Interrogation of coarsely sampled tilted fiber Bragg grating (TFBG) sensors with KLT

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Abstract: Tilted fiber Bragg gratings (TFBG) can be used as refractive index sensors, as their cladding modes, amplitude, and wavelength changes with the outer refractive index. However, as cladding modes have bandwidths that are narrower than the resolution of most infrared spectrometers, they can be detected only with an optical spectrum or vector analyzers. In this work, we demonstrate that through ad hoc implementation, the Karhunen-Loeve transform (KLT) algorithm can be used to demodulate a TFBG even using a coarse interrogator (156 pm), whereas cladding modes cannot be discriminated in the TFBG spectrum. We observe that the KLT output results are a reliable indicator to detect refractive index changes up to 1.85 \cdot 10^{-3} refractive index units (RIU), down to a resolution of \sim 10^{-5} RIU. The KLT can be used to demodulate TFBG sensors and biosensors operating in small refractive index change conditions.

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1. Introduction

Optical fiber refractive index sensors represent an emerging technology for the analysis of the constitutive parameters of fluids and gasses. Several devices and optical structures have been proposed for refractive index sensors. A first class of sensors is based on optical gratings and includes tilted fiber Bragg grating (TFBG) [1], etched FBGs (EFBG) [2], long-period grating (LPG) [3] among others; grating-based devices encode the refractive index dependency on the grating spectrum. A second class of devices makes use of resonant cavities or microstructures, whose spectrum is also dependent upon the refractive index external to the fibers; surface plasmon resonance (SPR) [4], lab-on-fiber (LoF) [5], single-multi-single mode (SMS) structures [6], and tapered micro-fibers [7] are some of the most popular refractive index sensing devices. Refractive index detection is at the base of fiber-optic biosensors [8, 9]. In order to use optical fibers for detection of analyte of interest, ligands need to be attached on its surface. One of the widely used methods used is silanization which is covalent in nature and therefore allows long-term detection of analytes [10]. Usually, due to the requirement to detect low concentrations, it is necessary to implement a demodulation technique that is capable of discriminating low variations of refractive index in real time.

TFBGs represent an important technology for refractive index sensors [11–17], thanks to their advantageous properties compared to other fiber-optic system. At first, TFBGs can be fabricated with a single process through phase mask inscription, similarly to standard FBGs, without needing the fabrication of microstructures (such as SMS) or the deposition of thin films (such as SPR or LoF). TFBGs have a relatively low spectral occupancy, particularly for low tilt angles [14], which makes them suitable for wavelength division multiplexing (WDM), with bandwidth occupancy orders of magnitudes inferior to interferometers, LPG and SPR. Furthermore, the TFBG sensor maintains the mechanical robustness of the optical fiber (without its protective jacket), while EFBG and fiber tapers strongly shrink the fiber diameter, dramatically reducing its mechanical stability.

Several research works have been proposed using TFBGs as a sensing element for refractive index sensing [18, 19]. The TFBG spectrum results in a combination of the main (Bragg) reflection mode, the ghost mode, and cladding modes; the refractive index sensitivity is encoded in some of the cladding modes, which slightly change in amplitude and wavelength when the refractive index external to the TFBG region is changed [14, 20]. In several recent works, TFBGs have been used in combination with SPR sensors [19, 21, 22]; the TFBG spectrum is modulated by the SPR spectral envelope, resulting in an amplification of the cladding modes visibility. Biosensors based on TFBGs have been implemented for the detection of cancer biomarkers [23], and are leaning towards in vivo application [24].

Despite the favorable premises, there are several limitations in the TFBG demodulation that are hampering their operation in practical contexts. The main one is that cladding modes, in which the refractive index sensitivity is encoded, appear as an extremely narrow spectral lines, having bandwidth significantly narrower than the FWHM, where FWHM is the full-width half-maximum bandwidth of the Bragg mode. In a typical TFBG, cladding modes have a bandwidth that is narrower than the (pixel-based) wavelength resolution, which makes them substantially invisible on a standard infrared spectrometer or FBG analyzer with coarse spectral resolution, which are low-cost devices for FBG interrogation. Thus, it is necessary to use an optical spectrum analyzer (OSA) [12, 14] or optical vector analyzer (OVA) [23, 24] for the interrogation of a TFBG, which achieve a resolution bandwidth of 1-10 pm. OSA and OVA instruments however have a very slow response as it can take several minutes to sample the TFBG spectrum with a narrow wavelength resolution (compared to 1 kHz standard sampling rate of standard infrared spectrometer or FBG analyzer, they are not portable, and their cost is orders of magnitude higher. A partial solution consists of scanning only the small portion of spectrum covered by one cladding mode [12], but this is anyway not consistent with WDM. Another important limitation is the fact that the TFBG is inherently a transmission device; for this reason, a popular implementation is to use a metallic reflector at
the fiber end [23-24], in order to collect the so-called transmission-reflection spectrum [23]. In absence of an external reflector, cladding modes have a reduced fringe visibility, due to the ~4% Fresnel reflection at the fiber end. Furthermore, with low-tilted TFBGs the spectrum has a compact shape, more suitable for WDM where multiple fiber optic sensors operating at different spectral slices are inscribed on the same fiber.

