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Temperature sensitivity enhancement of nonlinear optical channel waveguide sensors using thermal-stress effect

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Abstract: Temperature sensitivity plays an important role in developing optoelectronic devices such as optical waveguide sensors. Thermal-stress effect can be used to control temperature sensitivity. The solution to estimate the stress induced effective index change in a slab waveguide is extended to estimate the temperature sensitivity of channel waveguide by use of effective index method. The present study demonstrates two different configurations. Temperature sensitivities for the proposed configurations are compared together and with the temperature sensitivity of the linear channel waveguide. The results exhibit that stress can control the thermal sensitivity of the channel waveguide sensors. It is also found that the higher the value of the nonlinear term in the nonlinear-linear-nonlinear structure, the higher is the temperature sensitivity at all values of combination of different thermal-stress gradients. Moreover, the temperature sensitivity has the highest value for the nonlinear-linear-linear structure for all values of combination of different thermal-stress gradients.

Keywords: Optical waveguide, thermal-stress, sensor, temperature sensitivity, channel waveguide.

تعزيز الحساسية الحرارية لقناة قائد الموجة الضوئيه غير الخطية باستشعار أثر الإجهاد الحراري

ملخص: تلعب الحساسية الحرارية دورا هاماً فى تطوير الاجهزه الإلكتروضــوئية مثــل مجــس المسلاك الضوئي. للتحكم في الحساسية الحرارية يمكن استخدام تأثير الإجهاد الحــراري. الحــل لتقدير فعالية الاجهاد علي التغيير في المعامل الفعال للمسلاك الضوئي تم تطويره لتقــدير درجــة حساسيه الحراره لمسلاك القناة باستخدام طريقة المعامل الفعال. هــذه الدراســة تتنــاول قناتــان مسلاكيتان مختلفتان. تم مقارنة الحساسية الحرارية للنموذجين المقترحين مع بعض ومع حــساسية قناة مسلاك خطي. النتائج تظهر انه يمكن السيطرة على الحساسيه الحرارية لمجس قناة المــسلاك. كما انه تبين أن حساسية النموذج غير الخطي المتماثل تزداد مع زيادة قيمة الحد غير الخطي عند جميع تغيرات الاجهاد بينما وجد ان النموذج غير الخطي غير المتماثل له أعلى حساسية عند جميع تغيرات الاجهاد.

1 Introduction

Integrated optics is the knowledge of integrating a variety of optical components for the production, focusing, splitting, combining, isolation, polarization, coupling, switching modulation and detection of light, all on a single chip. Optical waveguide provides the connections between these components [1]. Optical waveguide sensors appear as very attractive devices to be employed in a great number of application fields such as medicine, microbiology, particle physics, automotive, and environmental safety.

Optical waveguide sensors have attracted considerable attention because of their resistance to electromagnetic interference, good compactness and robustness and high compatibility with fiber networks. In particular, a biosensor has to be contextually highly sensitive and selective to the analytic material being detected, to be biocompatible and immune to external perturbations such as either pressure or temperature changes [2]. Planar optical waveguides are sensitive to parameter variations such as refractive index, absorption, and light-emitting processes. Parameter changes will cause modulation of light traveling within glass waveguides, and may be useful for optical sensors in industrial and clinical applications[3].

Haung and Yan have calculated the temperature sensitivities of the refractive index of planar channel waveguide consisting of three linear layers [4]. Tremendous work have been made to study the properties of waves guided by dielectric films and have produced a large amount of devices. To date, it has been assumed that the relative refractive indexes associated with all the media which constitute the waveguide are independent of the field intensity. Recently, dielectric film waveguides containing one or more media, whose refractive index depends on the local intensity, have motivated a great deal of theoretical interest [5, 6, 7]. Optical performance of an asymmetric optical slab waveguide sensor consists of dielectric slab inserted between a nonlinear cladding and a linear substrate can be controlled by different stress states for both TE modes [8] and TM modes [9]. Thermal sensitivity of a symmetrical optical slab waveguide sensor consists of dielectric film surrounded by nonlinear cladding and nonlinear substrate subjected to thermal stress has been considered [10,11].

