Laser beam deflection sensor in a planar optical waveguide based in the Mirage effect

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Abstract

The beam deflection of a guided mode in a planar optical waveguide is analyzed. The deflexion is caused by a gradual change in the depth of the waveguide that is transversal to its propagation direction. The beam deflection angle could be modulated by a change in the refractive index at the surface layer of the waveguide. We present numerical results to evaluate the deflexion in the case of a glass integrated structure.

Keywords: Planar optics, angle sensors, integrated optics

1. Introduction

Mirage effect has been widely used for the thermal characterization of materials. The configurations already proposed use the measurement of the variation of a photothermal signal in an interferometric [1] or in an angle beam deflection schemes [2, 3]. These systems have a high theoretical sensitivity, but due to complex fabrication techniques, this limit is rarely achieved. Planar integrated optics has demonstrated to be a reliable candidate for the development of devices with good performances and simple fabrication technology. However its use as a platform for beam deflection applications has been limited to only few developments [4].

In this work, we present the design of an optical integrated device for laser beam deflection measurements. It is based on the mirage effect where the deflection of the beam in a planar waveguide is caused by a gradual change in the propagation constant of the optical signal. This change is originated when a laser beam propagates along a waveguide with a gradient depth transversal to the direction of propagation. One may suppose that such a gradient could be generated by a selective ion-exchange mechanism in which the diffusion of the dopant in the substrate matrix will generate a gradient in the waveguide depth. After the description of the principle device, we analyze simulations results and briefly discuss its use as a sensor device.

2. Beam deflexion of a guided propagated mode

Let us assume a planar waveguide of thickness \( e \) and refractive index \( n_w \) on a substrate of refractive index \( n_s < n_w \). We will take our coordinate as shown in Fig. 1. If there is a gradient of the effective refractive index, \( n_{\text{eff}} \), of the mode, this last been on the plane of the waveguide, the guided beam will deflect. The beam axis will deflect toward the higher value of \( n_{\text{eff}} \).

Let us suppose that the thickness of the waveguide varies slowly only along the \( x \) direction, but is constant along the \( z \) axis, that is, we suppose \( e = e(x) \). In addition the change of the effective refractive index \( n_{\text{eff}} \) on \( x \) is small across the beam’s cross section.
In this case the lateral deflection angle of a slab guided 2D-beam may be approximated as,

\[ \theta = \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial e} \int \frac{de(x)}{dx} \hat{a}_z \cdot d\vec{s}, \]  

(1)

where \( s \) is the path of the beam on the \( x-z \) plane. To further simplify things let us assume a linear variation of the waveguide’s thickness on \( x \). Therefore \( de(x)/dx \) is constant and may be brought out of the integral in Eq. (1). If we now suppose that the deflection angle is small up to where the device ends (at \( z = L \)), then the path is always nearly parallel to the \( z \)-axis, and \( \hat{a}_z \cdot d\vec{s} \equiv dz \) through \( s \). The integral of \( dz \) is simply \( L \), and therefore we get,

\[ \theta \approx \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial e} \frac{de(x)}{dx} L. \]  

(2)

Now, this deflection angle will change if \( n_{\text{sup}} \) changes. Therefore, the deflection angle will be modified by variations of \( n_{\text{sup}} \). A small change in the refractive index of the upper external medium, \( \Delta n_{\text{sup}} \), will cause a change in deflection angle of

\[ \Delta \theta = \frac{\partial \theta}{\partial n_{\text{sup}}} \Delta n_{\text{sup}}. \]  

(3)

We may refer to the derivative on the right hand side of the latter equation as the sensitivity. From Eq. (2) we get that the sensitivity is given by,

\[ \frac{\partial \theta}{\partial n_{\text{sup}}} = \left( \frac{1}{n_{\text{eff}}} \frac{\partial^2 n_{\text{eff}}}{\partial n_{\text{sup}} \partial e} - \frac{1}{n_{\text{eff}}^2} \frac{\partial n_{\text{eff}}}{\partial e} \frac{n_{\text{eff}}}{\partial n_{\text{sup}}} \right) \frac{de(x)}{dx} L. \]  

(4)

The derivatives inside the parenthesis in the latter equation may be calculated numerically.