Traditional TFBG demodulation techniques, based on the amplitude or wavelength tracking of cladding modes [1, 25] cannot be applied when the resolution of the interrogator is coarse, as cladding modes are not visible in the TFBG spectrum. Overall, methods proposed for TFBG demodulation are mainly based on the amplitude tracking of a cladding mode [11, 23, 24] or by tracking the wavelength shift of spectral features [25]. In this work, we propose a new demodulation technique that allows tracking the spectral changes of the TFBG due to refractive index variations, using a coarse interrogator (156 pm wavelength resolution), which can operate even if cladding modes are not visible in the optical spectrum and even if the TFBG sensor operates in reflection. The core of the demodulation method is the KLT (Karhunen-Loeve Transform). The KLT has been recently applied in [26, 27] to the interrogation of uniform FBG using a coarse spectrometer, and in [28] to the interrogation of FBG arrays in a microwave photonics setup. In these implementations, the KLT was applied as in Maccone’s format [29, 30], particularly suitable to detect variations of small signals into noise. We will demonstrate that, despite the invisibility of TFBG cladding modes on the coarse interrogator, a suitable modification of the KLT is still capable of discriminating relatively small variations of refractive index (~10^{-5} RIU).

2. Setup and TFBG demodulation

The TFBG interrogation setup and process of demodulation is illustrated in Fig. 1, and resembles the standard low-cost white-light setup used in FBG sensing [26]. The schematic is detailed in Fig. 1(a). The source is a superluminescent LED (SLED, Exalos EXS210059-01, 20 mW emission power, 60 nm bandwidth 1530-1590 nm) controlled by a driver board (Exalos, EBD5020, 250 mA). The detector is an infrared CCD (charged-couple device) spectrometer (SM, Ibsen I-MON-512-USB, 1520-1600 nm) having 156 pm wavelength resolution over 80 nm bandwidth (correspondent to 512 pixel quantization), and an amplitude quantization of 16 bits (corresponding to spectral amplitude level 0 - 65535). The exposure time on the spectrometer is set to 10 μs, which corresponds to a dark level of ~4000. A 3-dB coupler is used to route light from the source to the sensor, and collect the reflection spectrum. The sensor is a low-tilted FBG (Technica S.A.) written in a single-mode fiber. The TFBG nominal parameters are: Bragg wavelength 1550.97 nm, reflectivity >97%, tilt angle 5°, FWHM 0.23 nm, length 1 cm. This setup, shown photographically in Fig. 1(b), is a low-cost interrogator and has been packaged in a portable prototype; a LabVIEW™ software has been designed to control the spectrometer in real-time, with 1 kHz acquisition rate via USB.
Fig. 1. Interrogation and demodulation of the TFBG. (a) Schematic of the white-light low-cost interrogation setup, inclusive of superluminescent LED (SLED) and its control board, 3-dB coupler, spectrometer (SM), and TFBG sensor. (b) Photograph of the interrogation prototype, assembled in a case, size 37 × 24 × 19 cm; top and side panels have been removed to visualize inner components. (c) Spectrum of a TFBG sensor used in experiments, as visualized on an optical spectrum analyzer with 10 pm resolution bandwidth. (d) Spectrum of the same TFBG sensor visualized on the coarse spectrometer. (e) Schematic of the TFBG demodulation; the adjusted KLT is divided into its building blocks.

