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Theoretical analysis of TM nonlinear asymmetrical waveguide optical sensors

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ABSTRACT

An extensive analytical analysis is carried out to investigate TM nonlinear asymmetrical waveguide sensors. The structure consists of a thin film embedded between two nonlinear media. The effect of the nonlinearity of the cladding and the substrate on the sensitivity of the sensor is studied. A comparison between the proposed nonlinear sensor and the conventional linear sensor is presented to show that nonlinear sensors have higher sensitivities. The condition required to maximize the sensitivity is also derived to provide the designer with the optimum structure of the proposed nonlinear sensor.
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1. Introduction

In several areas like environmental pollutants control, biotechnology, drug screening, and food safety, there is a growing need of sensors capable of monitoring of various chemical species. During the last two decades, there has been a remarkable interest and a great progress in the fabrication and development of optical sensors [1–4]. A variety of optical sensors based upon evanescent wave sensing techniques have been proposed such as surface plasmon resonance sensor [5], integrated optical waveguide sensors [6], the resonant mirrors [7], differential interferometry sensors [8].

The working principle of the planar dielectric waveguide sensor is to measure changes in the effective refractive index N due to changes in the cover refractive index n_c. Light is coupled into the waveguide at one end of the film and is guided in the guiding layer by total internal reflection at the film-cover and the film-substrate boundaries at a range of angles. The light is coupled out of the waveguide at the other end of the film where the intensity is measured by a detector. The measured spectrum of intensity versus angle or intensity versus N is referred to as a sensorgram. The basic sensing principle is to measure the change in the position of the intensity peak in the sensorgram for a change in the cover refractive index.

The purpose of this paper is to analyze p-polarized waves propagating in a linear thin film sandwiched between two nonlinear media for sensing applications and also to compare the sensitivity of the proposed nonlinear sensor with the widely used linear sensors.

2. Theory

A schematic structure of the waveguide under consideration is shown in Fig. 1. A guiding layer with permittivity ε_f and thickness h is coated onto a nonlinear substrate with permittivity ε_{nl3}. A nonlinear cladding layer with permittivity ε_{nl1} is coated onto the guiding layer. We will consider p-polarized waves that propagate in the x-direction (TM waves). The only nonvanishing components of the fields $\boldsymbol{E}$ and $\boldsymbol{H}$ are H_y, E_x, and E_z. Assuming the nonlinear dielectric functions to be of Kerr type, i.e., $\varepsilon_{nl1}=\varepsilon_c+\alpha_c|\boldsymbol{E}|^2$ and $\varepsilon_{nl3}=\varepsilon_s+\alpha_s|\boldsymbol{E}|^2$, where α_c and α_s are the nonlinear coefficients of the cladding and substrate, respectively and ε_c and ε_s are the linear parts of the permittivities. To solve the nonlinear wave equation for the magnetic field $\boldsymbol{H}$, one can write ε_{nl1} and ε_{nl3} as [9,10,12,13]:

$$\varepsilon_{nl1}=\varepsilon_c+\alpha'_c\left|H_{y1}\right|^2, \quad (1)$$

$$\varepsilon_{nl3}=\varepsilon_s+\alpha'_s\left|H_{y3}\right|^2, \quad (2)$$

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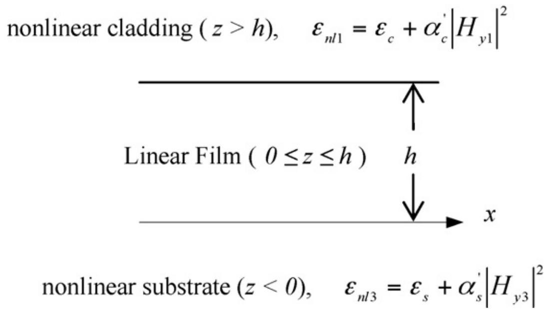

Fig. 1. Schematic structure of nonlinear slab waveguide sensor.

where $\alpha_c' = \alpha_c/\varepsilon_c c^2 \varepsilon_0^2$ and $\alpha_s' = \alpha_s/\varepsilon_s c^2 \varepsilon_0^2$, c is the speed of light in vacuum, ε_0 is the free space permittivity and H_{y1} and H_{y3} are the TM fields in the cladding and substrate, respectively.

