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Sensitivity of TM nonlinear magnetooptical integrated optical sensor

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Sensitivity of TM nonlinear magnetooptical integrated optical sensor

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Abstract

Purpose – The purpose of this paper is to consider a detailed investigation of transversal magnetic (TM) nonlinear magnetooptical integrated optical sensor. The sensitivities of two sensors are presented. The first sensor composed of a dielectric thin film surrounded by a lossless, nonmagnetic, isotropic cladding exhibiting a local Kerr-like dielectric nonlinearity, and a magnetic substrate chosen to be an iron garnet. The second sensor is formed by exchanging the cladding and the substrate media of the first sensor. The homogenous sensitivities of both sensors are calculated as a function of the waveguide thickness and the effective refractive index. The effect of nonlinearity on the sensitivities for both sensors is investigated.

Design/methodology/approach – The homogenous sensitivities of both sensors are calculated as a function of the waveguide thickness and the effective refractive index. The effect of nonlinearity on the sensitivities for both sensors is investigated. Numerical calculations are performed using the Maple program.

Findings – It was found that the sensitivity for the first sensor sensitivity increases with nonlinearity. While the sensitivity for the second sensor is hardly affected by the change of nonlinearity. It was also found that the thickness of the guiding layer is a critical parameter for the sensitivity of the optical sensor with the optimum thickness being just above cut-off in case of the first structure and at the cut-off in the case of the second structure.

Originality/value – A detailed investigation of TM nonlinear magnetooptical integrated optical sensor is considered. The two proposed structures are used to investigate the parameters to get the optimal sensitivity, which is an important issue is the sensor design.

Keywords Sensors, Magnetooptics, Nonlinear material, Sensitivity, Integrated optics, Optical components, Sensitivity analysis, Optics

Paper type Research paper

1. Introduction

Integrated optical sensors are the only technology, which allows the direct detection of biomolecular interactions; therefore, they can be used to detect water pollutants in environmental control (Numata *et al.*, 1989). The applications of nonlinear electromagnetic waves in optoelectronic devices have been discussed in several papers (Segeman and Seaton, 1985; Yasuamoto *et al.*, 1996; Boardman and Egan, 1986; Mihalache, 1989). Such sensors are designed for several purposes including biological, environmental,

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and other fields of applications (El-Khozondar *et al.*, 2007; El-Khozondar, 2008). Dötsch *et al.* (2005) have investigated the applications of magnetooptical waveguides. The magnetooptical materials have several applications such as current transducers (Massey *et al.*, 1975; Nagatsuma *et al.*, 1985), defect detection in steels (Numata *et al.*, 1989), recording readout heads (Nomura and Tokumaru, 1984), magnetooptic memories (Martens and Voermans, 1984; Hartmann *et al.*, 1984), isolators (Gniadek, 2005; El-Khozondar *et al.*, 2008; El-Khozondar *et al.*, 2009), and sensors (Numata *et al.*, 1991) among other devices.

Gniadek (2005) presented the concept of an integrated isolator based on nonreciprocal cut-off of TM modes in magnetooptical planar structure, where one layer is nonlinear. Alcantara *et al.* (2005) presented a new multifunctional optical device operating simultaneously as an optical switch and an optical isolator. We made a further step in this paper by introducing a study of a nonlinear magnetooptical sensor.

The main idea of sensors are based on evanescent field sensing: although light is confined within the core of the waveguide, part of the guided light travels within the medium surrounding the waveguide and therefore its field can interact with the environment (Kooyman and Lechuga, 1997). Thus, a biomolecular interaction between a receptor molecule, previously deposited on the waveguide surface, and its complementary analyte, produces a change in the refractive index at the sensor surface that induces a variation in the optical properties of the guided light via the evanescent field.

The principle measurement of the planar waveguide sensor is the homogeneous sensitivity. The homogeneous sensitivity S_h is defined as the variation rate of effective refractive index N of order m upon a variation of the cover's refractive index (Brioude and Parriaux, 2000).

The purpose of this paper is to study the homogeneous sensitivity for planar waveguide sensors composed of a thin dielectric film surrounded by nonlinear and magnetooptic layers. The sensitivity is first calculated for the sensor where the substrate media is magentooptic material and the cover media is nonlinear material. Then the sensitivity is measured for the sensor structure where the magnetooptic material is covering the film and the nonlinear material is the substrate.