The present study is dedicated to understand the thermal sensitivities of the refractive index of the optical channel waveguide sensor subjected to different stress states. Two different configurations are demonstrated. First one is the channel waveguide sensor consists of dielectric channel surrounded by nonlinear cladding and nonlinear substrate. The other configuration has a dielectric channel, nonlinear cladding, and linear substrate. In section 2, temperature sensitivity dependence on the thermal stress will be summarized. Next, attention will be directed towards channel waveguide sensor structure. The temperature sensitivity of the effective index under thermal stress can be solved analytically for a planar waveguide. Asymmetric slab nonlinear waveguide sensor in which only one layer is nonlinear cladding is considered in sections 3, and symmetric nonlinear waveguide sensor in which both cladding and substrate are nonlinear media is summarized in section 4. The focus of section 5 is on estimating the temperature sensitivity of effective index for a channel waveguide under thermal stress by using the effective-index method [12-14]. Section 6 is dedicated to discuss the results. In this section the relation between thermal sensitivity of effective index in terms of thermal-stress is compared for both proposed configuration with the linear case in which both cladding and substrate are linear.

2 Effect of thermal stress on temperature sensitivity of channel waveguide

The dielectric constant of anisotropic and inhomogeneous medium, ε, is

$$e = \begin{pmatrix} n_{xx}^2 & n_{xy}^2 & n_{xz}^2 \\ n_{xy}^2 & n_{yy}^2 & n_{yz}^2 \\ n_{xz}^2 & n_{yz}^2 & n_{zz}^2 \end{pmatrix}, \tag{1}$$

where n_{xx}, n_{yy}, n_{zz}, n_{xy}, n_{xz}, n_{yz} are the refractive indexes. The photo-elastic effect causes the refractive indexes change with stress and strain [4]. The relation between refractive index, n, and strain, γ for media with cubic structure is expressed by different authors [15, 16]. The variation of refractive index with temperature is given by the thermo-optic relation [15]. Considering the effect of stress and temperature on the dielectric film produces the refractive index change as

$$\Delta\begin{pmatrix} n_{xx} \\ n_{yy} \\ n_{zz} \\ n_{yz} \\ n_{xz} \\ n_{xy} \end{pmatrix} = B\,\Delta T \begin{pmatrix} n_{xx} \\ n_{yy} \\ n_{zz} \\ n_{yz} \\ n_{xz} \\ n_{xy} \end{pmatrix} - \begin{bmatrix} C_1 & C_2 & C_2 & 0 & 0 & 0 \\ C_2 & C_1 & C_2 & 0 & 0 & 0 \\ C_2 & C_2 & C_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & C_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & C_3 & 0 \\ 0 & 0 & 0 & 0 & 0 & C_3 \end{bmatrix} \begin{pmatrix} \Delta s_{xx} \\ \Delta s_{yy} \\ \Delta s_{zz} \\ \Delta s_{yz} \\ \Delta s_{xz} \\ \Delta s_{xy} \end{pmatrix} \qquad \textbf{(2)}$$

where C_1, C_2, and C_3 are stress-optics constants depend 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; and B is the thermo-optic coefficient depends on refractive index, wavelength, and temperature [4, 10]. The stress state in the core can be expressed as

$$s_{xx} = g_x E\,\Delta a\,\Delta T + s_{rx}\,, \qquad \textbf{(3)}$$

$$s_{yy} = g_y E\,\Delta a\,\Delta T + s_{ry}\,, \qquad \textbf{(4)}$$

$$s_{zz} = g_z E\,\Delta a\,\Delta T + s_{rz}\,, \qquad \textbf{(5)}$$

$$s_{yz} = s_{xz} = s_{xy} = 0, \qquad \textbf{(6)}$$

where E is Young's modulus of the core; $\Delta\alpha = \alpha_{cladding} - \alpha_{core}$ is the thermal-expansion coefficient mismatch between the cladding and the core; σ_{rx}, σ_{ry}, and σ_{rz} are residual stresses along x, y, z; and g_x, g_y, and g_z, are loading parameters which in most cases need to be determined numerically. The shear stresses in z direction are ignored because the waveguide is considered very long in the z direction.