After solving Maxwell's equations in the three layers of the structure and matching the tangential magnetic and electric fields, the dispersion relations for $\alpha_c' > 0$ and $\alpha_s' > 0$ are given by [11,14]:

$$k_0 q_f h - \arctan\left(\frac{X_c}{a_c}\tanh\ C_c\right) - \arctan\left(\frac{X_s}{a_s}\tanh C_s\right) - m\pi = 0, \quad (3)$$

where k_0 is the free space wave number, $q_f = \sqrt{\varepsilon_f - N^2}$, N is the effective refractive index, $C_c = k_0\sqrt{N^2 - \varepsilon_c}(h - z_c)$, $C_s = k_0\sqrt{N^2 - \varepsilon_s} z_s$, z_c and z_s are constants related to the field distribution in the covering medium and substrate, respectively, m = 0, 1, . . . is the mode order, a_s and a_c are two asymmetry parameters and X_s and X_c are two normalized variables given by

$$a_s = \frac{\varepsilon_s}{\varepsilon_f}, \quad a_c = \frac{\varepsilon_c}{\varepsilon_f}, \quad X_s = \frac{\sqrt{N^2 - \varepsilon_s}}{q_f}, \quad X_c = \frac{\sqrt{N^2 - \varepsilon_c}}{q_f}. \quad (4)$$

It is straightforward to show that X_s and X_c are related to each other by

$$X_c^2 = w(1 + X_s^2) - 1, \quad (5)$$

where $w = (1 - a_c)/(1 - a_s)$. The effective refractive index can be written in terms of a_s and X_s as

$$N = \sqrt{\varepsilon_f}\sqrt{\frac{a_s + X_s^2}{1 + X_s^2}}. \quad (6)$$

In the case of homogeneous sensing (the analyte is homogeneously distributed in the covering medium), the sensitivity of the sensor S_h is defined as the rate of change of the effective refractive index under an index change of the cover. Differentiating Eq. (3), with respect to N and calculating S_h as $(\partial n_c/\partial N)^{-1}$ we obtain:

$$S_h = \frac{\sqrt{a_c}\sqrt{1 + X_c^2}(a_c H_c + a_c \tanh C_c + 2X_c^2 \tanh C_c(1 - a_c)/(1 + X_c^2))}{X_c\sqrt{a_c + X_c^2}(a_c^2 + X_c^2 \tanh^2 C_c)(A_{TM} + G_{s\,TM} + G_{c\,TM})}, \quad (7)$$

where

$$H_c = k_0(h - z_c)X_c\sqrt{\varepsilon_f}\sqrt{\frac{1 - a_c}{1 + X_c^2}}(1 - \tanh^2 C_c), \quad (8)$$

$$G_{c\,TM} = \frac{a_c H_c + a_c \tanh C_c(1 + X_c^2)}{X_c(a_c^2 + X_c^2\ \tanh^2 C_c)}. \quad (9)$$

Replacing the subscript 'c' with the subscript 's' in Eq. (9) gives $G_{s\,TM}$:

$$H_s = k_0 z_s X_s\sqrt{\varepsilon_f}\sqrt{\frac{1 - a_s}{1 + X_s^2}}(1 - \tanh^2 C_s), \quad (10)$$

and

$$A_{TM} = \arctan\left(\frac{X_s}{a_s}\tanh C_s\right) + \arctan\left(\frac{X_c}{a_c}\tanh C_c\right) + m\pi. \quad (11)$$

Searching for the condition of maximum sensitivity in a structure of constant ε_c, ε_f, and ε_s requires the cancellation of the derivative of the sensitivity S_h with respect to guiding layer thickness h. This will enable us to find out the optimum guiding layer thickness which corresponds to the maximum sensitivity. Differentiating Eq. (7) with respect to X_s and using $\partial S_h/\partial h = (\partial S_h/\partial X_s)(\partial X_s/\partial h)$ and $\partial X_s/\partial h \neq 0$, the maximum sensing sensitivity condition can be obtained.

