NOVEL INTEGRATED OPTICAL REFRACTOMETER

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0. Abstract

A passive integrated optical waveguide refractometer based on bendloss changes in a spiral-shaped channel waveguide is proposed and fabricated in Si_3N_4/SiO_2-technology. The experimentally determined performance and the theoretical predictions, based on a simple model for so called 'Whispering Gallery Modes', agree very well. The minimum detectable refractive index change was measured to be $\Delta n=8 \cdot 10^{-6}$.

Keywords: refractometry, integrated optics, sensors.

1. Introduction

Integrated optical sensors for measuring chemical or physical quantities show interesting prospects because of their high sensitivity, small size, low price and the absence of electromagnetic interference. In the last decade many types of integrated optical sensors have been proposed and fabricated, where devices based on a Mach-Zehnder interferometer are generally considered as the most promising, due to their high sensitivity and intrinsic balancing [1]. Unfortunately, to exploit the full sensitivity potential, these devices often require on-chip modulation to tackle the phase ambiguity in the interference signal [2]. In this paper we introduce a novel passive waveguide refractometer [3], where refractive index changes induce a change in the bendloss of a spiral-shaped channel waveguide. Here no on-chip modulation is required. Measurements on a device fabricated in Si_3N_4/SiO_2-technology are presented and its performance is compared with theory.

2. Sensing principle

The losses of a bent optical waveguide increase strongly with a decrease of either the bending radius or the effective refractive index contrast defining the waveguide [4]. In the sensor we propose a single mode channel waveguide has been used which has a spiral shape as illustrated in figure 1a. The radius of curvature R of the waveguide decreases in the propagation direction so for a given effective refractive index contrast $\Delta N=(N_g-N_b)$, where N_g and N_b are the refractive indices of the waveguide and the background respectively, the losses will gradually increase in the propagation direction and at a certain point in the spiral all the light will be lost by the waveguide. The sensor principle is based on the shift of this point in the propagation direction caused by an increasing lateral refractive index contrast. In this way the depth of propagation of the light into the spiral is a direct measure for the refractive index contrast.

A. Berg et al. (eds.), *Sensor Technology in the Netherlands: State of the Art*

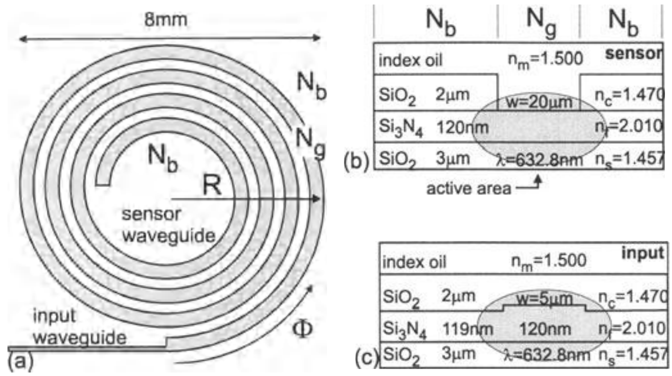

Fig. 1: Schematic representation of the refractometer, with a top-view of the spiral-shaped channel waveguide (a), a side-view of the sensor waveguide (b) and a side-view of the input waveguide (c).

3. Design

In literature simple expressions can be found for the attenuation, A, in bent waveguides which are in the so called Whispering Gallery Mode (WGM) regime [4]

$$A = \frac{2}{\pi}\frac{1}{\sqrt{100\Delta}} \cdot 10^{2.29-2.17R_n-0.58R_n^2} \quad (\text{dB/rad}) \qquad (1)$$

$$\text{with} \quad \Delta \equiv \frac{\Delta N}{N_b} \quad \text{and} \quad R_n \equiv \frac{N_b R}{\lambda} \cdot \Delta^{\frac{3}{2}} \cdot 1.137^{\Delta - 0.01}$$

The total power loss in the spiral as a function of the propagated angle, $\alpha(\Phi)$, can be calculated
by integrating (1)

$$\alpha(\Phi) = \int_0^{\Phi} \frac{2}{\pi}\frac{1}{\sqrt{100\Delta}} \cdot 10^{2.29-2.17R_n(\Phi)-0.58R_n^2(\Phi)} \cdot d\Phi \quad (\text{dB}) \qquad (2)$$

