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Optically S-polarized surface waves in symmetrical nonlinear sensors: Thermal effects

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Abstract

A surface wave in a planar nonlinear waveguide is a current problem that has several applications in modern electronics and optics such as optical sensors design. The effect of thermal stress on the optical performance of a nonlinear symmetrical sensor is studied. The mathematical forms of the dispersion equation and thermal-stress sensitivity are analytically derived and plotted numerically. It is found that the thermal sensitivity of the sensor can be controlled by tuning the core size, by changing the loading materials, and by carefully selecting the materials.

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1. Introduction

Integrated optical sensor field is motivated by the expectation that optical sensors have significant advantages compared to conventional sensor types, i.e., their immunity to electromagnetic interference, the use in aggressive environment, capability of performing multi-functional sensors on one chip, and higher sensitivity [1]. The properties of waveguide sensing in dielectric films have been studied intensively for a number of years and have resulted in a large number of devices. Nonlinear optical surface waves that propagate along planar interfaces between dielectric media have been investigated considerably because of their applications in all optical switches [2–4].

The essential part of the optical waveguide sensor is the ability to transform, in an efficient way, a chemical or a biological reaction in a measurable signal [5]. Substantial efforts have been made to enhance the sensitivity of waveguide sensors. Huang and Yan [6] studied the effect of thermal stress on the sensitivity of three linear layers symmetric to optical waveguide sensors. El-Khozondar et al. [7] showed that different stress states can control the stress sensitivity of a three-layer asymmetrical optical waveguide sensor, which consists of a dielectric core surrounded by linear substrate and nonlinear cladding.

In this study, a three-layer nonlinear symmetrical optical waveguide sensor is considered. The substrate and cladding are taken to be nonlinear media surrounding a dielectric core. In Section 2, the thermal-stress

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effects on the temperature sensitivity of optical performance have been introduced. The field equations and the dispersion equation are derived analytically in Section 3. Section 4 evaluates the temperature sensitivity for a nonlinear medium. Numerical results are discussed in Section 5, followed by the conclusion in Section 6.

2. Thermal-stress effects on the temperature sensitivity of optical performance

The practical waveguide is usually under an anisotropic and inhomogeneous stress state. The dielectric constant of an anisotropic and inhomogeneous medium, ε, is

$$\varepsilon = \begin{bmatrix} n_{xx}^2 & n_{xy}^2 & n_{xz}^2 \\ n_{xy}^2 & n_{yy}^2 & n_{yz}^2 \\ n_{xz}^2 & n_{yz}^2 & n_{zz}^2 \end{bmatrix}, \quad (1)$$

where n_{xx}, n_{yy}, n_{zz}, n_{xy}, n_{xz}, and n_{yz} are functions of temperature, stress, and wavelength [8]. The relation between the refractive index and temperature (thermo-optic relation) is

$$\frac{\partial n}{\partial T} = Bn, \quad (2)$$

where T is the temperature and B is the thermo-optic coefficient, which is usually a function of refractive index, wavelength, and temperature. Combining the effect of stress and temperature on the dielectric film gives the refractive index change as

$$\Delta \begin{pmatrix} n_{xx} \\ n_{yy} \\ n_{zz} \\ n_{yz} \\ n_{xz} \\ n_{xy} \end{pmatrix} = B\Delta T \begin{pmatrix} n_{xx} \\ n_{yy} \\ n_{zz} \\ n_{yz} \\ n_{xz} \\ n_{xy} \end{pmatrix} - \begin{bmatrix} C_1 & C_2 & C_2 & 0 & 0 & 0 \\ C_2 & C_1 & C_2 & 0 & 0 & 0 \\ C_2 & C_2 & C_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & C_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & C_3 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_3 \end{bmatrix} \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{pmatrix}, \quad (3)$$

where C_1, C_2, and C_3 are stress-optics constants depending on Young's modulus, shear modulus, and Poisson's ratio; $\Delta n = n(T) - n(T_0)$, $\Delta T = T - T_0$; σ_{xx}, σ_{yy}, σ_{zz}, σ_{yz}, σ_{xz}, and σ_{xy} are stress components.

