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Design method for a distributed Bragg resonator based evanescent field sensor

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ABSTRACT

This paper presents an analytic design method for a distributed Bragg resonator based evanescent field sensor. Such sensors can, for example, be used to measure changing refractive indices of the cover medium of a waveguide, as well as molecule adsorption at the sensor surface. For given starting conditions, the presented design method allows the analytical calculation of optimized sensor parameters for quantitative simulation and fabrication. The design process is based on the Fabry–Pérot resonator and analytical solutions of coupled mode theory.

1. Introduction

Evanescent field sensors are commonly used to measure the refractive index at an optical interface or to detect molecular adsorption at a surface [1–3]. These sensors are based e.g. on fibers or integrated planar waveguides which consist of a high refractive index core medium enclosed by a low refractive index cladding medium. When light is coupled into the waveguide core, an electromagnetic mode is formed that propagates in the direction of the waveguide. The electromagnetic field of the mode is not limited to the core. It has a tail (evanescent field) which penetrates into the cladding medium. Its amplitude decays exponentially with distance from the core interface into the cladding. This field can be used to probe the properties of the cladding medium. The properties of the cladding are described by the cladding or cover refractive index n_c. If n_c changes, the evanescent field is affected and the system is detuned. With an appropriate measurement setup, this detuning can be measured.

Waveguide sensor elements of this kind have been demonstrated in various configurations like optical ring resonators [4], fiber Bragg gratings [5], fiber based distributed Bragg resonators [5], waveguide Bragg gratings [6], waveguide interferometers [7], and microspheres [8]. All of these elements show a characteristic spectral response that can be used to analyze the cover medium.

1.1. Sensor element

In this paper, a distributed Bragg resonator (DBR) sensor based on planar waveguides is analyzed. Similarly to the single mode DBR biosensor presented by Kehl et al. [9], the waveguide sensor is composed of two Bragg gratings placed in a distance d from each other. In Fig. 1a the sensor principle is illustrated. The sensor consists of a glass substrate with a refractive index n_s. On top of the glass substrate a thin film with thickness h and refractive index n_f is deposited, which acts as guiding layer. The Bragg gratings, each with a grating period Λ, are set into the waveguide layer. Bragg gratings can e.g. be fabricated by lithography with subsequent dry etching. This technology allows the fabrication of (binary) relief gratings with a depth of h_g. On top of the guiding layer is the cover medium. The evanescent field sensor is used to probe the refractive index of the latter medium.

If light is coupled into the sensor, it is spectrally filtered by the DBR structure. In Fig. 1b the transmission spectrum of such a structure is illustrated. Depending on the refractive index of the cover, the spectral filter characteristics of the sensor shift to longer or shorter wavelengths. These shifts can be detected by two different methods, as described in the following.

1.2. Measurement configurations

In one configuration, the sensor is illuminated by a broadband light source and the transmission characteristics are recorded by a

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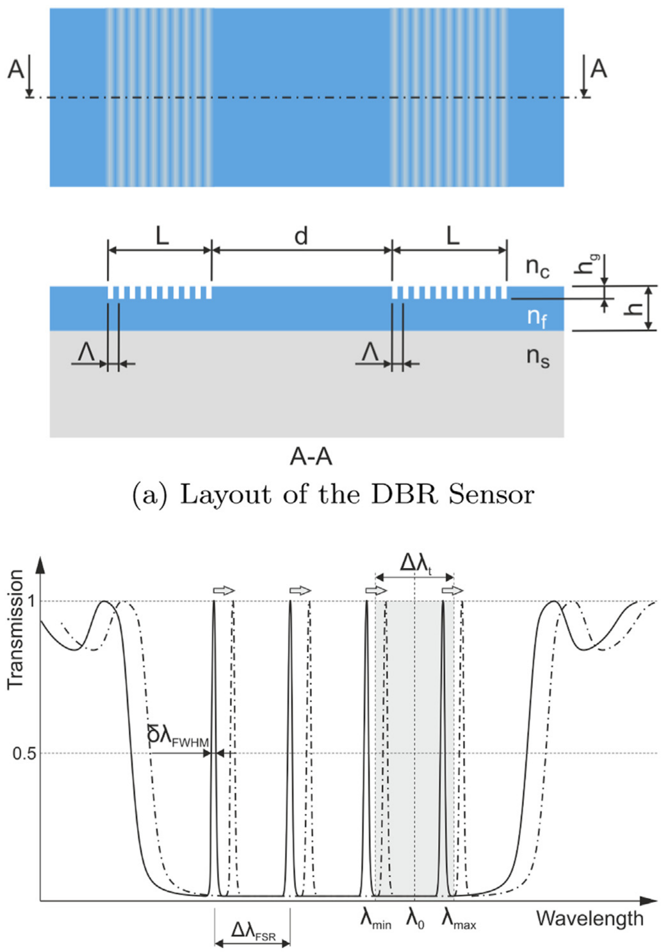

