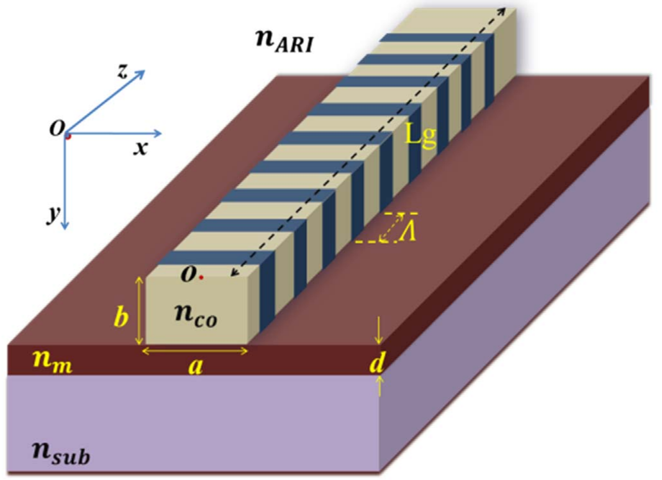


Fig. 1. 3-D view of the considered MCLRW structure with a Bragg grating written in the core.

ambient medium. A brief analysis of a Bragg grating in MCLRW for calculating its ARI sensitivity and figure of merit (FOM) is presented in Section 4 and finally the results are summarized in the Section 5.

2. Modal analysis

The considered structure, shown in Fig. 1, consists of 19.3 mol% GeO_2 doped SiO_2 as core, fused silica as substrate and a metal layer of Gold (Au) in between. The cross-sectional view of the considered MCLRW and its dielectric constant variation along y-direction is shown in Fig. 2. Modal field patterns and the effective indices of various modes supported by the MCLRW are obtained using the perturbation method /Kumar's method [11,12], in which the given structure's (Fig. 2) refractive index distribution is written as,

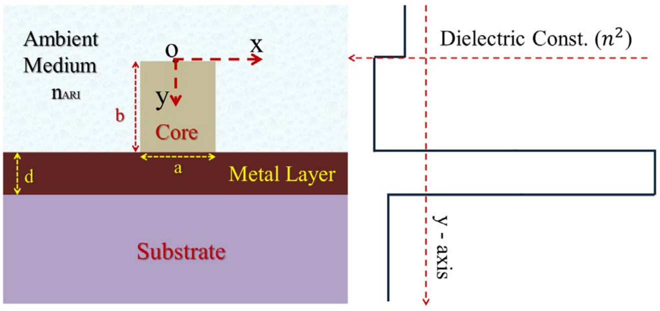
$$n^2(x, y) = n_0^2(x, y) + \delta n^2(x, y) \tag{1}$$

where, $n_0(x, y)$ is the unperturbed refractive index distribution given as,

$$n_0^2(x, y) = n'^2(x) + n''^2(y) - n_{co}^2 \tag{2}$$

with n'(x) and n''(y) are varying as,

$n'^2(x) = \begin{cases} n_{co}^2 |x| < a/2 \\ n_{ARI}^2 |x| > a/2 \end{cases}$ & $n''^2(y) = \begin{cases} n_{ARI}^2 y < 0 \\ n_{co}^2 0 < y < b \\ n_m^2 b < y < (b+d) \\ n_{sub}^2 y > (b+d) \end{cases}$ and δn^2 is the difference between the dielectric constant distribution of the given and the unperturbed waveguide, given by



(a) (b)

Fig. 2. (a) Cross sectional view of the MCLRW and (b) its dielectric constant distribution in the y-direction.

$$\delta n^2(x, y) = \begin{cases} (n_{co}^2 - n_{ARI}^2) & \begin{cases} \frac{(|x| > a/2, \quad y < 0)}{(|x| > a/2, \quad y > b)} \end{cases} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

The solution of the wave equation for the unperturbed profile (Eq. (2)) are of the form,

$$\psi_{m,n}(x, y) = X_m(x) Y_n(y) \tag{4}$$

where, $\psi_{m,n}(x,y)$ represents the electric or magnetic field components of the MCLRW modes. Using the method of separation of variables it can be shown that $X_m(x)$ and $Y_n(y)$ are the solution of wave equation for the planar waveguide structure, characterized by $n'(x)$ and $n''(y)$ respectively. If β_m and β_n are the modal propagation constants corresponding to $X_m(x)$ and $Y_n(y)$ respectively, the propagation constants of the modes for the unperturbed profile can be shown to be given by,

$$\beta_{0m,n}^2 = \beta_m^2 + \beta_n^2 - k_0^2 n_{co}^2 \tag{5}$$

After considering the effect of $\delta n^2$the final propagation constants of the modes become as,

$$\beta_{m,n} = \sqrt{\beta_{0m,n}^2 + \delta\beta^2} \tag{6}$$

where, the first order correction $\delta\beta^2$ is given as,

$$\delta\beta^2 = k_0^2 \frac{\iint \delta n^2(x, y) |\psi_{m,n}(x, y)|^2 dxdy}{\iint |\psi_{m,n}(x, y)|^2 dxdy} \tag{7}$$

with k_o being the free space propagation constant.

It is worthy to mention that, the quasi-TE mode is TE like for $n''(y)$ and TM like for $n'(x)$. Accordingly, β_n and β_m are obtained by solving the TE (for $n''(y)$) and TM (for $n'(x)$) eigenvalue equations respectively. The reverse is true for quasi-TM mode.

In all our calculations presented in the next sections, wavelength dependent refractive index $n(\lambda)$ of core and substrate has been calculated using well known Sellmeier formula given as [13],

$$n(\lambda) = \sqrt{1 + \sum_{i=1}^{3} A_i \frac{\lambda^2}{\lambda^2 - \lambda_i^2}} \tag{8}$$

where λ is the free space wavelength and, A_i and λ_i are the Sellmeier constants whose values are different for different concentration of GeO_2 [13]. At a wavelength of 1.55 µm refractive index of the core and substrate are found to be 1.471458 and 1.444024 respectively. Further, for the dielectric constant (ε_m) of metal layer, the Drude model has been used which is expressed as [14],

$$\varepsilon_m(\lambda) = \varepsilon_\infty \left[1 - \frac{\omega_p^2}{\omega(\omega + i\Gamma)} \right] \tag{9}$$

where ε_∞ is the high frequency value of dielectric constant, ω_p is plasma frequency and Γ is the damping frequency, for Au the values of which are 8.6, 4.264 PHz and 0.1274 PHz respectively. At 1.55 µm the dielectric constant comes out to be −95.981+10.956*i*.

3. Effect of the metal layer

As mentioned previously, the RI sensitivity of the device depends on the fractional modal power (FMP) in the ambient medium, which is defined as,

$$FMP_{amb} = \frac{\iint_{ambientregion} |\psi_{m,n}|^2 dxdy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |\psi_{m,n}|^2 dxdy} \tag{10}$$

As the modal effective index approaches ambient RI, the field in the ambient region increases, leading to a higher FMP in the ambient medium. We observed that a metal layer adjacent to the core region