Sensors and Materials, Vol. 8, No. 4 (1996) 185–191
MYU Tokyo

S & M 0236

Integrated Optical Wavelength Scanner for Refractometric Gas Measurements

Elmar Wagner, Iliyana Hinkov and Vladimir Hinkov

Fraunhofer Institute for Physical Measurement Techniques,
Heidenhofstrasse 8, 79110 Freiburg i.Br., Germany

(Received October 4, 1994; accepted April 24, 1995)

Key words: gas sensor, acoustooptics, integrated optics, refractive index sensor, $LiNbO_3$

We have experimentally demonstrated the feasibility of a novel acoustooptical gas sensor and we have shown that its optical and acoustic parts can achieve the expected performance. Work is underway to realize a sensor comprised of the two parts and operating in real gas atmosphere.

1. Introduction

Integrated optical evanescent field sensors can be used for sensing chemical and biochemical compounds. Various devices such as Mach-Zehnder interferometers,[1] Fabry-Perot resonators[2] and integrated optic input or output grating couplers[3] have been applied for signal detection; however all have some limitations.

We propose a novel acoustooptical detection principle[4] which allows measurement of absolute values with the high accuracy of interferometric sensors. An efficient reference channel can be incorporated in the sensing waveguide, so that stable performance of the sensor, even for laser diodes, can be expected.

In this paper, we also report on a series of experiments aimed at verifying the acousto-optical detection concept.

2. Principle of Acoustooptical Gas Sensor

The structure of the proposed acoustooptical gas sensor is schematically shown in Fig. 1. It essentially consists of an integrated collinear acoustooptical transversal electric to transversal magnetic (TE-TM) mode converter with an interdigital transducer for the excitation of the surface acoustic waves (SAWs). The device is fabricated on an (X-cut) $LiNbO_3$ substrate. A gas-sensitive layer, which changes its refractive index as a result of the absorption of a given gas, is deposited. The optical channel waveguide of the converter is formed by means of Ti-diffusion. It is monomodal and guides the two fundamental TE and TM modes only. The SAWs are guided in an acoustic waveguide also fabricated by Ti-diffusion. On top of the Ti-waveguide and below the gas-sensitive layer a thin (cut-off) proton-exchanged (PE) layer is produced, forming a two-layer waveguiding structure. In the PE-layer, the extraordinary index of refraction is strongly increased, whereas that of the ordinary one is reduced.[5] In this manner, the extraordinary mode of the two-layer structure is "pulled" to the surface and becomes very sensitive to index changes in the cover (refractive index n_c), i.e., the gas-sensitive layer. At the same time, the ordinary mode is removed from the surface and obtains a very low refractive index sensitivity. Consequently, an index change in the gas-sensitive layer will cause a change in the waveguide birefringence. This change can be detected with the acoustooptical collinear TE-TM mode converter. In fact, the frequency f_a of the SAWs necessary for the phase matching in such a converter depends on the waveguide birefringence in the following way:

$$f_a = (V_a/\lambda_0)\mathrm{x}\left|n_{\mathrm{eff}}^{\mathrm{TM}} - n_{\mathrm{eff}}^{\mathrm{TE}}\right|. \tag{1}$$

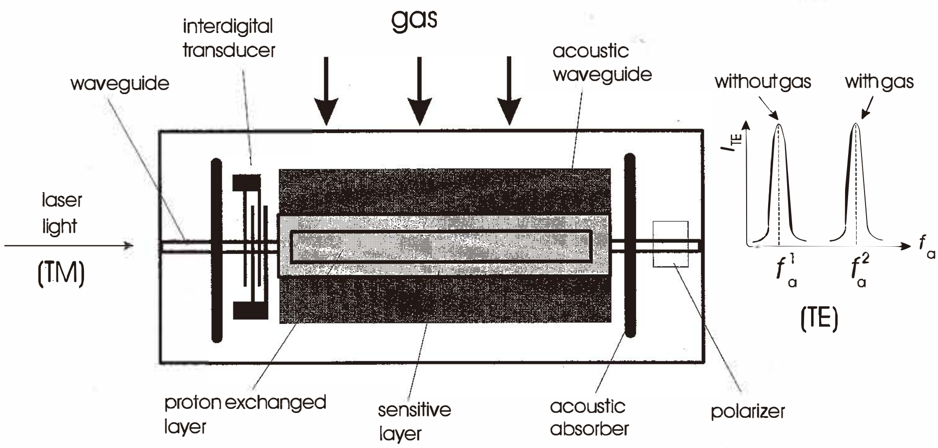

Fig. 1. Schematic diagram of the proposed acoustooptical gas sensor.