As can be seen [6], when the guiding layer thickness decreases, the evanescent field in the substrate for conventional symmetry ($n_s > n_c$) and in the cladding for reverse symmetry ($n_s < n_c$) is enlarged till it approaches infinity at cut-off. The guiding layer thickness at cut-off is obtained from Eq. (3) with $X_s = 0$ for conventional symmetry, to yield:

$$h_{\text{cut-off}} = \frac{1}{k_0\sqrt{\varepsilon_f}\sqrt{1 - a_s}}\arctan\left(\frac{\tanh C_c}{a_c}\sqrt{\frac{a_s - a_c}{1 - a_s}}\right) + m\pi. \quad (12)$$

The fraction of total power propagating in the covering medium is one of the most important quantities affecting the sensitivity of the sensor. For TM modes, the time averaged power flow in the x-direction per unit width in the y-direction can be expressed as

$$P = \frac{Nk_0}{2\omega\varepsilon_0\varepsilon_r}\int_{-\infty}^{\infty} H_y^2\, dz = P_s + P_f + P_c. \quad (13)$$

The fraction of total power flowing in the nonlinear cladding is

$$\frac{P_c}{P_{\text{total}}} = \frac{(X_c/a_c\alpha_c')\sigma_c}{(X_c/a_c\alpha_c')\sigma_c + (X_s^2 \sec h^2 C_s/2\alpha_s')[k_0 q_f h x_+ + (1/2)\sin(2k_0 q_f h)x_- + (X_s b/a_s)\tanh C_s] + (X_s/a_s\alpha_s')\sigma_s}, \quad (14)$$

where $\sigma_c = 1 - \tanh C_c$, $\sigma_s = 1 - \tanh C_s$, $x_+ = (1 + (X_s^2/a_s^2))\tan h^2 C_s$, $x_- = (1 - (X_s^2/a_s^2))\tanh^2 C_s$ and $b = 1 - \cos(2k_0 q_f h)$.

3. Representation and discussion

A computer program was generated to solve the transcendental equation given by Eq. (3) for N and the sensitivity was calculated using Eq. (7). We took silicon nitride, Si_3N_4, with refractive index equal to 2 as a guiding layer ($\varepsilon_f = 4$). The free space wavelength was considered to have the value 1550 nm, $\tanh C_c = 0.6$ and $\tanh C_s = 0.7$. Only the fundamental mode ($m = 0$) will be considered since it leads to the highest sensitivity [15]. The resulting sensitivity curves as functions of the waveguide film thickness are shown in Figs. 2 and 3. Several general characteristics should be observed. At the cut-off thickness these sensitivities go to zero for normal symmetry ($n_c < n_s$). In this limit, all the power of the mode propagates in the substrate due to the infinite penetration depth. Consequently, the sensor probes the substrate side only. For the sensitivity to have a nonzero value, the thickness of the guiding layer has to be greater than the cut-off thickness. In the other limit, far beyond the cut-off point, the effective waveguide thickness approaches the film thickness which means that all the power propagates in the film. In this case, the sensitivities approach zero again. Between these two limits, there is a maximum in the sensitivity curves, just above the cut-off thickness, representing an optimum where a relatively large part of the total mode power propagates in the covering medium. For comparison, we plotted the sensitivity of a linear sensor and the sensitivity of the proposed nonlinear sensor in Fig. 2. We see that nonlinear sensors have higher sensitivities at lower thickness of the guiding film. In Fig. 3, we considered a reverse symmetry waveguide

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