Using this expression the point were the light is lost by the waveguide, defined as $\Phi_{\alpha=20dB}$, can be calculated.
The performance of the device will be determined by the choice made for the initial radius, R_0, and the angular dependency of the radius, $\delta R/\delta\Phi$, together with the waveguide cross section. From (1) it can be deduced that the sensitivity becomes higher with a larger bend radius. Nevertheless the bending radius will be limited by the device size we allow; in our case 1cm^2. From this we choose a initial radius R=4mm.The optimisation of $\delta R/\delta\Phi$ was done by evaluating a number of different spiral shapes and an attractive spiral shape was found to be

$$R(\Phi) = \frac{4}{1+\frac{\Phi}{25}} \quad (mm) \tag{3}$$

For obtaining a sensitive refractometer it is essential to find a waveguide geometry which converts a refractive index change in a sensing layer, Δn_m, efficiently into a change in the effective refractive index contrast, ΔN, i.e. we need a large value for $\delta\Delta N/\delta n_m$. This can be obtained by the waveguide illustrated in fig. 1b. If the refractive index of the index oil (in general the sensing layer showing the Δn_m) changes, only the effective refractive index of the waveguide, N_g, will change, whereas the refractive index of the background, N_b, will remain unchanged because here the optical field does not penetrate the oil. This means that for this type of waveguide optimizing $\delta\Delta N/\delta n_m$ is the same as optimizing $\delta N_g/\delta n_m$, which has been extensively studied earlier [5]. For our sensing device we chose to use a He-Ne laser with a wavelength λ=632.8nm and quasi-TE polarization. For the structure with the parameters as shown in figure 1b, made in the in our laboratory available Si_3N_4/SiO_2-technology [6], we then find $\delta\Delta N/\delta n_m$=0.19.

Using (2) and (3) together with the waveguide geometry (fig. 1b), we can calculate $\Phi_{\alpha=20dB}$, i.e. how far the light propagates into the spiral before the light is lost, as a function of the applied refractive index difference between the SiO_2-cladding and the index oil, n_m-n_c. This is the dotted curve in fig. 2. A straight-waveguide attenuation of 0.5dB/cm was incorporated in this analysis. It can be seen that $\delta\Phi/\delta n_m \approx 400 \cdot 2\pi$ rad.

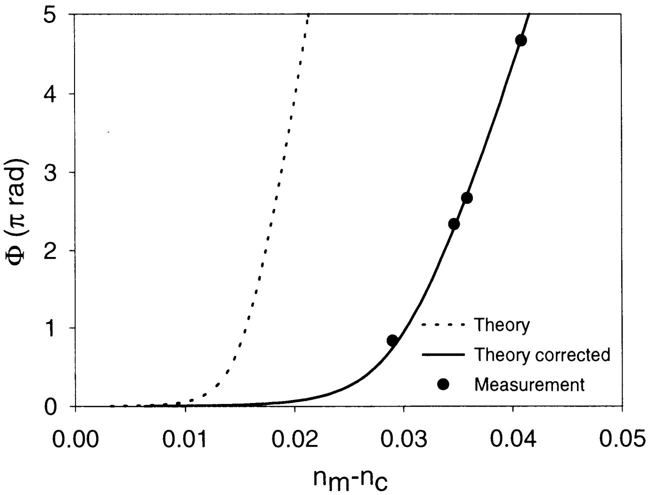

Fig. 2: Penetration angle of the light into the spiral ($\Phi_{\alpha=20dB}$) versus n_m-n_c. The dotted line is the theoretical curve, the solid line the theoretical curve for a residual SiO_2 layer of 40nm thickness; the dots are the experimental values.

4. Measurements and discussion

For demonstrating the feasibility of the sensing principle, measurements on the device were performed with a ccd-camera, allowing a simple determination of the point where the intensity of the light scattered by the waveguide, i.e. the light inside the waveguide, is reduced 20dB with respect to the intensity at the beginning of the spiral. The refractive index n_m was varied using several refractive index oils. Fig. 3 shows the penetration of the light into the spiral for four different values of n_m. The sensing capability of this device is clearly illustrated; the higher the refractive index of the oil the further the light penetrates the spiral (fig. 3a-d).