2. Theory

A schematic drawing of the sensor device is shown in Figure 1. The sensor consists of a dielectric thin film surrounded by a nonlinear cladding and a magnetic substrate. In this work, we will consider only p-polarized waves propagating in the *z*-direction. The non-vanishing components of the fields are (E_x, H_y, E_z). The transverse electric

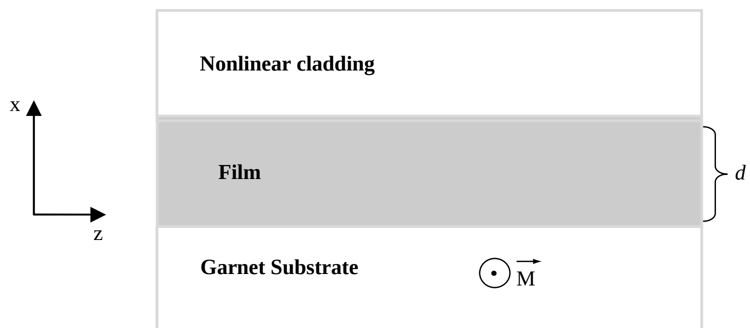

Figure 1. Basic geometry of the sensor

and magnetic modes are assumed to oscillate as $\exp[j(\omega t - \beta z)]$, where $\beta = Nk$ denotes the propagation constant, N is the effective refractive index, and $k = 2\pi/\lambda$ the vacuum wave number with λ being the vacuum wavelength, $\omega = ck$ the angular frequency, and c the speed of light.

The film is linear dielectric with permittivity ε_f and permeability μ_f. The cladding is N-4-nitrophenyl-(L)-prolinol (NPP) (Ledoux *et al.*, 1990) that is lossless, nonmagnetic, isotropic and exhibits a local Kerr-like dielectric nonlinearity (Segeman and Seaton, 1985; Yasuamoto *et al.*, 1996; Boardman and Egan, 1986; Mihalache, 1989; El-Khozondar *et al.*, 2007; El-Khozondar, 2008):

$$\varepsilon_c = \begin{pmatrix} \varepsilon_{xx} & 0 \\ 0 & \varepsilon_{zz} \end{pmatrix}, \tag{1}$$

where $\varepsilon_{xx} = \varepsilon_{zz} = \varepsilon(I) = (\varepsilon_{cL} + \varepsilon_{NL})$, where I denotes the dependency on the intensities of the fields, ε_{cL} is the linear term and ε_{NL} is the nonlinear term which is proportional to the fields intensities $\varepsilon_{NL} = \alpha(|E_x|^2 + |E_y|^2)$,where α is the nonlinearity coefficient. The substrate consists of an iron garnet with dielectric tensor ε_s which is defined by (Gerhardt *et al.*, 1993):

$$\varepsilon_s = \begin{pmatrix} \varepsilon_{xx} & 0 & j\varepsilon_{xz} \\ 0 & \varepsilon_{xx} & 0 \\ -j\varepsilon_{xz} & 0 & \varepsilon_{xx} \end{pmatrix}, \tag{2}$$

The magnetization $\vec{\mathrm{M}}$ is adjusted in the substrate plane perpendicular to the field propagation. All numbers in the dielectric tensor are real. Gyrotropy, represented by the off-diagonal components ε_{xz}, is the result of magnetization and related to the specific Faraday rotation θ_F by $|\varepsilon_{xz}| \approx 2n_s|\theta_F|/k$, where n_s is the refractive index of the substrate.

Solving Maxwell's equations to obtain the solutions for the transverse fields H_y and E_z then applying the boundary conditions (continuity of E_z and H_y) results in the transverse equation (Gniadek, 2005):

$$k\gamma_f d = \theta_c + \theta_s + m\pi, \tag{3}$$

where:

$$\theta_c = \tan^{-1}\left(\frac{1}{\gamma_f}\,\frac{\varepsilon_f}{\varepsilon_{cL}\eta}\sqrt{\frac{(3\eta-1)(N^2-\eta^{NL})}{(\eta+1)}}\right), \tag{4}$$

and:

$$\theta_s = \tan^{-1}\left(\frac{1}{\gamma_f}\,\frac{\varepsilon_f}{\varepsilon_{vs}}\left[\gamma_s - N\frac{\varepsilon_{xz}}{\varepsilon_{xx}}\right]\right), \tag{5}$$

$$\gamma_f = \sqrt{n_f^2 - N^2}, \quad \gamma_s = \sqrt{\varepsilon_{vs} - N^2}, \quad \varepsilon_{vs} = \varepsilon_{xx} - \frac{\varepsilon_{xz}^2}{\varepsilon_{xx}}, \quad \eta = \frac{\varepsilon(I)}{\varepsilon_{cL}}, \quad \eta^{NL} = \frac{2\varepsilon_{cL}\eta^2}{3\eta - 1},$$

and m is an integer representing the mode order.

