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Improvement of an Evanescent Field IR-Absorption Sensor by utilizing a Photonic Taper Structure

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Abstract

Integrated IR-absorption sensors are attractive for various industrial applications, e.g., online condition monitoring of liquids such as lubrication oil. Therefore, we are working towards a fully integrated absorption sensor based on IR-absorption in the evanescent field of an integrated waveguide utilizing thermally generated and detected IR-radiation. To this end, we employ the absorption in the evanescent field of a single-mode waveguide with high sensitivity in the mid-infrared region, which is particularly interesting for a number of applications. Using grating couplers, the broadband radiation can be coupled in and out of the waveguide, where the grating couplers also facilitate spectral separation of prescribed wavelengths. This concept enables to integrate all components of an absorption sensor into a single sensor element. In our recent work, we investigated the grating couplers and the slab waveguide regarding the overall performance of the absorption sensor. In this contribution, we present numerical and experimental results showing that an appropriately designed tapered waveguide facilitates improved energy density, which in turn yields an improvement of the overall performance of the IR-absorption sensor element.

Keywords: IR-absorption; sensors; waveguide; evanescent field; taper

1. Introduction

In industry, a vast variety of processes can be optimized by means of online measurement of chemical properties of fluids in order to reduce costs of maintenance or increase productivity as well as production quality. Since the spectroscopic absorption measurement in the mid-IR-region is a powerful method to determine the chemical composition of fluids, we work on a fully integrated IR-absorption sensor for online measurements. Our IR-absorption sensor [1, 2] is based on IR-absorption in the evanescent field region of an integrated mono-mode waveguide. Due to the targeted mid-IR-region and the restrictions emerging from the aimed full integration of the IR-sensor, we utilize thermally generated and detected IR-radiation. The proposed sensor concept represents an alternative to commercial IR-spectrometers - which are in general expensive and bulky instruments – with reduced

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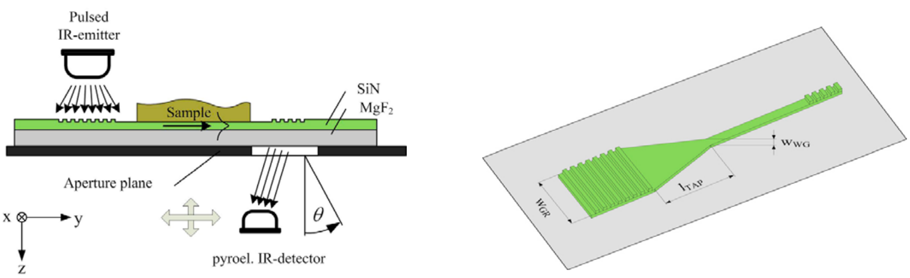

Fig. 1(a): Sketch of the measurement setup utilized to investigate the waveguide structure. The emitter and the detector could also be placed on the same side of the waveguide structure. However, in order to avoid scattered IR-radiation disturbing the IR-detector signal and to simplify the positioning, the emitter and the detector are positioned on the opposite side of the metallic aperture plate.
Fig. 1(b): Sketch of an integrated taper structure of the SiN-waveguide on a MgF2-substrate.

spectral resolution. In contrast to other research groups, which have been working on single elements of a spectrometric measurement setup, e.g., miniaturized spectrometers [3] or optical fibers as transducer, we aim at a fully integrated IR-absorption sensor.

2. System Concept

The fully integrated absorption sensor concept is sketched in Fig. 1 (a). In our previous work, we have successfully shown that a slab SiN/MgF_2-waveguide structure can be utilized, e.g., as oil deterioration sensor [1, 2]. For the coupling between the waveguide and the ambient, two grating couplers are employed, which couple broadband thermal IR-radiation into the waveguide and the attenuated IR-radiation towards a thermal IR-detector, respectively. To achieve a spectroscopic measurement, we utilize the dispersive feature of the grating coupler, which couples the IR-beams out of the waveguide at angles depending on the wavelength. Since we are concerned with less sensitive thermal IR-detectors than cryogenically cooled IR-detectors, we attempt to improve the sensitivity by means of exploiting the features of photonic structures.

