



Introduction of an angle interrogated, MEMS-based, optical waveguide grating system for label-free biosensing

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ABSTRACT

The presented label-free optical biosensor system relies on a MEMS micro-mirror to interrogate waveguide grating regions at a high repetition rate in the kHz range by scanning the angle of the incident coherent light. The angle-tunable MEMS mirror permits an extended scanning range and offers the flexibility to measure at various wavelengths and optical powers – an interesting feature for an enhanced surface-to-bulk sensitivity ratio and extended, multiplexed sensor arrays.

An excellent refractometric sensitivity with a limit of detection towards effective refractive index changes of $\Delta n_{\text{eff}} < 2 \times 10^{-7}$ and long-term stability ($< 10^{-6} \text{ min}^{-1}$) is reported, as well as the capability to perform affinity measurements for large ($> 150 \text{ kDa}$) and small ($< 250 \text{ Da}$) molecules. With fully-integrated optics, electronics and fluidics, the compact, low-power and affordable sensor unit is well-suited for in situ environmental monitoring or point-of-care diagnostics.

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1. Introduction

Label-free, dielectric waveguide based biosensors are well-known integrated-optical transducers to determine the presence, concentration and interaction of surface-bound (bio)molecular species [1]. Said sensors are commonly used in various fields such as the pharmaceutical industry [2], in biomedical and forensic applications, as well as food, feed [3] and environmental monitoring [4]. Miscellaneous interferometric [5] and resonant [6] transducer configurations have been presented. Waveguide grating couplers represent a subcategory of the latter group and different angular and spectral interrogation schemes for input and output grating couplers are known [7–11]. Here, a novel readout concept based on a scanning MEMS (micro-electro-mechanical system) mirror for the angular interrogation of input grating couplers at a high repetition rate is presented. The main advantages of the introduced configuration are high sensitivity and stability, large,

tunable dynamic range, flexibility regarding the interrogating light source, compact size, low weight and comparatively low cost.

After a brief introduction of the theoretical fundamentals of waveguide grating sensors, the interrogation scheme will be described and the properties of the presented configuration will be assessed in greater detail. The practical realization of the sensor device and the conducted experimental characterization will be detailed, which will then be summarized and concluded in the subsequent paragraphs.

Common planar optical waveguides exhibit a three-layer structure with a high refractive index film F between a supporting substrate S and a cover medium C . The waveguide film acts as a conduit for the propagating light by means of total internal reflection. Light can be coupled in and out of the waveguide via diffractive gratings, formed by a periodic corrugation of the waveguide film [12,13]. The guided mode is excited with maximal efficiency if light impinges the grating at the coupling angle θ_c when the coupling condition

$$n_a \cdot \sin(\theta_c) = n_{\text{eff}} - \frac{m_g \lambda}{\Lambda} \quad (1)$$

is fulfilled, where Λ denotes the grating period, λ the vacuum wavelength of the propagating light, m_g the grating diffraction order,

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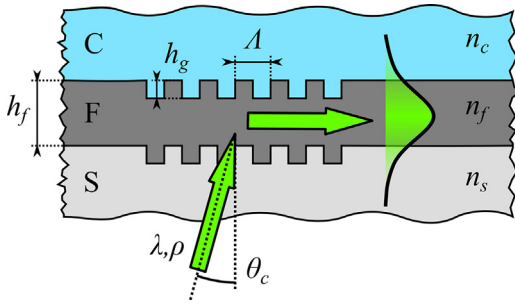


Fig. 1. Schematic representation of a common waveguide grating coupler, consisting of a substrate S , waveguide film F with a layer thickness of h_f and cover layer C with refractive indices n_s , n_f and n_c , respectively. A corrugated grating with a depth of h_g and period Λ acts as a coupling element for the incident coherent light with wavelength λ and polarization ρ impinging at the coupling angle θ_c , thereby creating a guided mode.

n_a the refractive index of the ambient medium and n_{eff} the waveguide's effective refractive index. The effective refractive index n_{eff} depends on various parameters

$$n_{eff} = f(n_c, n_f, n_s, h_f, \lambda, \rho) \quad (2)$$

such as the refractive index and thickness of the waveguide film n_f and h_f , the wavelength λ and polarization ρ of the incident light and the substrate and cover refractive indices n_s and n_c . Any changes in the latter will affect n_{eff} and via Eq. (1) alter the angle θ_c at which light will be coupled into or out of the waveguide [13]. The grating therefore not only acts as a light coupling element but also as a sensitive, refractometric transducer. Since, in general, (bio)molecules adsorbing to the sensor surface exhibit a different refractive index than the displaced cover medium, waveguide grating couplers can be used as highly sensitive, label-free optical sensors. The described structure and relevant parameters of a common waveguide grating coupler are illustrated in Fig. 1.