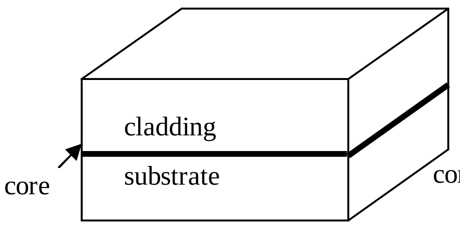

Figure 1: Schematic of Channel waveguide.

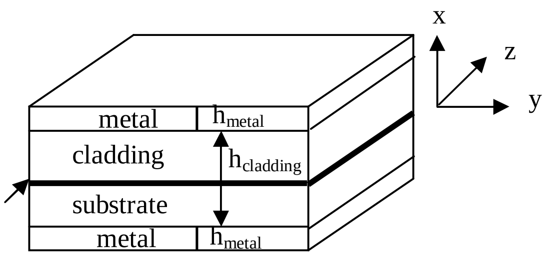

Figure 2: Schematic of Channel waveguide sensor supported by two metal plates on both side.

Figure 1 displays a basic geometry of channel waveguide where thermal stress is assumed to be induced by thermal mismatch between core and cladding. The loading parameters in this case are: $g_x=0$ and $g_y=g_z=1/(1-\nu)$, where ν is Poisson's ratio of the core. If two identical metal plates are attached on both sides of waveguide, as shown in figure 2, the loading parameters are $g_x=0$ and

$$g_y=g_z=\frac{1}{1-u}\left(1+\frac{a_{mtal}-a_{cladding}}{a_{cladding}-a_{core}}\text{x}\frac{1}{1+\dfrac{1-u_{metal}}{1-u_{cladding}}\dfrac{E_{cladding}}{E_{metal}}\dfrac{h_{cladding}}{h_{metal}}}\right), \quad \textbf{(7)}$$

where h is the thickness of metal plates. Various loading methods can induce different thermal stresses in the waveguides. The refractive index profile of the core under stress states expressed by equations (3, 4, 5, 6) can be obtained from equation 2, as

$$n_{xx}=n_o+\left(Bn_o-C_1g_xE\Delta a-C_2\left(g_y+g_z\right)E\Delta a\right)\Delta T-C_1s_{rx}-C_2\left(s_{ry}+s_{rz}\right), \quad \textbf{(8)}$$

$$n_{yy}=n_o+\left(Bn_o-C_1g_yE\Delta a-C_2\left(g_x+g_z\right)E\Delta a\right)\Delta T-C_1s_{ry}-C_2\left(s_{rx}+s_{rz}\right), \quad \textbf{(9)}$$

$$n_{zz}=n_o+\left(Bn_o-C_1g_zE\Delta a-C_2\left(g_x+g_y\right)E\Delta a\right)\Delta T-C_1s_{rz}-C_2\left(s_{rx}+s_{ry}\right), \quad \textbf{(10)}$$

Differentiating equations (8, 9, 10) with respect to temperature, *T*, gives the temperature sensitivity of the refractive index as

$$\frac{\mathrm{d}n_{xx}}{\mathrm{d}T}=Bn_o-C_1g_xE\Delta a-C_2\left(g_y+g_z\right)E\Delta a, \quad \textbf{(11)}$$

$$\frac{\mathrm{d}n_{yy}}{\mathrm{d}T}=Bn_o-C_1g_yE\Delta a-C_2\left(g_x+g_z\right)E\Delta a, \quad \textbf{(12)}$$

$$\frac{\mathrm{d}n_{zz}}{\mathrm{d}T}=Bn_o-C_1g_zE\Delta a-C_2\left(g_x+g_y\right)E\Delta a, \quad \textbf{(13)}$$

The temperature sensitivity of channel waveguide is estimated using the effective index method. Though, effective index method is an approximate method, it produces good results due to the small variation of thermal stress [12-14]. This method takes advantage of the fact that the temperature sensitivity of the effective index can be solved analytically for a planar waveguide. Then, the solution is extended for a channel waveguide.