In case of homogenous sensing, the analyst is homogeneously distributed in the covering media. The sensitivity S_h is defined as the rate of change of the modal effective index N of order m upon a change of the cover's index (n_c). We will assume that the changes will appear only on the linear part of the cladding dielectric-parameter ε_c. Since $n_c = \sqrt{\varepsilon_{cL} + \varepsilon_{NL}}$, then:

$$\frac{\partial N}{\partial n_c} = 2n_c \frac{\partial N}{\partial \varepsilon_{cL}}. \tag{6}$$

Differentiating equation (3) with respect to εcL:

$$kd\frac{\partial \gamma_f}{\partial \varepsilon_{cL}} = \frac{\partial\left(\tan^{-1}\theta_c\right)}{\partial \varepsilon_{cL}} + \frac{\partial\left(\tan^{-1}\theta_s\right)}{\partial \varepsilon_{cL}} \tag{7}$$

To extract $\partial N/\partial \varepsilon_{cL}$, then using equation (6), the sensitivity will be:

$$S_{h(NL)} = \frac{\partial N}{\partial n_c} \tag{8}$$

The second sensor is modeled by exchanging the cladding and the substrate. The same above procedure is followed. The dispersion equation then reads:

$$k\gamma_f d = \theta_c + \theta_s + m\pi, \tag{9}$$

where:

$$\theta_s = \tan^{-1}\left(\frac{1}{\gamma_f}\frac{\varepsilon_f}{\varepsilon_{sL}\eta}\sqrt{\frac{(3\eta-1)\left(N^2-\eta^{NL}\right)}{(\eta+1)}}\right), \tag{10}$$

and:

$$\theta_c = \tan^{-1}\left(\frac{1}{\gamma_f}\frac{\varepsilon_f}{\varepsilon_{vc}}\left[\gamma_c - N\frac{\varepsilon_{xz}}{\varepsilon_{xx}}\right]\right), \tag{11}$$

$$\gamma_f = \sqrt{n_f^2 - N^2}, \quad \gamma_c = \sqrt{\varepsilon_{vc} - N^2}, \quad \varepsilon_{vc} = \varepsilon_{xx} - \frac{\varepsilon_{xz}^2}{\varepsilon_{xx}}, \quad \eta = \frac{\varepsilon(I)}{\varepsilon_{sL}}, \quad \eta^{NL} = \frac{2\varepsilon_{sL}\eta^2}{3\eta-1},$$

and m is an integer representing the mode order.

The homogeneous sensitivity is calculated by differentiating equation (9) with respect to ε_{vc}:

$$kd\frac{d\gamma_f}{d\varepsilon_{vs}} = \frac{d\left(\tan^{-1}\theta_c\right)}{d\varepsilon_{vs}} + \frac{d\left(\tan^{-1}\theta_s\right)}{d\varepsilon_{vs}} \tag{12}$$

Then using the fact that $n_{vc} = \sqrt{\varepsilon_{vc}}$, the sensitivity for the sensor with magnetic cladding will be:

$$S_{h(MO)} = \frac{\partial N}{\partial n_{vc}} = 2n_{vc}\frac{\partial N}{\partial \varepsilon_{vc}} \tag{13}$$

This sensitivity can be related very easily to the Faraday rotation which is impeded in the value of ε_{vc}.

3. Numerical calculations and discussion

The numerical calculations have been performed using typical magnetooptical material parameters. These parameters are $\varepsilon_{xx} = 5.1$, $\varepsilon_{xz=}0.08$ (Doorman *et al.*, 1984). The value of ε_{xz} depends on the wavelength in addition to the Faraday rotation as explained in the introduction. The wavelength $\lambda = 1.15\ \mu$m is chosen such that it gives a reasonable large value of ε_{xz} (Gniadek, 2005). In addition, λ is close to the absorption band of the iron-garnets, which leads to higher sensitivity of the sensor (Antonov *et al.*, 1969). We also consider different wavelength to study the effect of the change of wavelength on the performance of the sensor. The additional wavelengths are chosen to be 1.5 μm and 1.3 μm. For the nonlinear material, the linear part of the dielectric index (ε_L) is chosen to be equal to 4. The film parameters are chosen to be $\varepsilon_f = 5.5$ and $\mu_f = 1$. Only the fundamental mode TM_0 will be considered since it leads to highest sensitivity (Brioude and Parriaux, 2000). The field is assumed to have an amplitude of 10^6V/m.