Here, V_a is the phase velocity of the SAW, λ_0 is the optical wavelength, and n_{eff}^{TM} and n_{eff}^{TE} are the effective mode indices of the two fundamental modes. A polarizer was additionally incorporated on the chip, also fabricated by means of proton exchange.(6)

3. Experiments

3.1 *Investigation of the optical two-layer waveguiding structure*

The optical and acoustical two-layer waveguiding structure was fabricated in the following manner. First, 130-nm-thick Ti stripes were deposited and photolithographically structured on the sample surface (10×25 mm^2 chips) in order to form the SAW waveguides. The Ti stripes were indiffused for 24 h at 1050°C in dry oxygen atmosphere in a closed platinum container. Secondly, the optical waveguides were fabricated by indiffusing 45-nm-thick and 2- to 5.5-μm-wide Ti-stripes. Subsequently, proton exchange was performed for different time intervals to produce layers with different thicknesses (0.18 to 0.22 μm). We used benzoic acid buffered with 1 mol% lithium benzoate as a proton source. The temperature of the proton exchange was 180°C.

The end faces of the chips prepared in this manner were polished to allow coupling of a laser beam into the waveguides. The polished end faces also served as mirrors to form low-finesse Fabry-Perot waveguide resonators which were used to measure the refractive index sensitivity of the waveguides. The resonators were optically excited with a semiconductor laser diode of 0.84 μm wavelength. The signal transmitted was detected with a photodiode and analyzed with an electronic unit based on the homodyne detection principle, to measure optical phase shifts in the resonators. We added dropwise index-matching fluids (refractive index n_{oil}) with differing indices on the surface of the waveguides and measured the phase shifts produced. The results obtained from chips with PE-layers of different thicknesses are summarized in Fig. 2. The sensitivity E of the TE mode, which is proportional to the slope of the curves, increases with increasing PE-layer thickness. The TM mode has a very low sensitivity. An exact comparison shows that E_{TE} is larger than E_{TM} by a factor of 10^3. The maximum value of E_{TE} obtained for $n_c = 1.48$ was about 0.0133.

3.2 *Propagation of SAWs on sensor chip*

The propagation of the SAWs on the surface of the sensor chip should be affected by the presence of the gas-sensitive layer and the proton-exchange layer. We have investigated this by means of a laser-diffraction probe.

First, we measured the additional propagation losses produced by the proton-exchange layer. The light beam of a He-Ne laser (0.633 μm) was reflected from the sample surface on which a SAW propagated. It was diffracted on the periodic perturbation produced by the SAW and we measured the intensity of the first diffraction maximum as a function of the distance of the laser spot from the interdigital transducer. This intensity is proportional to the power P_{ac} of the SAW at the spot of observation. In Fig. 3, an experimental curve (i) is shown for data measured on a sample proton-exchanged for 1.55 h. The propagation losses of the SAW are proportional to the slope of the curve and in this case, it is 0.6 dB/cm. In comparison, the propagation loss measured on samples without a proton exchange is 0.4 dB/cm.

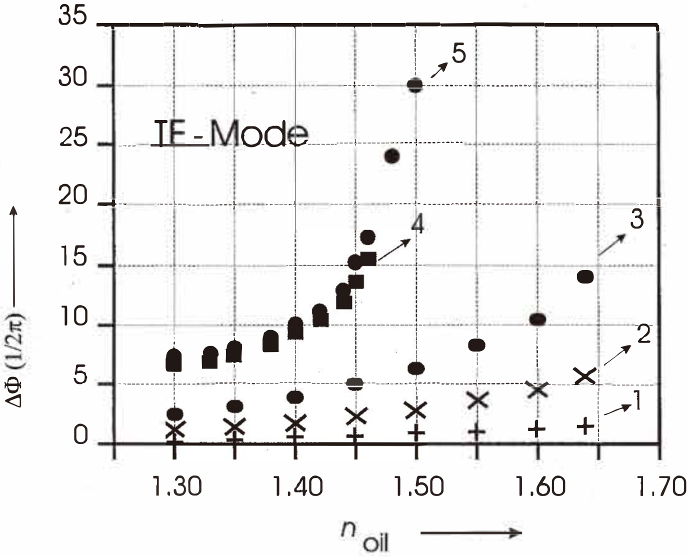

Fig. 2. Dependence of the phase shift $\Delta\Phi$ on n_{oil}. The exchange time increases from curve 1 to curve 5.