3 Asymmetric nonlinear slab waveguide sensor

Asymmetric nonlinear slab sensor has the structure shown in figure 3 in which the middle layer consists of an inhomogeneous film with the thickness on the order of the wavelength and has a higher refractive index than the surrounding region. The surrounding media are linear substrate and nonlinear cladding with an intensity dependent refractive index. The dielectric function of the nonlinear medium (Kerr type) is expressed as

$$e_c = e_{0c} + a\left|E_y\right|^2, \qquad \textbf{(14)}$$

where e_{0c} is the linear relative permittivity and α is the nonlinear coefficient [5, 6]. The light is confined in the x direction within the central core, propagates in the z direction, and has no variation in the y direction. Transverse electric field (TE) has been considered in the slab waveguide having electric field components (0, e_y $e^{j(\omega t-\beta z)}$, 0) and magnetic field components (h_x $e^{j(\omega t-\beta z)}$, 0, h_z $e^{j(\omega t-\beta z)}$), where $\beta = n_{eff}\, k$, n_{eff} is the effective refractive index, $k = \omega/c$ is the propagation constant, ω is the radian frequency and c is the speed of light. Applying the fields into Maxwell's equations, the field equations for each layer is obtained [8].

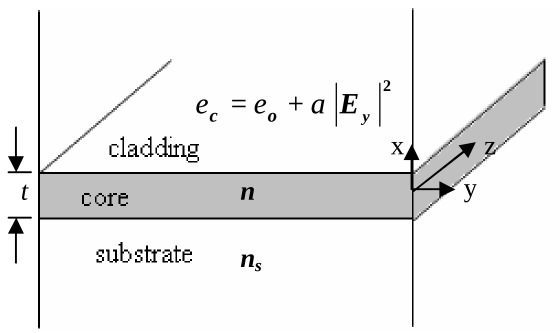

Figure 3: Three-layer asymmetric nonlinear waveguide sensor.

Applying the boundary conditions leads to the dispersion equations for TE modes are

$$\tan p = \begin{cases} b + \sqrt{b^2 + 1} & \text{even modes} \\ b - \sqrt{b^2 + 1} & \text{odd modes} \end{cases} \qquad \textbf{(15)}$$

where $p = \frac{kt}{2}\sqrt{n^2 - n_e^2}$, $b = \tan(k_1 - k_2)$, with $\tan(k_1) = \sqrt{\frac{n_e^2 - n_s^2}{n^2 - n_e^2}}$, and $\tan(k_2) = \frac{k\sqrt{n^2 - n_e^2}}{h}$, $h = q_c \tanh\left(q_c\left(\frac{t}{2} - x_0\right)\right)$, n_s is the refractive index of the substrate, n is the refractive index of the core, and $q_c = k\sqrt{n_e^2 - e_0}$, $\Lambda = \frac{k^2}{2}a$, and x_0 is constant of integration at which power is maxima [8]. Equation 15 expresses the relationship between the effective refractive index and the core thickness.

4 Symmetric nonlinear slab waveguide sensor

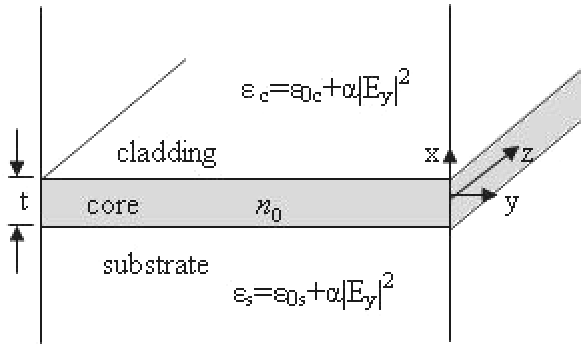

Figure 4: Three-layer symmetric nonlinear waveguide sensor.