2. Materials and methods

The presented system relies on a waveguide grating coupler sensor chip as the optical transducer, produced at Optics Balzers AG (Balzers, Liechtenstein), consisting of a borosilicate glass substrate (D263T by Schott, Mainz, Germany, $n_s = 1.53$, all refractive indices expressed at $\lambda = 532$ nm) and a tantalum-pentoxide Ta_2O_5 waveguide ($n_f = 2.15$). The sensor chip with an outer dimension of $17.75 \times 17.75 \times 0.7$ mm³ possesses 24 corrugated grating regions with a grating period Λ of 360 ± 0.1 nm and a grating depth h_g of 12 ± 2 nm, as depicted in Fig. 2 with a schematic top (a) and side (b) view.

The grating was produced by interference lithography and directly dry-etched into the substrate by using reactive ion etching

(RIE) in a CHF_3/Ar plasma. The developed photoresist was removed by O_2 plasma stripping, followed by the magnetron sputtered deposition of the Ta_2O_5 waveguide, as illustrated in Fig. 3 [14,15]. The sensitive grating areas are divided in two adjacent regions, each with a lateral extent of 0.9×0.9 mm², whereas they only differ in the waveguide film thickness h_f . The thinner grating region with a film thickness of $h_{f1} = 82 \pm 2$ nm serves as an in-coupling grating and is designed for maximal sensitivity towards refractive index changes [15–18]. The second grating with a film thickness of $h_{f2} = 232 \pm 2$ nm acts as an out-coupling element for the propagating light. This feature was produced by the deposition of a sacrificial photoresist layer in the regions where a thinner waveguide thickness was desired, followed by sputtering a second layer of Ta_2O_5 and a subsequent lift-off process to uncover the thinner waveguide regions. By having two different film thicknesses for the two gratings, the out-coupled beam emerges from the chip at a different angle than the otherwise interfering reflection of the in-coupled beam, which could also be solved by having grating regions with different periods [19].

In the here introduced angle interrogated optical sensor (ARGOS) system, the chip is illuminated by a collimated beam with a diameter of 15 mm of a temperature and current stabilized diode pumped solid state laser source at an emission wavelength of 532 nm (DJ532-10, Thorlabs, Newton, NJ, USA). Various lasers with different wavelengths ($\lambda = 532, 633$ nm, 780 nm, 850 nm) and optical powers ($P_{em} = 0.5$ –20 mW) have been implemented and tested as described by our previous work [15]. The DJ532-10 was chosen due to its favourable combination of spectral stability, narrow linewidth, short wavelength, optical power, compact size and reasonable cost. Impinging at the coupling angle of the in-coupling grating θ_c , the incident coherent light is exciting the fundamental transverse magnetic mode (TM_0) of the waveguide, which is subsequently coupled out of the latter through the second grating onto a light sensitive photodiode (SFH250V, Avago Technologies, San Jose, CA, USA). The interrogation principle is illustrated in Fig. 4.

For sensing purposes, the in-coupling angle is monitored by constantly scanning the angle of incidence of the impinging light, which is accomplished via an oscillating, electrostatically driven MEMS mirror (2.5×3 mm², BA0050, Opus Microsystems, Taiwan) and a 4f optical configuration to guarantee beam collimation and expansion to a diameter of 15 mm to cover all waveguide grating regions. This time-dependent detuning of the incident angle $\theta_{inc}(t)$

$$\theta_{inc} = \frac{\theta_{scan}}{2} \sin(2\pi ft) + \theta_0 \quad (3)$$

where θ_{scan} equals the scan range or twice the mirror's oscillation amplitude (typically < 1 degree), which can be tuned by the mirror driving controls, and θ_0 the initial angle of incidence (which is set to θ_c at the beginning of a measurement), results in a time-dependent, varying light intensity profile $I(t)$ (resonance peak)

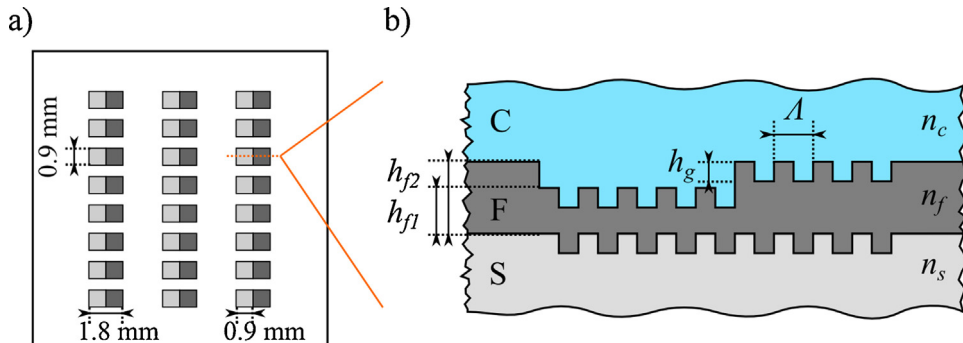


Fig. 2. Schematic top (a) and side view (b) of the waveguide grating sensor chip, with a thinner (h_{f1}) in-coupling and thicker (h_{f2}) out-coupling grating region (not to scale).

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