(a) Layout of the DBR Sensor

(b) Transmission Spectrum of the DBR Sensor

Fig. 1. (a) Shows the layout of a distributed Bragg reflector (DBR) sensor. L is the length of the Bragg grating, d is the length of the Fabry–Pérot resonator, h is the thickness of the guiding layer, h_g is the depth of the grating, and Λ is the grating period of the Bragg grating. (b) Illustrates the transmission spectrum of a DBR structure, where $\Delta\lambda_{FSR}$ is the free spectral range (FSR) between two resonances, $\delta\lambda_{FWHM}$ the full width at half maximum of the resonances, λ_0 the design wavelength, and $\Delta\lambda_t = \lambda_{max} - \lambda_{min}$ the tuning range of the light source.

high-resolution optical spectrum analyzer (OSA). The spectral resolution in this configuration is limited by the resolution of the OSA. The major drawback of this set-up is the high acquisition cost of both the spectrum analyzer and the broadband source.

The second measurement configuration is set up by using a narrow-band light source with a tunable central wavelength, e.g. a vertical-cavity surface-emitting laser (VCSEL), and a simple photodiode for the transmission measurement. While tuning the central wavelength, the transmitted power is measured as a function of wavelength. The resolution of this configuration is limited by the tuning resolution and the spectral full width at half maximum (FWHM) of the source. The main advantage of this configuration is the reduced system cost that allows the realization of a fairly low-priced reader system. The main disadvantage is the limited spectral tuning range of narrow-band light sources like VCSELs or the high costs for wide range tuneable laser sources.

Bragg gratings are sensitive to temperature changes and have therefore also been used as sensing elements for temperature sensors [11]. For biosensor applications, signal drifts due to temperature have to be suppressed by adequate temperature control e.g. with a thermo electric cooler (TEC). By using a TEC the temperature can be controlled in a range of about ± 0.05 K. Additionally smaller drifts can be compensated by using a reference Bragg grating waveguide resonator with defined cover material [10]. Several authors investigated the influence of temperature on the performance of integrated waveguide sensors [12–15].

1.3. VCSEL based distributed Bragg resonator biosensor

Evanescent field sensors based on distributed Bragg resonators can be used as biosensors. Biosensors are systems consisting of a biological detection system (bioreceptor) and a sensor element (transducer) [16]. The transducer of the presented sensor is the DBR waveguide structure. Bioreceptors are immobilized on the waveguide surface. They are selective molecules that can adsorb specific target molecules. Typically, the sensors use (a) antibody/antigen interactions, (b) nucleic acid interactions, (c) enzymatic interactions, or (d) cellular interactions for the detection of biomolecules [16].

To detect the amount of adsorbed biomolecules at the sensor surface, the evanescent field of the resonator waveguide mode is designed to penetrate the adsorption layer. Due to the interaction with the biomolecules, the propagation constant and the effective refractive index of the mode are altered compared to the situation before adsorption. As a result, the spectral filter response of the sensor is shifted.

As mentioned in the introduction, a DBR based evanescent field sensor-system can either be built using a broadband source or a narrow-band laser source. A biosensor concept based on a narrow-band source reader system was introduced by Kehl et al. [9].

In the present paper, an analytical method to design an optimized sensor for such a narrow-band system is presented. The sensor parameters are designed to achieve a system with maximum sensitivity for a given material system or for given refractive indices n_s and n_f.

2. Methods

In the following section, the theory to express the spectral characteristics of a DBR sensor is outlined. The DBR sensor can be divided into three main functional elements. The first element is the slab waveguide, which guides the light through the system. The second element is the Bragg grating forming a waveguide reflector. The third element is the Fabry–Pérot resonator consisting of two Bragg grating reflectors. These functional elements are described in more detail below.

The goal of the analytical calculation is to determine the transmission spectrum of the DBR structure. The spectral response of the sensor can be calculated by combining the Fabry–Pérot resonator theory with analytical solutions for the Bragg gratings. This analytical approach leads to a system design method that can be used to calculate appropriate sensor parameters for the development of sensitive transducer elements. The resulting parameter sets are valuable starting points for further numerical calculations with more advanced simulation tools.

2.1. Slab waveguide

A slab waveguide supports a discrete number of modes. The propagation constant β of the modes for transversal electric (TE) and transversal magnetic (TM) polarization can be calculated by the characteristic Eq. (1) which is based on Maxwell's equations [17,19–21].