The resulting homogeneous sensitivity curves for the sensor with first structure $S_{h(NL)}$ as function of the waveguide film thickness is shown in Figure 2. Several general characteristic may be observed. At the cutoff thickness, $S_{h(NL)}$ starts at small values. This is because the refractive index of the cladding is lower than the refractive index of the substrate. In this limit, almost all the power of the propagating mode goes to the substrate due to the large penetration depth. Consequently, the sensor mainly probes the substrate side. In the other limit, far beyond the cutoff point, the effective waveguide thickness approaches the film thickness, which means that all the power propagates in the film. In this case, the sensitivity approaches zero. Between these two limits, there is a maximum in the sensitivity curve, representing an optimum where a relatively large part of the total power propagates in the covering medium. In Figure 2, we plot the sensitivity at different nonlinearity measures. We noticed that the sensitivity increases as the nonlinearity increases and is larger than when the cladding is linear with a value of $\varepsilon_{NL} = 0$.

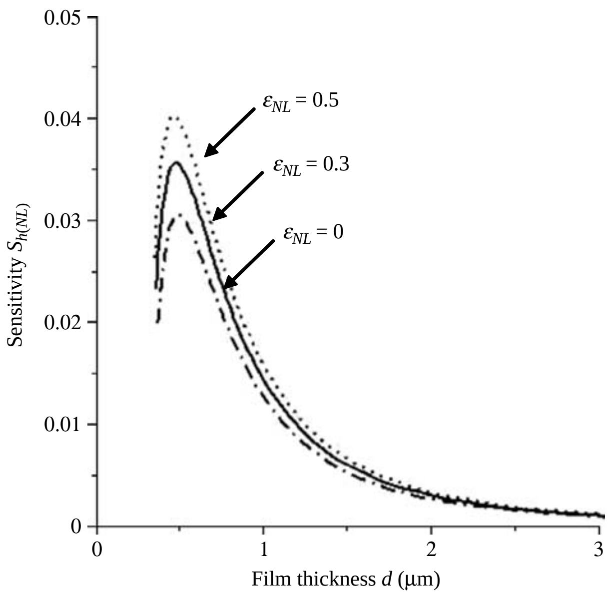

Figure 2.
Sensitivity of the sensor with structure of nonlinear cladding, linear film, and MO substrate measured as function of film thickness (d) at different values of ε_{NL}

In Figure 3 the sensitivity $S_{h(NL)}$ is plotted as a function of the effective index of refraction N. The figure shows that the sensitivity starts with small value at $N = 2.26$ (this value of N occurs at the cutoff since it is equal to $n_{vs} = \sqrt{\varepsilon_{vs}}$). The sensitivity approaches zero at the other end at $N = 2.345$ which is equal to the guiding layer refractive index. The maximum occurs in between these two values just above the cutoff and depends only on the values of the nonlinearity.

Figure 4 shows the resulting homogeneous sensitivity for the second sensor $S_{h>(MO)}$ as a function of the waveguide thickness. The refractive index of the cover is larger than that of the substrate. As a result, the longer tail of the evanescent field will be in the covering medium. The penetration depth of the evanescent field at the cutoff film thickness is infinite in the cladding. At this point, the sensitivity takes its maximum because all the power propagates in the covering media. It is also noticeable from Figure 4 that the effect of the nonlinearity is negligible on the homogeneous sensitivity of the sensor with magnetic cladding.

Figure 5 shows the sensitivity $S_{h(MO)}$ as a function of the effective index of refraction N. The figure shows that the sensitivity goes to zero at 2.34, which is about the guiding layer's refractive index. The sensitivity increase as the value of N approaches the cutoff value (this value of N occurs at $n_{vc} = \sqrt{\varepsilon_{vc}}$). At this point, the sensitivity takes its maximum because all the power propagates in the covering media. The nonlinearity almost does not affect the performance of the sensor.

