

Demodulation of Tilted Fiber Bragg Grating Refractive Index Sensors with KLT

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Abstract—Tilted fiber Bragg grating (TFBG) sensors have been employed in fiber-optic refractive index sensors and biosensors, thanks to their inherent sensitivity. However, low-cost coarse-sampling spectrometers are not able to discriminate TFBG cladding modes, which are used for refractive index sensing. In this work, we demonstrate that it is possible to detect small refractive index variations by analyzing the TFBG spectrum with the Karhunen-Loeve Transform (KLT), even if the cladding modes are not visible in the optical spectrum. The proposed work is a key asset towards the development of low-cost fast-response fiber-optic biosensors, as it shifts the complexity from the optical sensing structure to the signal-processing algorithm used for demodulation.

Keywords—Optical fiber sensors; Fiber Bragg Grating (FBG); tilted FBG (TFBG); refractive index sensor; optical biosensor

I. INTRODUCTION

Optical fiber refractive index sensors are a modern approach to chemical and biological detection. Several approaches have been documented, based on several optical structures that are inherently sensitive to the variations of the refractive index on the boundary of an optical fiber. Examples of modern fiber-optic refractive index sensors are: in-fiber surface plasmon resonance [1] [2], based on a resonance condition of an optical fiber coated with a thin metallic layer; tapered micro-fibers based on evanescent field [3]; single-multi-single mode fiber structures [4] based on modal interference; lab-on-fiber fabricated on the fiber tip [5]; tilted fiber Bragg grating (TFBG) [6] [7] [8] [9], based on a grating fabricated within a fiber core at a tilt angle θ that excites a number of cladding modes.

In particular, TFBG-based sensors have attracted a strong research effort within the latest years, thanks to their capability to support refractive index sensing intrinsic to the grating structure (as opposite to many alternatives, which require the fabrication of micro-structures) with a good sensitivity, a small active region, and maintaining the original mechanical strength of the fiber [9]. Functionalization of TFBG sensors, in particular for cancer biorecognition, have been recently reported [7] [8].

The main challenge towards the consolidation of refractive index sensors based on TFBG, and their functionalization, is

related to the TFBG interrogation. The TFBG sensing principle is based on the analysis of the narrowband cladding modes [9]. Cladding modes are much narrower than the main grating mode; for this reason, the works reported in [6] [7] [8] [9] make use of an optical spectrum analyzer (OSA), or an optical vector analyzer (OVA) as a detector. These instruments however are extremely bulky, not portable, and their cost is not compatible with low-cost medical devices. In addition, to enhance the amplitude of cladding modes, several techniques are introduced to enhance the amplitude of cladding modes [6] [9]. Since the cladding modes are evanescent, the cladding modes appear in the TFBG transmission spectrum; only a small fraction of the modes (~4% Fresnel reflection at the fiber tip) is reflected; however in applicative scenarios the interrogation of a grating in transmission is impractical [9].

Overall, there is a lack of a suitable interrogation technique for a TFBG, that is able to convert small variations of the refractive index into a robust and sensitive output, even if the TFBG is interrogated with a low-cost, coarse-sampling interrogator and in reflection.

In this work, we introduce a new methodology based on the Karhunen-Loeve Transform (KLT). The KLT, as in Maccone's implementation [10] [11], was firstly introduced in the field of fiber-optic sensors for the interrogation of standard Bragg grating sensors [12] and Fabry-Perot sensors [13]. In this framework, the KLT can be used to detect small variation of the cladding modes in the TFBG optical reflection spectrum, almost invisible when detected with a coarsely sampling spectrometer. This work paves the road towards refractive index sensors and biosensors based on TFBG and interrogated with a low-cost hardware.

II. MEASUREMENT SETUP

The experimental setup is based on a white-light interrogation system similar to [12]. A fiber-coupled broadband superluminescent LED (Exalos EXS model, 1520-1500 nm), current-driven by a control board, is used as light source; light is routed to the TFBG sensor and backwards with a 50/50 coupler. The detector is a high-speed USB spectrometer (Ibsen I-MON-512-USB, 1520-1600 nm); the exposure time of the detector is set to 0.2 ms. The wavelength resolution of the spectrometer is 156 pm, which is much smaller than TFBG cladding modes.