Figures 1(c) and 1(d) illustrates the detection problem for a TFBG sensors used in experiments. In Fig. 1(c), the TFBG spectrum is detected using an OSA (Ando AQ 6300 series), having 10 pm resolution bandwidth. This narrow resolution allows a visualization of a dozen of cladding modes in the spectrum, having amplitude progressively decreasing towards the shorter wavelengths; the transmission spectrum of the TFBG, measured by the manufacturer, exhibits a similar fringe visibility. As in [1, 25], these are the cladding modes that are monitored for refractive index sensing. In Fig. 1(d), the spectrum of the same TFBG is shown as sampled by the spectrometer: since each element composing the CCD array integrates all the wavelengths within the resolution, the cladding modes are not visible in the TFBG spectrum, since the bandwidth of each mode is significantly inferior to the inter-pixel resolution. As expected, for wavelengths higher than the Bragg wavelength the reflectivity is null; however, we observe a reflection spectrum for wavelengths smaller than the Bragg wavelength that corresponds to the cladding fringes, even though the modes cannot be discriminated directly. Thus, the spectral envelope results as the integration of the reflection spectrum on each range of wavelength. Figures 1(c) and 1(d) illustrates the problem of TFBG demodulation with a coarse spectrometer: since the cladding modes are not spectrally relevant, it is necessary to apply a non-standard method to convert the small variation of spectral amplitude due to a refractive index change into a variation of a suitable metric.

The detection method is based on the KLT [26, 27, 29, 30], which however needs to be adapted to the specific problem; the demodulation technique is sketched in Fig. 1(e). Since the KLT is a digital signal processing method, the reflection spectrum of the TFBG $R(\lambda)$, where $\lambda$ is the wavelength, is regarded as a digital signal. Prior to apply the KLT, the signal is pre-processed: the dark level is estimated and subtracted from the spectrum, then the spectral
amplitude is normalized in order to compensate for eventual power fluctuations; finally, the spectral slice of length \( N \) and containing the whole dual-side spectrum of the TFBG is selected, defining the digital signal \( R = [R_1, R_2, \ldots, R_N] \) of length \( N \) and containing the TFBG optical spectrum.

As a first step, we apply the Fast Fourier Transform (FFT) to \( R \), obtaining the output \( G = [G_1, G_2, \ldots, G_N] \):

\[
G_k = \sum_{n=1}^{N} R_n e^{-j2\pi(k-1)(n-1)/N} \quad (1)
\]

for each \( k = 1, \ldots, N \). Then, in order to apply the KLT, we expand \( G \) into its symmetric Toeplitz matrix:

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

with size \( N \times N \). In the following analysis, we set \( N = 52 \) as in [26]. Finally, we can compute the KLT of the matrix \( M \), which corresponds to the determination of an orthonormal basis \( V \) of \( M \). As in Maccone’s implementation [29–31], this operation can be performed by calculating the singular value decomposition of \( M \):

\[
M = V \cdot D \cdot V^{-1} \quad (3)
\]

where: \( D \) is a diagonal matrix containing on its main diagonal all the eigenvalues of \( M \); \( V \) is a matrix containing on its columns the eigenvectors corresponding to each eigenvalue in \( D \). The result of Eq. (3) is the eigenvalue string \( \hat{\xi} = [\hat{\xi}_1, \hat{\xi}_2, \ldots, \hat{\xi}_N] \) which is the main diagonal of \( D \), sorted in ascending order \( \hat{\xi}_1 \leq \hat{\xi}_2 \leq \ldots \leq \hat{\xi}_N \).

It is noted that the arrangement in Eq. (2) allows converting the optical problem, i.e. the analysis of extremely small changes of TFBG optical spectrum, which are enhanced by the phase of the FFT in Eq. (1), into Gray’s information theory problem [32, 33], which was solved by Maccone for the detection of extremely small signals buried into noise [34]. In Maccone’s and Gray’s work the KLT is applied to the covariance matrix (which is a Toeplitz matrix) of the weak signal corrupted by noise; hereby, the Toeplitz matrix expansion allows applying the KLT to the matrix \( M \); since it is a Toeplitz matrix, its eigenvalues are real and positive.
This implementation of the KLT is illustrated in Fig. 2. At first, in Fig. 2(a), the TFBG spectra for four different refractive index values is reported; however, as the cladding mode variations are minimal, and flattened by the resolution of the spectrometer, it is not possible to directly demodulate the TFBG spectrum. The KLT, which reports the value of all $\zeta_k$ eigenvalues, $k = 1, \ldots, N = 52$, shows a trend more similar to [27]: for all values of refractive index, we observe that the low-rank eigenvalues ($k = 1$ to 42) yield a nearly zero value; as in [34], however, high-rank eigenvalues are instead responsible of encoding the information of the TFBG spectrum, and have a much higher value, ranging from 0.2 to 2.8; the values of $\zeta$ are reported normalizing the spectrum as in Fig. 2(a).