The effect of different wavelength on the performance of both sensors is shown in Figures 6 and 7. The wavelengths are chosen arbitrary to be equals to 1.5, 1.3, and 1.15 μm. The sensitivity $S_{h(MO)}$ strength has not been affected by the wavelength. Figures 6 and 7 show that the sensitivity curve is shifted to the right as the wavelength increase. That is the maximum sensitivity appears at different film thickness as λ changes. As λ increases, the film thickness increases.

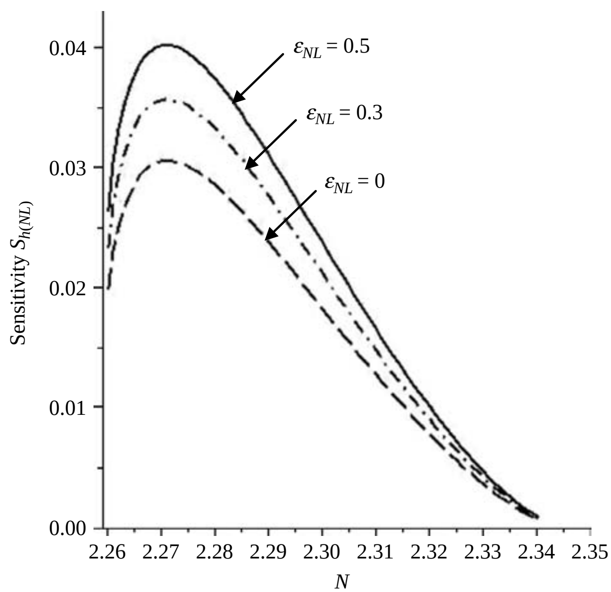

Figure 3.
Sensitivity of the sensor with structure consisting of a nonlinear cladding, a linear film, and a MO substrate measured as function of the effective refractive index (N) at different values of ε_{NL}

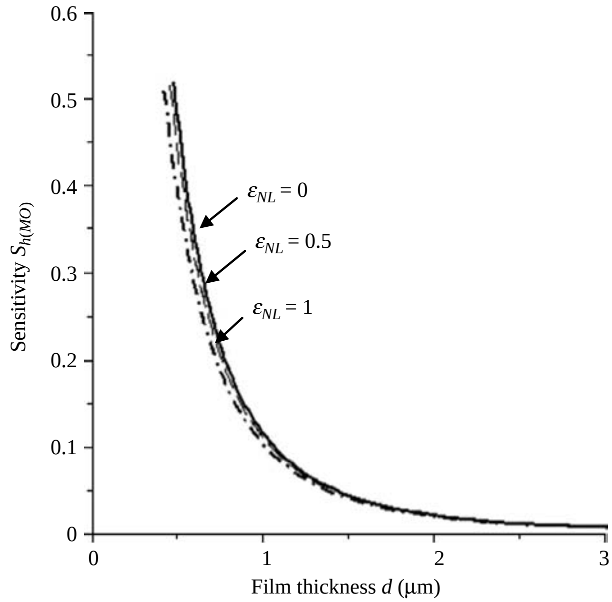

Figure 4.
Sensitivity of the sensor with structure consisting of a MO cladding, a linear film, and a nonlinear substrate measured as function of film thickness (d) at different values of ε_{NL}

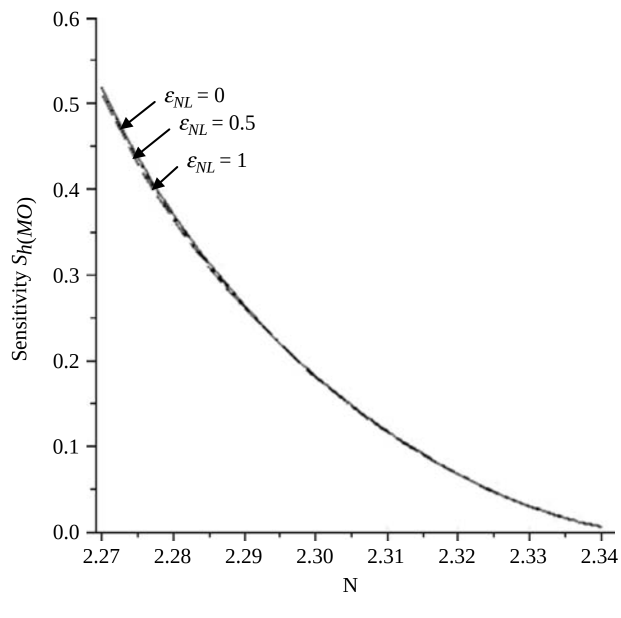

Figure 5.
Sensitivity of the sensor with structure consisting of a MO cladding, a linear film, and a nonlinear substrate measured as function of effective index of refraction (N) at different values of ε_{NL}