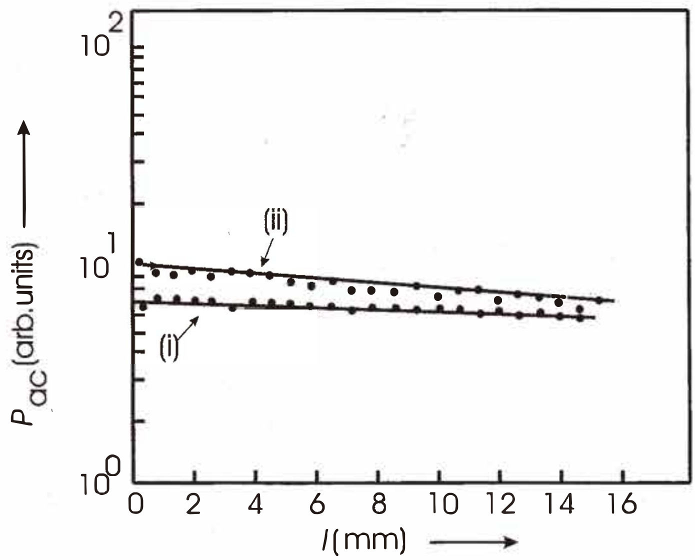

Fig. 3. SAW loss measurement plots.

In some additional experiments we spun a thin (150 – 200 nm) film of Pyralin (PD) (purchased from DuPont Company) onto the sample surface in order to measure the influence of a gas-sensitive layer on the SAW propagation. PD is a polyimid which changes its refractive index under the influence of water vapor. The coated samples were baked in air at 55°C for 30 min. On the samples coated in this manner we measured SAW propagation losses on the order of 1 dB/cm (see Fig. 3, curve (ii)).

3.3 *TE-TM mode conversion in the two-layer structure*

In order to prove the acoustooptical sensor concept we have carried out experiments on samples with thin proton-exchange layers. The experimental setup is shown in Fig. 4. (The interdigital transducer is tilted with respect to the Y-axis of the crystal to compensate for the SAW walk-off observed on X-cut $LiNbO_3$.) The light beam of a semiconductor laser diode passed through a polarizer and was coupled into the optical waveguide by means of a microscope objective lens. After the interaction, the light beam was coupled out of the waveguide with another microscope objective lens, passed through an aperture to block out the substrate light, and was detected with a photodiode.

The SAWs were excited with an RF generator whose output amplitude was modulated with low frequency. This allowed simultaneous observation of the converted and the nonconverted light intensity. Figure 5 shows the experimentally obtained dependence of the converted light intensity as a function of the SAW frequency. The central acoustic frequency was 349.39 MHz for this sample, which had been proton-exchanged for 1.71 h. We found that the central acoustic frequency of the TE-TM mode conversion depends on the PE time (see Table 1). This effect can be explained by the change of the waveguide birefringence produced by the PE film.

Coupling efficiencies up to 96% (interaction length 22 mm) have been achieved with RF powers of approximately 1–3 mW. The bandwidth of the mode conversion was only 137 kHz.

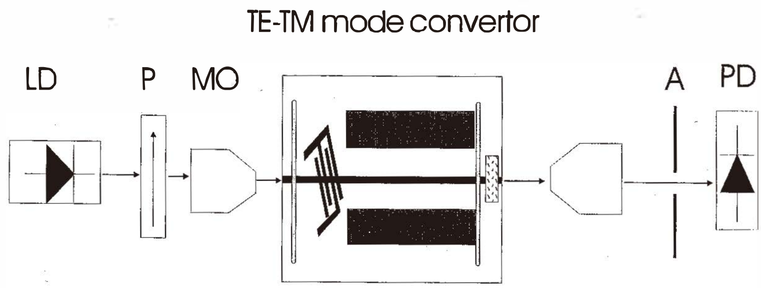

Fig. 4. Experimental setup used to investigate the TE-TM mode conversion: LD-laser diode; P-polarizer; MO-microscope objective lens; A-aperture; PH-photodiode.