Figure 4 displays the schematic of symmetric nonlinear waveguide sensor which consists of an inhomogeneous film with higher refractive index than the surrounding nonlinear (Kerr type) cladding and substrate regions. The dispersion equation for this configuration is [10, 11]

$$ktp = \begin{cases} 2\tan^{-1}\left(\frac{q}{p}\tanh C\right) & \text{even modes} \\ -2\cot^{-1}\left(\frac{q}{p}\tanh C\right) & \text{odd modes} \end{cases} \qquad \textbf{(16)}$$

where $p = \sqrt{n^2 - n_e^2}$, $q_i = \sqrt{n_e^2 - e_{oi}}$, i denotes s for substrate and c for cladding, $q = q_c = q_s$, and $C = kqx_0$. The effective refractive index as function of core thickness can be calculated from equation 16.

5 Nonlinear Channel waveguide sensor:

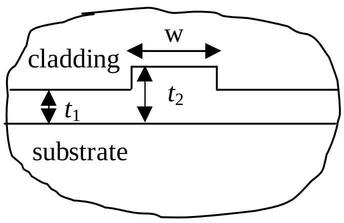

Figure 5: Two dimensional channel waveguide where the core region is magnified.

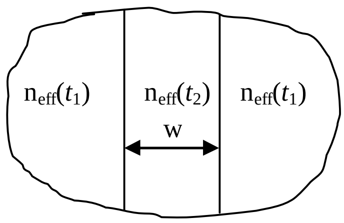

Figure 6: Effective index model equivalent planar waveguide.

Channel waveguides are most common optical waveguides. In the channel waveguide, the light is confined in two directions perpendicular to the light propagation direction, z direction. The confined light in the two directions in the channel waveguide can be directed to desired locations. Figure 5 illustrates basic configuration of the channel waveguide. The ridge in the core region confine light in the y direction, and the top and the bottom cladding regions confine light in the x direction. Although numerical methods are usually necessary to solve the mode for this kind of structure, the effective index method is an approximation method to obtain the closed form solutions [4]. This method is used to show the thermal-stress effects on the temperature sensitivity of effective index for the lower order E^x mode.

The waveguide is assumed under the homogenous stress state (in-plane stress), and the cladding and the substrate do not have an elasto-optic effect. According to the effective index method, the waveguide structure in Figure 5 can be equivalent to a planar waveguide shown in figure 6. $n_e(t_1)$ and $n_e(t_2)$ are obtained by applying a planar waveguide analysis equation 17, under the ridge where the core thickness is t_2 to obtain $n_e(t_2)$ and away from the ridge where the core thickness is t_1 to obtain $n_e(t_1)$, for the planar TE lowest mode.

$$\sqrt{n^2 - n_e^2}\,\tan\left(k\,\frac{t}{2}\sqrt{n^2 - n_e^2} \right) = \sqrt{n_e^2 - n_1^2}, \qquad \textbf{(17)}$$

where n is the refractive index of the film, n_e is the effective index, n_1 is the surrounding refractive index, t is the thickness of the film.