However, the profile of the KLT applied to TFBG has a slightly different outcome than in the uniform FBG application: while in [27] we observed a rapid decay of $\zeta_k$ for $k < (N-2)$, in Fig. 2(b) the decay is smoother. This is largely due to the different profile of the grating: the high-rank eigenvalue confines, and separates from noise, the contribution of the high-reflectivity portion of the grating which corresponds to the main Bragg mode [26, 29, 30].

Thus, the contributions related to cladding modes tends to be confined in the engenvalues having rank ranging between $(N-3)$ and $(N-10)$. We select $\zeta_{N-4}$, i.e. the 48th eigenvalue, as the demodulation function of the TFBG. This is the main difference from [26, 32, 34], in which the KLT was used as a principal component analysis algorithm, while for TFBG demodulation we search for the smaller spectral energy contributions variations.

The inset in Fig. 2(c) shows the variation of $\zeta_{N-4}$ for the different values of sucrose concentration: we observe that, as a matter of fact, the KLT is effective in discriminating the value of refractive index, returning an output that has a variation sufficient for a detection. On the other side, we observe that the $\zeta_{N-4}(n)$ function has a non-monotonic pattern; this was already observed in the application to the standard KLT applied to FBG tracking. The effect, that is highlighted by Fig. 2(c) inset, is that the variation of $\zeta_{N-4}$ for a positive refractive index does not follow a linear pattern, but is rather non-monotonic and non-linear, at least for variations of sucrose concentration higher than 6.25%. This behavior was observed also in previous works [26–28] due to the core of the KLT, that amplifies the slight variations of the TFBG spectrum into detectable variations of the eigenvalue string, when the cladding modes exhibit a change that is hardly detectable in the strain. This is in general a weakness of the KLT, since it cannot discriminate large changes of refractive index without a complementary
algorithm; however. However, when operating in biosensors the main challenge is to detect small variations of refractive index, below $10^{-3}$ RIU [19, 35, 36] or below 0.5% concentration of sucrose: in this task, similar to a small signal-analysis, the capability of the KLT to convert slight spectral variations into still visible changes of $\xi_{N,4}$ has the best outcome.

3. Experimental results

Experiments have been carried out to evaluate the response of the KLT demodulation to different values of refractive index; we focus our analysis on small variations of refractive index (concentration of sucrose up to 1%). For the measurements, the outer buffer of the TFBG has been stripped, and the TFBG has been immersed in a mixture of water (refractive index $n \approx 1.333$) and sucrose in concentration up to 1% (refractive index variation $\Delta n \approx 1.85 \times 10^{-3}$ for this concentration). A number of studies [37–39] used different sucrose concentrations for calibration of fiber optic based sensors and in the calibration process of Biacore SPR measurement instruments [40]. Several solutions have been prepared, with sucrose ranging from 0% to 60% by serial dilution. In order to examine performance in refractive index sensing, and preserve avoid the influence of temperature, all solutions have been maintained in a temperature-controlled laboratory environment at the constant temperature of ~26°C for >1 day. Refractive index measurements have been performed in absence of temperature variations ($\pm 0.01$ °C detected on the thermometer of the temperature controller during the measurement time, lasting few minutes). In particular, we focus our analysis on sucrose concentrations ranging from 0.1% to 1% in steps of 0.1% (accuracy $\pm 0.005\%$), corresponding to refractive index step variations of $=1.85 \times 10^{-4}$ refractive index units (RIU); and on concentrations ranging from 0.01% to 0.1% with steps of 0.01% correspondent to refractive index steps of $=1.85 \times 10^{-5}$ RIU, in order to measure the resolution [9, 24].

![Fig. 3. Refractive index measurement using the KLT decoding: the chart reports $\xi_{N,4}$ as a function of time, increasing the concentration of sucrose from 0% to 1% in steps of 0.1%.](image)

The first result is shown in Fig. 3, where the sucrose concentration is raised from 0% to 1% in steps of 0.1%; the chart reports the measurement performed in a time-domain chart, initializing the calculation in water (1 minute) and reporting the change of $\xi_{N,4}$ as the sucrose level is increased (approximately, each 30 s). This corresponds to a refractive index change of $1.85 \times 10^{-3}$ RIU in steps of $1.85 \times 10^{-4}$. We observe that, for small values of sucrose concentration, we always observe an unambiguous variation of the KLT output $\xi_{N,4}$ as the sucrose concentration changes: $\xi_{N,4}$ decreases from 0.5288 to 0.5250, thus with a change of $-0.71\%$. This experiment demonstrates the successful detection of small concentration levels through the modified KLT: for this concentration level, we observe an average variation of
the KLT output of $-0.38\%$ for each $10^{-3}$ RIU, or $-0.71\%$ per each 1% sucrose concentration change.