A thermal IR-source simply represents a heated body emitting IR-radiation described by Planck's law. In case of a thermal emitter, the power emitted by the surface is proportional to the surface area and the temperature. Thus increasing the width (coupling area) of a grating coupler increases the energy coupled into the waveguide but not the energy density of the guided wave. A taper structure on the other hand increases the energy density but not the total guided energy. Thus, introducing a taper structure (Fig. 1(b)) enables the implementation of a wide grating coupler – yielding high energy in a wide waveguide – in conjunction with a small waveguide guiding the IR-radiation,

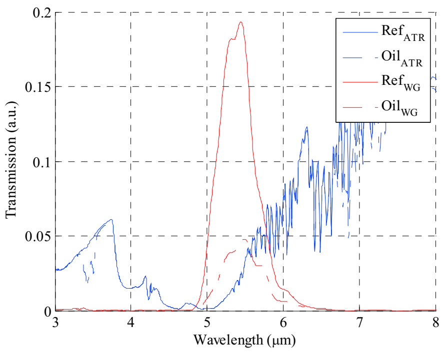

Fig. 2: Comparison of a commercial ATR-element (legend: ATR) with the slab waveguide structure (legend: WG). Solid lines represent reference measurements – required for normalization - and the dash-dotted lines the corresponding sample measurement.

which can be utilized in combination with a small IR-detector obeying less noise than larger detectors.

Even though the design of the taper structure could be discussed without considering the sensitivity of the (mono-mode) waveguide with respect to the absorption in the evanescent field, it is worth to compare the sensitivity of the proposed waveguide to a commercial ATR-element. In Fig. 2 measurements carried out by means of an FTIR-spectrometer are shown for the commercial ATR-element (3 reflections) and the slab waveguide structure, which features the equivalent sensitivity as the (tapered) waveguide with reduced (w_{WG}) at hand. In the targeted wavelength range (5 -6 µm) [1], the attenuation of the IR-radiation due to the absorption in the evanescent field only shows a significant change between the reference measurement and the oil measurement for our slab waveguide structure.

3. Numerical Results

In order to obtain a suitable taper structure, we have carried out numerical simulations using the beam propagation method (BPM, *RSoft*). For the simulation a rectangular input waveguide with the width of the grating coupler is modelled, which is followed by a linear taper structure and a rectangular waveguide representing the sensing element. The excitation of the 3D-model is given by a beam with Gaussian intensity profile, which is suitable since a thermal emitter (as use in the setup) usually is hotter in the centre.

The results of the 3D-simulation, indicating spurious scattering losses, are shown in Fig. 3. In Fig. 3 (a) the total guided power in the rectangular structure is shown for a taper with a length of l_{TAP} = 5mm and different widths of the input waveguide. The output waveguide –representing the sensing element - is kept constant at a width of 200µm. Considering Fig. 3 (a) it is apparent that the normalized guided power decreases rapidly for increased input width, which is caused by scattering losses. However, since an increased width of the input waveguide (width of the grating coupler) simultaneously increases the total power coupled into the waveguide, one has to consider the power density, as shown in Fig 3 (b) for a taper of l_{TAP} = 10mm. Furthermore, the power density is the parameter of interest since the power density determines the detector signal of the IR-detector measuring the IR-beam coupled out of the waveguide (see Fig (1) (a)). High power density in conjunction with a small detector area results in a high signal to noise ratio (SNR). The power density shown in Fig. 3 (b) reveals that an input coupler width of w_{WR} = 2.5mm (width of fabricated samples) would improve the overall performance by a factor of 6 for a detector with an area of 200x200µm.

4. Measurements

For the lab investigation of the micro-structured samples, we built up a measurement setup, as sketched in Fig. 1 (a). The positioning of the IR-emitter is done by a manual translation stage, whereas the IR-detector is position by a motorized translation stage. The thermal elements are driven and read out by a data acquisition box