4. Conclusion

The concept of an integrated sensor, which combines the magnetooptic and nonlinear effect, was presented. The homogeneous sensitivities of the zero TM modes propagating in dielectric film sandwiched between a magnetooptical layer chosen to be of iron garnet

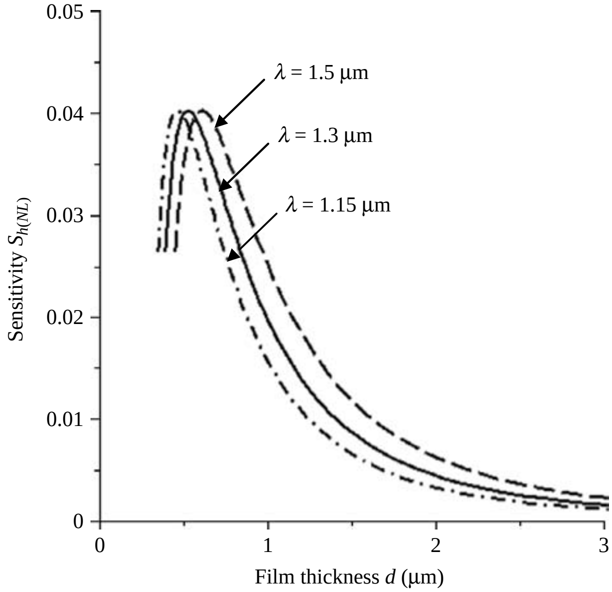

Figure 6.
Sensitivity of the sensor with structure of nonlinear cladding, linear film, and MO substrate measured as function of film thickness (d) at different values of λ and at $\varepsilon_{NL} = 0.5$

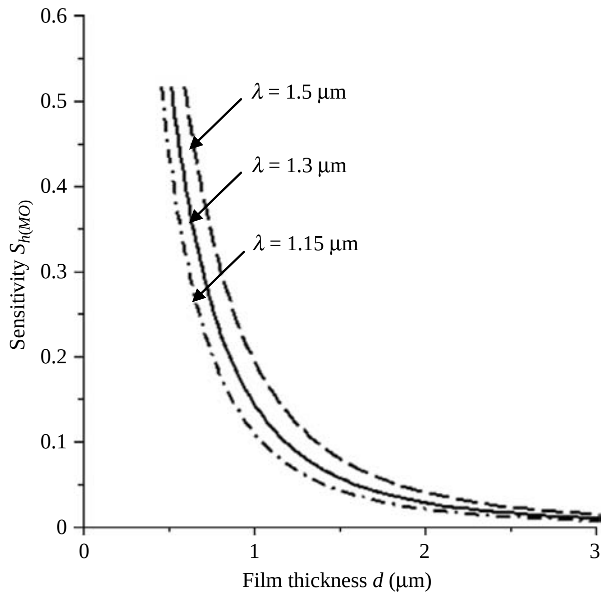

Figure 7.
Sensitivity of the sensor with structure consisting of a MO cladding, a linear film, and a nonlinear substrate measured as function of film thickness (d) at different λ and $\varepsilon_{NL} = 0.5$

and nonlinear Kerr-like behaving layer is extensively studied. In this study, we calculated the homogeneous sensitivity when the nonlinear material is chosen to be the cladding and the magnetooptic material is the substrate. In this case, which might be useful for biological measurements like detecting growth rates of the bacteria, we noticed that the sensitivity of the sensor increases with nonlinearity. This means that nonlinearity may be considered for enhancing such types of sensors. On the other hand, when we calculated the sensitivity of the zero TM modes for the sensor where the cladding is magnetooptic and the substrate is nonlinear, we found that the nonlinearity has a minor effect on the performance of the sensor. Such sensors are useful for example in measuring Faraday rotation.

The homogeneous sensitivities of both sensors are calculated as a function of the thickness of the waveguide. It is shown that the thickness of the guiding layer is a critical parameter for the sensitivity of the optical sensor with the optimum thickness being just above cutoff in case of the first structure and at the cutoff in the case of the second structure.

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She is a recipient of international awards and recognitions, including the Fulbright Scholarship, DAAD short study visit, Alexander von Humboldt-Stiftung Scholarship, Erasmus Mundus, and the Islamic University Deanery Prize for Applied Sciences.

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