As the waveguide is usually very long in one direction, denoted as z, the shear stresses in this direction can be ignored. Therefore the dielectric tensor becomes

$$\varepsilon = \begin{bmatrix} n_{xx}^2 & n_{xy}^2 & 0 \\ n_{xy}^2 & n_{yy}^2 & 0 \\ 0 & 0 & n_{zz}^2 \end{bmatrix}, \quad (4)$$

and the stress state in the core can be expressed as

$$\sigma_{xx} = g_x E\,\Delta\alpha(T - T_0) + \sigma_{rx}, \quad (5)$$

$$\sigma_{yy} = g_y E\,\Delta\alpha(T - T_0) + \sigma_{ry}, \quad (6)$$

$$\sigma_{zz} = g_z E\,\Delta\alpha(T - T_0) + \sigma_{rz}, \quad (7)$$

$$\sigma_{yz} = \sigma_{xz} = \sigma_{xy} = 0, \quad (8)$$

where E is Young's modulus of the core; $\Delta\alpha = \alpha_{\text{cladding}} - \alpha_{\text{core}}$ is the thermal-expansion coefficient mismatch between cladding and the core; σ_{rx}, σ_{ry}, and σ_{rz} are residual stresses along x, y, and z; g_x, g_y, and g_z, are loading parameters, which in most cases need to be determined numerically. For simplicity, thermal stress is assumed to be due to thermal mismatch between core and cladding. The loading parameters in this case are $g_x = 0$ and $g_y = g_z = 1/(1-v)$, where v is Poisson's ratio of the core [9]. To study the stress effect on nonlinear waveguides, we assume that the core should be under hydrostatic stress state, i.e., $\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = \sigma$.

3. The electric field in the symmetrical nonlinear optical sensor

The waveguide sensor is assumed to consist of an anisotropic inhomogeneous core as described in Section 1, surrounded by nonlinear substrate and cladding. We assume that a core of finite linear layer occupies the region $0 \leqslant z \leqslant t$. The two surrounding nonlinear layers occupy the regions $z<0$ and $z>t$ as substrate and cladding, respectively. The dielectric function of the nonlinear layers is chosen to be a Kerr-like function, which is characterized by

$$\varepsilon_i = \varepsilon_{0i} + \alpha_i E^2, \quad (9)$$

where ε_{0i} is a frequency-independent linear part, α_i is the nonlinearity coefficient, and $i = \text{c, s}$ denotes cladding or substrate [10–12]. Only TE modes (S-polarized waves) are considered, which propagate along the x-axis and has the oscillating form expressed as follows:

$$\vec{E} = (0, E_y, 0)e^{(ik_0(n_e x - ct))} \quad \text{and} \quad \vec{H} = (H_x, 0, H_z)e^{(ik_0(n_e x - ct))}, \quad (10)$$

where $n_e = k/k_0$ is the effective index, k_0, c are the wave number and the speed of light in free space, respectively. For TE modes, applying Eq. (2) into Maxwell's equations for fields in free space results in the wave equations for cladding and substrate [10–12] and for core [9] as follows:

$$\frac{\partial^2 E_y}{\partial z^2} - k_0^2(n_e^2 - \varepsilon_c)E_y + \alpha_c k_0^2(E_y^3) = 0 \text{ (cladding)}, \quad (11)$$

$$\frac{\partial^2 E_y}{\partial z^2} + k_0^2(n^2 - n_e^2)E_y = 0 \quad \text{(core)}, \quad (12)$$

$$\frac{\partial^2 E_y}{\partial z^2} - k_0^2(n_e^2 - \varepsilon_s)E_y + \alpha_s k_0^2(E_y^3) = 0 \text{ (substrate)}. \quad (13)$$