The sensor is a commercial TFBG (Technica S.A.) fabricated on a standard single-mode fiber, with tilt angle $\theta = 5^\circ$ and 80% reflectivity. The protective buffer of the fiber has been removed prior to operation.

III. TFBG DEMODULATION

The TFBG demodulation is performed using the KLT [12] as in Maccone's implementation [10]. Calling $R(\lambda) = [R_1, R_2, \dots, R_N]$, the TFBG reflection spectrum as detected by the spectrometer on the wavelengths $\lambda_1, \lambda_2, \dots, \lambda_N$ (where $N = 510$, equal to the spectrometer pixels); at a first step, we compute the Fast Fourier Transform (FFT) of the R :

$$\underline{G} = [G_1, \dots, G_N] = \text{FFT}\{R_1, \dots, R_N\}. \quad (1)$$

Subsequently we expand $\underline{G}$ into its Toeplitz matrix M :

$$\underline{\underline{M}} = \begin{bmatrix} G_1 & G_2 & G_3 & \cdots & G_N \\ G_2 & G_1 & G_2 & \cdots & G_{N-1} \\ G_3 & G_2 & G_1 & \ddots & \vdots \\ \vdots & \vdots & \ddots & \ddots & G_2 \\ G_N & G_{N-1} & \cdots & G_2 & G_1 \end{bmatrix}. \quad (2)$$

Then, we can apply the KLT, by decomposing M into an orthonormal basis. As suggested in [10] [11], we can apply the singular value decomposition to decompose M :

$$\underline{\underline{M}} = \underline{\underline{V}} \times \underline{\underline{D}} \times \underline{\underline{V}}^{-1} \quad (3)$$

where: $\underline{\underline{D}}$ is a diagonal matrix that contains all the N eigenvalues $\xi_1, \xi_2, \dots, \xi_N$ on its main diagonal, arranged in ascending order such that $\xi_1 < \xi_2 < \dots < \xi_N$; $\underline{\underline{V}}$ is a matrix that contains, on each i -th column, the eigenvector corresponding to the i -th eigenvalue. Since M is a Toeplitz matrix, its eigenvalues are purely real.

As in Maccone's findings [11], the KLT is a good technique to isolate the noise contributions from the main signal. In particular, the high-rank eigenvalues are less influenced by noise while low-rank eigenvalue confine most of the noise energy. Thus, we can select the highest rank eigenvalue ξ_N as a main metric, and we can report the variations of ξ_N recorded when the TFBG is exposed to refractive index change.

IV. EXPERIMENTS

Experiments have been performed by exposing immersing the TFBG, in a solution of water (refractive index 1.330) and sucrose (refractive index 1.513), both held at room temperature. A pipette has been prepared to add drops of water and sucrose in the surrounding of the stripped TFBG.

At first, Fig. 1 shows the TFBG reflection spectra, as detected on the spectrometer, whereas the wavelength is sampled over 510 pixels and the amplitude is quantized over 16 bits (spectral amplitude ranging within 0 – 65532). The coarse sampling of the spectrometer, as well as the fact that the TFBG is interrogated in reflection and not in transmission-

reflection as in [9], results in a spectrum in which the cladding modes do not appear, at the wavelengths smaller than the Bragg wavelength (1553.8 nm).

Fig. 2 shows the advantage of using a KLT as a detection algorithm, over amplitude-tracking approaches [6] [7]. The eigenvalue string $\xi_1, \xi_2, \dots, \xi_N$ is substantially constant with the refractive index; but as in [12] for a standard Bragg grating, the highest rank eigenvalue ξ_N has a clearer dependence on the refractive index, and tends to decrease when the refractive index n increases.

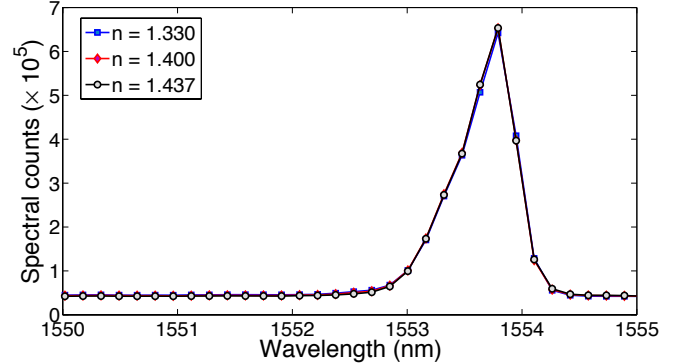


Fig. 1. TFBG spectrum for different refractive indices n , as detected on the coarsely sampling spectrometer.