The equivalent channel waveguide shown in Figure 6 is a planar symmetric three-layer waveguide with core index $n_e(t_2)$, cladding index $n_e(t_1)$ and width w. The relation of the lowest-order E^x mode effective index n_{E^x} of the channel waveguide is obtained by [4]

$$\sqrt{n_e^2(t_2)-n_{E^x}^2}\,\tan\left(k\,\frac{w}{2}\sqrt{n_e^2(t_2)-n_{E^x}^2}\right)=\sqrt{n_{E^x}^2-n_e^2(t_1)}\,. \qquad \textbf{(18)}$$

Differentiating equation 18 with respect to the temperature, T, gives the temperature sensitivity $\left(\frac{dn_{E^x}}{dT}\right)$ of the E^x mode effective index of the channel waveguide as

$$n_{E^x}\frac{dn_{E^x}}{dT}=\frac{n_e(t_2)\frac{dn_e(t_2)}{dT}\left(1+k\,\frac{w}{2}\,\frac{n_e^2(t_2)-n_e^2(t_1)}{\sqrt{n_{E^x}^2-n_e^2(t_1)}}\right)+n_e(t_1)\frac{dn_e(t_1)}{dT}\left(\frac{n_e^2(t_2)-n_{E^x}^2}{n_{E^x}^2-n_e^2(t_1)}\right)}{1+\frac{n_e^2(t_2)-n_{E^x}^2}{n_{E^x}^2-n_e^2(t_1)}} \qquad \textbf{(19)}$$

The values of $n_e(t_1)$ and $n_e(t_2)$ can be obtained from equation 15 for asymmetric nonlinear structure and from equation 16 for symmetric nonlinear structure. The sensitivity of both configurations will be compared with linear configuration in which both cladding and core are linear media.

6 Numerical results

The thermal sensitivity has been calculated for symmetric channel waveguide consists of nonlinear cladding and nonlinear substrate. Similar calculations are made for asymmetric channel waveguide sensor with nonlinear cladding and linear substrate. Calculation results have been compared to the results of the linear channel waveguide sensor. The parameter values taken in all the numerical calculations are: λ= 0.83 µm, dn_s = 1X10^{-5} $^{o}C^{-1}$, dn = 2X10^{-5} $^{o}C^{-1}$, n_0 = 3.5 and tanh$C$ varies in the interval (-1, 1).

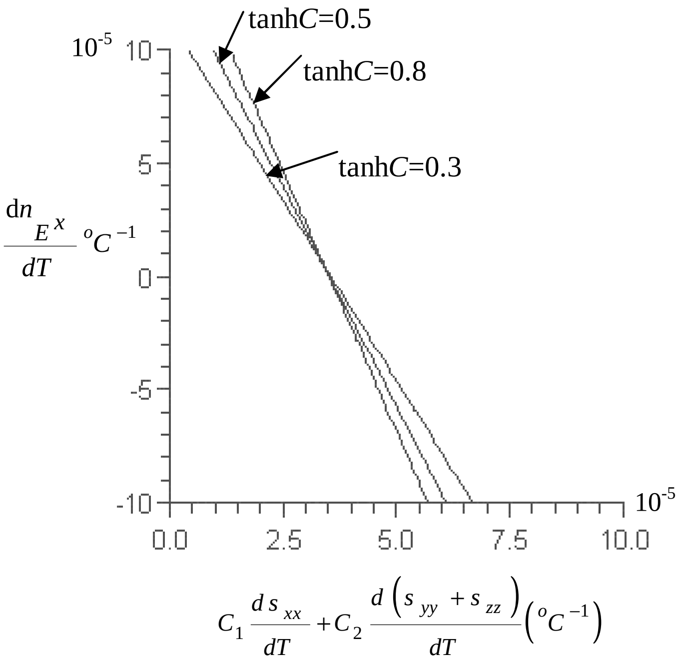

Figure 7 : Temperature sensitivity of the effective refractive index of the fundamental mode (m=0) versus different thermal-stress gradients at different values of nonlinearity for channel waveguide made of three layers: linear slab, nonlinear cladding and nonlinear substrate.

Figure 7 shows the temperature sensitivity of the effective refractive index (n_E^x) of the symmetrical channel waveguide as a function of the combined thermal-stress gradients at different values of nonlinearity (tanh*C* = 0.3, 0.5, and 0.8). Figure also shows that as the combination of thermal-stress gradients vary the sensitivity changes. The relation between the combination of stress gradients and the temperature sensitivity is linear. This indicates that the sensitivity can be controlled by varying the applied thermal stresses. It is clear that the temperature sensitivity is maximum at tanh*C*=0.8 for all values of the gradient of thermal stress which means that at the linear limit the temperature sensitivity reaches its maximum as seen in Figure 8.