Fig. 4. Estimation of the resolution capacity of the KLT. The chart reports the value of $\xi^{-4}_{N_{KLT}}$ as a function of time, varying the sucrose concentrations from 0.01% to 0.10% in steps of 0.01%.

For the same TFBG, we performed a test changing the sucrose concentration from 0% to 0.1% in steps of 0.01%; the result is shown in Fig. 4, in order to determine the capacity of the TFBG sensor demodulated through KLT to detect the very small refractive index changes, as required by most biosensing applications [22–24]. Through variations of sucrose in 0.01% steps, it is possible to observe that we can always obtain a detectable variation of the eigenvalue $\xi^{-4}_{N_{KLT}}$. Overall, the chart suggests that the resolution of the detection method, i.e. the smallest variation of refractive index clearly detectable from the noise floor, is $\sim10^{-5}$ RIU, or $\sim0.005\%$ sucrose. We observe also that KLT output variation is not linear with the refractive index variation: this is inherent in the KLT, that as in [26] does not return a linear and monotonic output as a function of the measurand change. The slight variation of eigenvalue amplitude between Fig. 3 and Fig. 4 can be attributable to both the slight variation of the emitted power of the SLED, and the slight temperature variation (1°C) that was experienced by the spectrometer and measured with its inner temperature chip sensor.

Fig. 5. Calibration (left) and accuracy (right) of KLT output $\xi^{-4}_{N_{KLT}}$ as a function of small refractive index variation $\Delta n$. 
The performance analysis of KLT detection is shown in Fig. 5, where results are reported in terms of refractive index variation $\Delta n$. The left chart shows the calibration function, which is obtained from Fig. 3 by taking the mean value of $\xi_{N,4}$ for each refractive index. We observe that, for a small-signal analysis, the behavior is not far from a linear function (with slope $-2.05$ RIU$^{-1}$), although Fig. 2 suggests that increasing the analysis to values of $\Delta n$ larger than $10^{-2}$ will result in a non-monotonic function. The right figure shows the detection accuracy, in terms of $\xi_{N,4}$, which is obtained by calculating the standard deviation of $\xi_{N,4}$ at each constant value of $\Delta n$. We observe that the accuracy ranges from $2.4 \cdot 10^{-6}$ to $3.9 \cdot 10^{-6}$; using the previous linear approximation, this corresponds to an accuracy of $1.9 \cdot 10^{-6}$ RIU, a value that is also compatible with the resolution-test in Fig. 4 as it is one order of magnitude inferior.

In all experiments, the average execution time of the KLT is 0.97 ms, using an Intel 2.6 GHz Core i5 processor with 16 GB RAM, making it a computationally affordable method for processors and field-programmable gate array (FPGA).

5. Conclusions

In conclusions, we presented a method based on KLT to demodulate a TFBG sensor for refractive index detection, using a coarse interrogator (156 pm resolution). Even if the spectral resolution is insufficient to visualize the TFBG cladding modes, the KLT is capable of converting a small refractive index change into a varying output. In order to accomplish this, the KLT is modified from its original implementation [26, 27], as we use as refractive index sensing method a lower-rank eigenvalue ($\xi_{N,4}$). Experiments show that the KLT can successfully demodulate small refractive index changes (in the order of $1.85 \cdot 10^{-3}$ RIU), and yields a resolution in the order of $10^{-5}$ RIU.

Overall, the main impact of this investigation is the possibility of obtaining a detection limit sufficient for small refractive index detection, even with a very low cost, high speed, and portable hardware with coarse sampling resolution, whereas TFBG require an OSA [12, 14] or OVA [23] or tunable scanning laser based on semiconductor optical amplifier [41], which have narrow wavelength resolution but have slow response time, and are not portable and affordable but several applications. On the other side, the KLT has few drawbacks, that will be investigated in future work; the main one is the non-linear and non-monotonic pattern of the $\xi_{N,4}(\Delta n)$ function, which requires obtaining a calibration for each TFBG and operating only on a small range of $\Delta n$. The discussed results have been obtained for a TFBG inscribed in a telecom fiber, having smaller tilt angle and higher mode confinement than most TFBG-based refractometers [42]. Thus, the KLT appears as an effective method to demodulate small refractive index changes, and for this reason is well suited for biosensing.

The results presented in this work have been obtained with a low-tilted FBG inscribed in a telecom fiber, which results in a more compact cladding mode profile than most TFBG-based refractometers [16, 19, 42], and more similar to the model in [43].

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