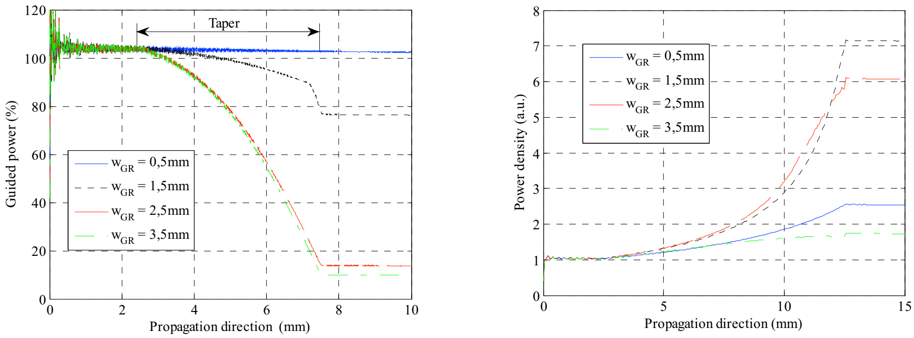

Fig. 3 (a): The guided power along the waveguide is normalized to the guide power at the launch-aperture. The length of the taper (t_{TAP} = 5mm, w_{WG} = 200µm) corresponds to the taper geometry utilized for the measurement shown in Fig. 4.
Fig. 3 (b): Regarding the overall performance of the sensor system, the power density is a suitable figure of merit. For a taper with l_{TAP} = 10mm and w_{WG} = 0.2mm the power density at the IR-detector can be improved by a factor of about 7, which could be even more for longer tapers.

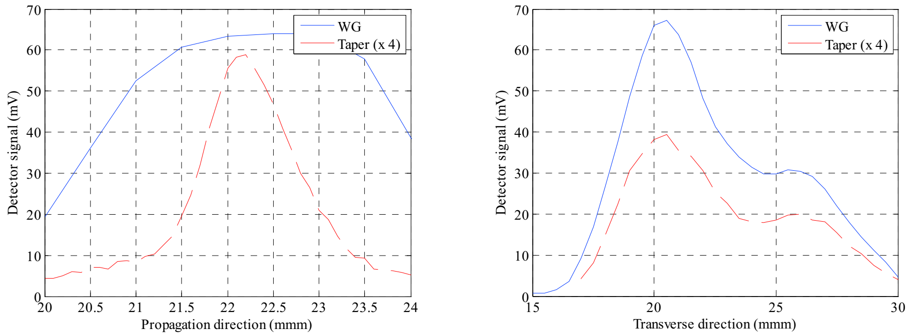

Fig. 4: Response of the thermopile detector obtained with a pulsed IR-emitter for a non-tapered (blue; w_{GR}=2.5mm, w_{WG} = 2.5mm) as well as a tapered waveguide (red; w_{GR} = 2.5mm, l_{TAP} = 5mm, w_{WG} = 0.2mm) at a gap coupler-detector z ≈ 5mm. Fig. 4 (a): The transverse (x) scan shows the confinement of the IR-beam due to the reduced waveguide thickness obtained with the taper structure; Fig 4(b): The y-scan (propagation direction) features a spectral measurement indicating a SiN intrinsic absorption peak at the notch at about y=24mm.

(U2542A, *Agilent*). The IR-detector, which is equipped with an elliptic reflector, is electrically pulsed at a frequency of 2Hz. The recorded IR-detector signal is digitally treated in order to achieve a measurement value for each detector position. To demonstrate the capabilities of the new design, measurements have been carried out using a thermopile detector (0.25x0.25mm). The resulting measurements are shown in Fig. 4 (a) and Fig. 4 (b) for a x-scan and a y-scan (see Fig. 1(a)), respectively.

The measurement signal obtained with the tapered structure is multiplied by a factor of 4 in order to achieve a suitable representation. According to the numerical simulations the investigated structures should reveal an improved detector signal of about 1.7 (deduced from Fig. 3(a)). Even though the actual signal obtained with the tapered structure is reduced by a factor of about 4, the effect of the taper can be seen at the reduced width (x-direction) of the signal shown in Fig. 4(a). Unfortunately, the current samples do not show the full potential of the proposed taper design, which is caused by defects in the fabricated SiN-waveguides. We are currently working on the fabrication of new taper structures with longer tapers and fewer impurities, which should result in smaller scattering losses to further improve the guided power density at the output grating coupler.

5. Conclusion

In this contribution, we present numerical as well as experimental results concerning an improved design of the waveguide structure of an integrated IR-absorption sensor system based on IR-absorption in the evanescent field of a waveguide. In order to improve the overall performance of the sensor system we introduced a taper structure to enhance the power density of the guided IR-radiation. For the design of the taper, numerical simulations have been carried out by means of the beam propagation method. Based on the results of the simulation, we fabricated micro-structured samples, which were investigated by a lumped measurement setup consisting of simple elements enabling the integration into a sealed sensor housing. The expected improvement due to the taper structure could not be fully verified by the experimental investigation. However, since there are a number of defects present in the current micro-structure samples, which can be visualized with an optical microscopy, we are convinced that the currently fabricated new set of samples will confirm the numerical results.

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