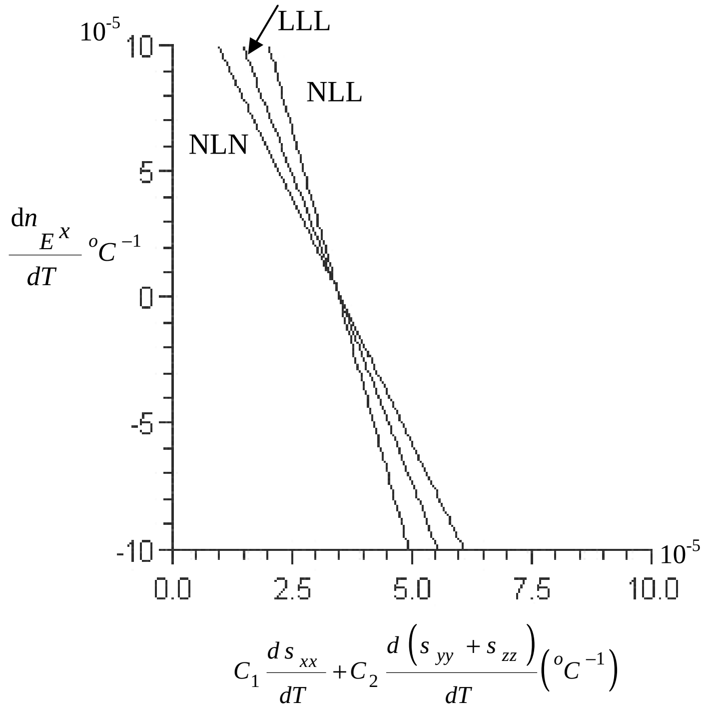

Figure 8: Temperature sensitivity of the effective refractive index of the fundamental mode (m=0) versus different thermal-stress gradient at Tanh *C* = 0.5 for different configurations of three-layer channel waveguide. Below: nonlinear cladding, linear slab, and nonlinear substrate (NLN). Middle: linear cladding, linear media and linear substrate (LLL). Above: nonlinear cladding, linear slab, and linear substrate (NLL).

Figure 8 shows the thermal stress sensitivities for symmetric channel waveguide and asymmetric channel waveguide compared to each other and to the linear channel waveguide. The figure shows that the sensitivities of all types of channel waveguide can be controlled by changing the applied thermal stress. The relation between the thermal stress sensitivities and the combination of stress gradients is linear. However, the temperature sensitivity of the asymmetric nonlinear case has the maximum value for all values of the combined thermal- stress gradients compared to the other configurations.

In figure 7 and figure 8, all lines coincide at one point no matter what the chosen configuration is. This point corresponds to the value of the combination of stress gradient equals Bn_0. At this point the thermal stress sensitivity as defined by $\left(\frac{dn_{E^x}}{dT}\right)$equals zero.

7 Conclusion

Thermal stress in the channel waveguide can be controlled by selecting materials and load methods, such as attaching a bimetal plate. Thus, temperature sensitivities of the effective index of the channel waveguide can be carefully tuned. Moreover, the temperature sensitivity of the channel waveguide can be controlled by changing the nonlinearity value symbolized by tanh*C*. The temperature sensitivity of effective refractive index of symmetric nonlinear channel waveguide increases as the nonlinear term values increase at all values of combined thermal-stress gradients and reaches its maximum at the linear limit. Moreover, the temperature sensitivity of the effective refractive index of asymmetric nonlinear channel waveguide has the maximum value compared to the other configurations for all values of the combined thermal-stress gradients. The result might help the manufacturer in designing and fabricating high performance channel waveguide sensor.

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