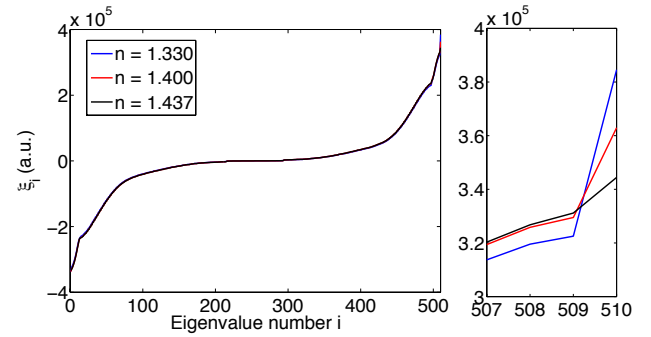


Fig. 2. Eigenvalue string $\xi_1, \xi_2, \dots, \xi_N$ obtained for different KLT analysis of the TFBG under different refractive index conditions. On the right chart, only the 3 highest rank eigenvalues are reported.

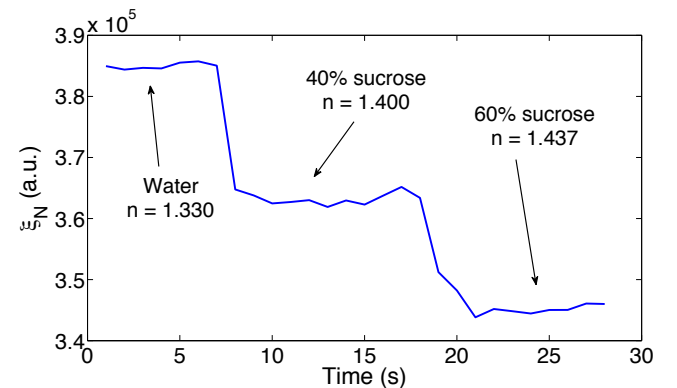


Fig. 3. Highest rank eigenvalue ξ_N obtained when the refractive index is changed from 1.330 to 1.437 by varying sucrose level.

A time-domain measurement is shown in Fig. 3. In two subsequent steps, the refractive index of the TFBG is changed

by increasing the amount of sucrose, from 1.330 to 1.437. The TFBG responds instantaneously to the refractive index variation: a 6% decrease of ξ_N is obtained when the sucrose concentration rises from 0% to 40%, and a further reduction of 4.5% is observed when the sucrose concentration rises to 60%.

The response of the KLT algorithm is high-speed, as the computation time for a 510-size KLT is 142 ms (algorithm implemented in Matlab, on 2.6 GHz Intel Core i5 processor) while the spectrometer sampling frequency is 1 kHz. This implementation is much faster than OSA-based systems, whereas the narrow resolution bandwidth results in spectral measurement of several minutes duration.

V. CONCLUSIONS

TFBGs are a modern approach to chemical sensing and biosensing; but their implementation is hampered by the need of a bulky and expensive instrument for spectral detection, such as an OSA or OVA, and the need to increase the coupling and reflectivity of cladding modes to enhance their recognition.

In this work, we demonstrated the possibility to use a KLT algorithm, typically used to detect weak signal changes covered by intense noise, to detect the spectrum of the TFBG when exposed to refractive index changes. The TFBG is simply interrogated by a low-cost white light setup, and no additional devices are used to enhance the TFBG detection. The KLT output ξ_N changes when a small refractive index change is detected, even if the cladding modes are practically invisible in the spectrum. The KLT method, that is also finding increasing number of applications in fiber-optic sensors demodulation [12-15] and is based on a derivation of principal components analysis [16], appears as a key asset for the demodulation of the TFBG cladding modes at the boundary of the signal-to-noise ratio limits.

Future work will address a full characterization of the calibration function, and optimization of tilt angle of the TFBG, as well as the integration of KLT with signal denoising techniques based on wavelet.

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