3. Numerical results

We have considered an integrated structure composed by a surface waveguide fabricated by a classical Na+/K+ ion exchange process in a soda-lime glass substrate. The depth gradient \( \nabla e \) could be generated using a variable depth Aluminum mask deposited along the \( z \)-axis that will reduce the number of K+ ion diffused in the substrate. This will produce a gradient in the waveguide refractive index and depth. For simplicity, as mentioned in the above section, we only take into account the depth gradient. We have calculated the cutoff thicknesses for the TE0 and TE1 modes for the waveguide (Fig. 2). The single mode propagation is
convenient to have a well directed beam deflected. This is because the modal dispersion will produce a different deflexion angle for each mode resulting in a spatially expanded output signal. Additionally the sensitivity will be also different for each mode reducing the efficiency in sensing. The single mode condition is attempt for a waveguide thickness value between 0.6 to 1.8 μm.

We have numerically evaluated the sensitivity (Eq. 4) attain for a water immersed and a typical polymeric sensitive layer sensors of refractive index $n_{\text{sup}}=1.33$ and $n_{\text{sup}}=1.80$ respectively. The waveguide depth gradient was considered to be extended along a distance $x_f - x_i = 3\text{mm}$ that could be easily controlled in sputtering deposition of the Aluminium mask. Also a propagating distance $L=1 \text{ cm}$ was used. Results are shown in Fig. 3. In the case of an the aqueous sensor (Fig. 3a) the maximum sensitivity $\Delta \theta = 0.52^\circ$ is obtained for refractive index change in water of $\Delta n_{\text{sup}}=0.01$. In the case of using a sensitive layer of higher refractive index a sensitivity of $\Delta \theta = 3^\circ$ was calculated (Fig. 3b). This is due to the fact that the upper layer increases the effective refractive index value of the mode and enhanced the overlapping of the optical field in this layer resulting in a better sensitivity of the sensor. However the thickness of polymeric layer has to be thin enough to avoid the confinement of the mode in this layer canceling the deflexion effect. It can be noted from Fig. 3b that for higher values of $\Delta n_{\text{sup}}$ the sensitivity reached is enhanced.

![Graph](image)

**Fig. 2.** Calculated effective refractive index of the TE modes as a function of the waveguide depth for a $K^*$ exchanged waveguide at the wavelength of 635nm.

![Graph](image)

**Fig. 3.** Beam deflexion change as a function of the waveguide depth caused by different superstrate refractive index change in the case of: a) an aqueous surrounding medium ($n_{\text{sup}}=1.33$) and b) a polymeric sensitive layer ($n_{\text{sup}}=1.8$ and $e_{\text{sup}}=0.05 \text{ μm}$).
According to Eq. 4 the sensitivity of the device can be improved by increasing the depth gradient in the waveguide or by increasing the propagating length. The numerical results for the sensitivity of the integrated structure proposed, show that the deflexion obtained for a sensor application is in some order comparable to that obtained with other works using planar waveguides [see by example Ref. 4].

4. Discussion
We described the design of a planar integrated beam deflecting structure. The beam deflection is produced as an optical beam propagates through a waveguide with a depth gradient transversal to the axis of propagation. We discuss the sensor application for aqueous and high refractive index sensitive layer sensors. The sensitivity calculated were of \( \Delta \theta = 0.52^\circ \) and \( \Delta \theta = 3^\circ \) respectively for a change in the refractive index of the sensitive layer of \( \Delta n_{sup} = 0.01 \). This deflexion could be easily measured by a conventional blade position sensor or a CCD camera.

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References