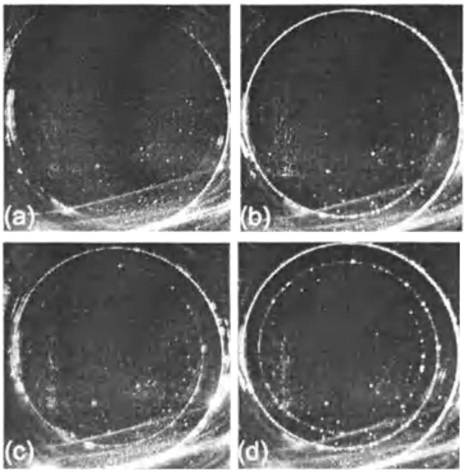

Fig. 3: Scattered light in the spiral for different values of n_m; n_m=1.4990 (a), 1.5047 (b), 1.5059 (c) and 1.5109 (d). Note that the pictures have an initial rotation of π/12 rad.

In fig. 2 the dots indicate how far the light penetrates the spiral ($\Phi_{\alpha=20dB}$) as a function of n_m-n_c. It is clear that the theoretical curve does not coincide with the experimentally found points. The reason for this was found by Scanning Electron Microscopy to be a 40nm thick residual layer of SiO_2 in the sensing waveguide area, apparently due to a too short etching time in the sensing waveguide defining etch step. The solid line in fig. 2 is the theoretical curve calculated for the real structure and it clearly agrees with the experimental points very well. This residual layer however results in a reduction of the slab sensitivity to $\delta\Delta N/\delta n_m$=0.10, resulting in $\delta\Phi/\delta n_m \approx 210 \cdot 2\pi$ rad.

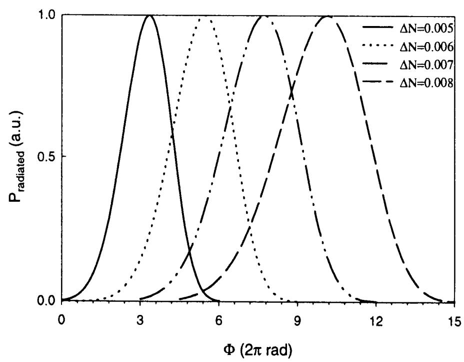

Fig. 4: Power radiated from the spiral versus the penetration angle, for different ΔN.

The resolution of the sensor can be evaluated by plotting the radiated power, δP/δΦ, versus the penetration angle for different values of ΔN (fig. 4).

$$P_{radiated} = \frac{\partial P}{\partial \Phi} = -\frac{\partial}{\partial \Phi}\left[10^{-\frac{\alpha(\Phi)}{10}}\right] \qquad (4)$$

If we assume that the position of the peaks can be measured with an accuracy of 1/1000 of its FWHM, with a detector array or ccd-camera, a sensing resolution of $\Delta n=8\cdot 10^{-6}$ can be achieved, while for the originally designed structure a resolution of $\Delta n=4\cdot 10^{-6}$ can be calculated. This number can be improved by using a larger initial bend radius for the spiral. Also facilities for compensation of temperature effects can be incorporated. Furthermore the working point, i.e. the sensitivity region, can be adjusted to the specific application. Note here that SiO_xN_y layers can be made with a refractive index in the range $1.45<n<2.00$. Device to device reproducibility depends on technological limitations, which should be determined carefully.

5. Conclusions

In conclusion a novel highly sensitive passive integrated optical spiral-shaped waveguide refractometer was proposed and fabricated in Si_3N_4/SiO_2 technology. A resolution in the refractive index of $\sim 8\cdot 10^{-6}$ is shown, and a value of $4\cdot 10^{-6}$ is calculated for an even not completely optimized structure. The experimental performance of the device agrees very well with the simple model derived for WGM waveguide bends. The sensor concept is shown to be flexible (the range can be adjusted to practical specifications) and is expected to be well applicable in making useful integrated optical sensing systems.

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