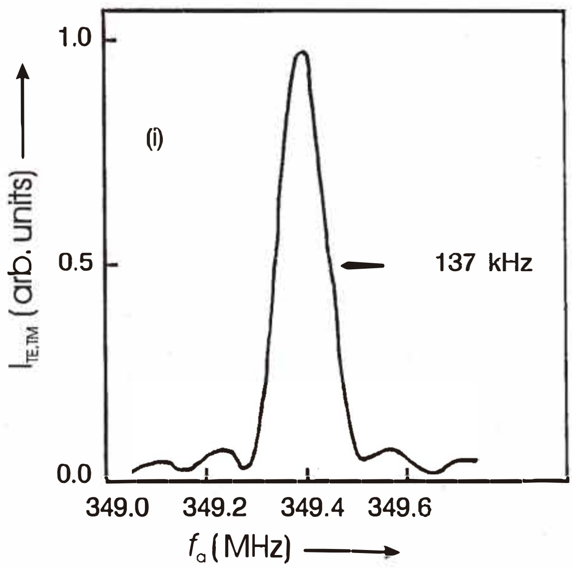

Fig. 5. Transmission characteristics of a TE-TM mode converter.

Table 1
Dependence of f_a on the PE time.

PE time (h)	1.14	1.41	1.55	1.64	1.71
f_a (MHz)	350.96	350.71	350.15	349.65	349.39

4. Discussion

In the previous sections, we demonstrated that the optical as well as the acoustic part of the proposed acoustooptical gas sensor can successfully perform their functions. Here we will discuss the expected sensitivity of the sensor. A change of the refractive index of the gas-sensitive film δn_c will lead, through the evanescent fields of the two fundamental modes, to changes of their effective indices δn_{eff}^{TE} and δn_{eff}^{TM}. From eq.(1) we have

$$\delta f_a / \delta n_c = (V_a / \lambda_0) |(\delta n_{eff}^{TE} / \delta n_c) - (\delta n_{eff}^{TM} / \delta n_c)|. \quad (2)$$

For our waveguiding structure we have shown that

$$\delta n_{eff}^{TM} / \delta n_c << \delta n_{eff}^{TE} / \delta n_c, \quad (3)$$

and from eq. (2), the refractive index sensitivity δn_c of the sensor can be written as

$$\delta n_c = (\lambda_0/V_a)(\delta f_a/E^{TE}), \quad (4)$$

where $E^{TE} = (\delta n_{eff}^{TE}/\delta n_c)$ is the refractive index sensitivity of the TE mode.

To obtain a high value of δn_c we need a waveguiding structure with large E^{TE} (in our case 0.0133) and we also must be able to detect frequency changes δf_a as small as possible as intensity changes of the converted mode. In this aspect, a small bandwidth of the TE-TM mode conversion is desirable since, in this case, we expect transmission characteristics with very steep edges. We were still able to observe fast SAW frequency changes of as small as 100 Hz as changes of the intensity of the converted mode. With $\lambda_0 = 0.84$ μm and $V_a = 3750$ m/s we can evaluate, using eq. (4), a very good value of $\delta n_c = 1.68 \times 10^{-6}$ for the refractive index sensitivity. A reference channel is necessary to compensate for wavelength fluctuations of the laser and temperature changes in the substrate in order to be able to detect not only fast but also slow changes and to obtain a temporarily stable system. The collinear interaction in the TE-TM mode converter allows simple implementation of a reference channel using the same waveguide and acoustic wave. In fact, we can cover only one part of the Ti waveguide with the PE layer, which serves as the measurement channel. The uncovered part shows no sensing effect and can serve as a reference channel. Since the mode conversion in the two parts takes place at different acoustic frequencies (see chapter 3.3) the signal analysis will be facilitated. In a similar manner, one can also construct a multielement sensor covering several portions of the measurement channel with differing gas-sensitive films.

5. Conclusions

In conclusion, we have experimentally demonstrated the feasibility of a novel acoustooptical gas sensor and we have shown that its optical and acoustic parts can achieve the expected performance. Work is underway to realize a sensor comprised of the two parts and operating in real gas atmosphere.

References

1 U. Hollenbach, C. Efstathion, N. Fabricius, H. Oeste and H. Götz: Tech. Abstracts of the International Congress on Optical Science and Engineering, Hamburg (1988) paper, p. 1014.

2 W. Konz, A. Brandenburg, R. Edelhäuser, W. Ott and H. Wölfelschneider: Optical Fiber Sensors, eds. H. Arditty, J. Daking and R. Kersten (Springer Verlag, Berlin, Tokyo, New York, 1989).

3 W. Lukosz and K. Tiefenthaler: Sensors and Actuators **15** (1988) 273.

4 V. Hinkov: German patent, DE 39 29 340 Al (1991).

5 V. Hinkov and E. Ise: J. Lightw. Technol. **LT-4** (1986) 444.

6 I. Hinkov and V. Hinkov: Proc. European Conference on Integrtaed Optics, ECIO '93 Neuchatel (1993), post-deadline paper.