Tilted Fiber Bragg Grating Refractometer Using Polarization-Dependent Loss Measurement

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***Abstract*—In this letter, a novel demodulation technique based on the monitoring of the polarization-dependent loss in a 1-nm wavelength range is proposed to measure the surrounding refractive index by means of weakly tilted fiber Bragg gratings. A 1 10^{-3} refractive index resolution as well as a temperature-insensitive behaviour are reported.**

***Index Terms*—Fiber Bragg gratings, polarization, refractive index, sensor.**

I. Introduction

REFRACTOMETRY is necessary in various areas including quality control in the food industry, process monitoring, and biomedical applications. Due to the need for miniature and minimally invasive refractometers that can be interrogated remotely, optical fiber sensors, and more specifically fiber gratings sensors, have been widely developed. To measure surrounding refractive index (SRI) changes by monitoring the resonant wavelength of fiber gratings, the guided light has to be brought in contact with the outer boundary of the fiber cladding. In this way, the evanescent field of the optical modes penetrates the external medium to sense the SRI. Among the different configurations used to obtain such a mode distribution, tilted fiber Bragg gratings (TFBGs) are very interesting. In comparison to long-period fiber gratings, they provide temperature-insensitive SRI measurements [1] and are less sensitive to bending [2].

TFBGs are characterized by a refractive index modulation pattern tilted by a certain angle with respect to the fiber axis so that they couple light from the fiber core to the cladding at discrete wavelengths below the Bragg wavelength. These couplings produce narrow attenuation bands in transmission corresponding to light modes contrapropagated in the fiber cladding [3]. Since they propagate near the cladding-external medium interface, these bands are sensitive to the SRI.

Up to now, two main demodulation techniques have been proposed to correlate the TFBG transmitted spectrum evolution with respect to SRI changes. In 2001, Laffont and Ferdinand presented a technique based on the monitoring of the area delimited by the cladding modes in the TFBG transmitted spectrum to find the SRI value [1]. More recently, Chan *et al.* showed that a local monitoring of selected cladding mode resonance shifts with respect to the Bragg wavelength can also be used for this purpose [4]. These two demodulation techniques present a good SRI sensitivity and are relatively insensitive to temperature changes. However, to correctly operate in the range of SRI values between 1.33 and 1.45, they require transmitted spectrum measurements on a wavelength range of a few tens of nanometers. For dynamic SRI sensing, this can be too time consuming so that it is important to find a novel technique operating in a reduced wavelength span. Moreover, it is also very interesting to extend the sensing range to SRI values below 1.33.

To reach these two goals, we propose here to use the polarization-dependent loss (PDL) evolution with wavelength associated to the TFBG transmitted spectrum for refractometry purposes. In the following, we demonstrate that the monitoring of the PDL maximum amplitude in a 1-nm range allows us to get rapid temperature-insensitive SRI measurements in the range 1.28–1.45 with a resolution equal to 1 10^{-3}.

II. Experimental Setup

In our experiments, we use TFBGs written into hydrogen-loaded single-mode fiber by means of the phase mask technique and an excimer laser emitting at 248 nm. To produce TFBGs, the phase mask is tilted in the plane perpendicular to the incident laser beam.

Due to the lateral inscription process, the refractive index profile is asymmetric in the fiber cross-section yielding ultraviolte (UV)-induced birefringence of the order of 10^{-6}–10^{-5} in the grating region. This birefringence leads to the existence of two orthogonal polarization modes (also called eigenmodes) that undergo different couplings through the grating. The birefringence is then manifested by the presence of two identical overlapping spectra shifted by a small quantity of the order of a few picometers. Due to the limited resolution of measurement devices, this wavelength shift is not visible in the amplitude spectrum which appears as if there was no birefringence. However, polarization-dependent properties are present within the grating. In particular, significant PDL evolution with wavelength may occur.

In practice, the PDL evolution with wavelength is deduced from Jones matrices using the Jones matrix eigen-analysis method [5]. For that purpose, as shown in Fig. 1, a tunable laser EXFO FLS 2600B, a linear polarizer, and a polarimeter Profile PAT 9000B were employed. The polarizer is used to set three different input states of polarization (typically 0°, 45°, and

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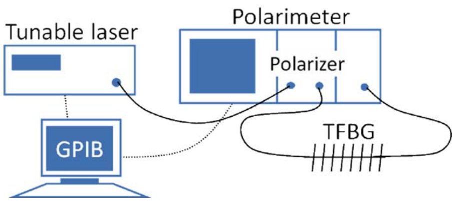

Fig. 1. Experimental setup used to compute the PDL evolution with wavelength. Equipments controlled by GPIB (general purpose interface bus).

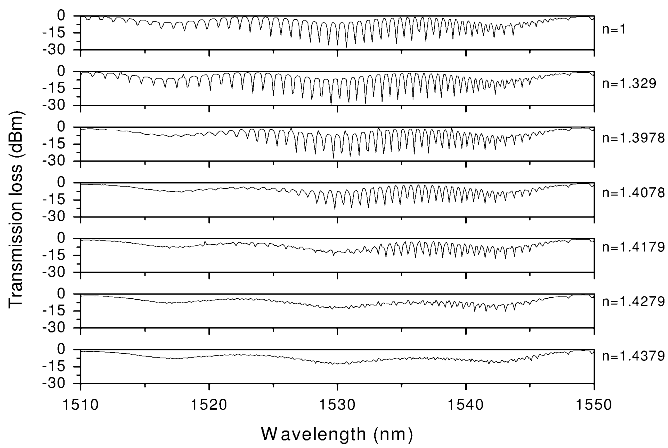

Fig. 2. Transmitted spectrum evolution of a 6° TFBG as a function of the SRI.

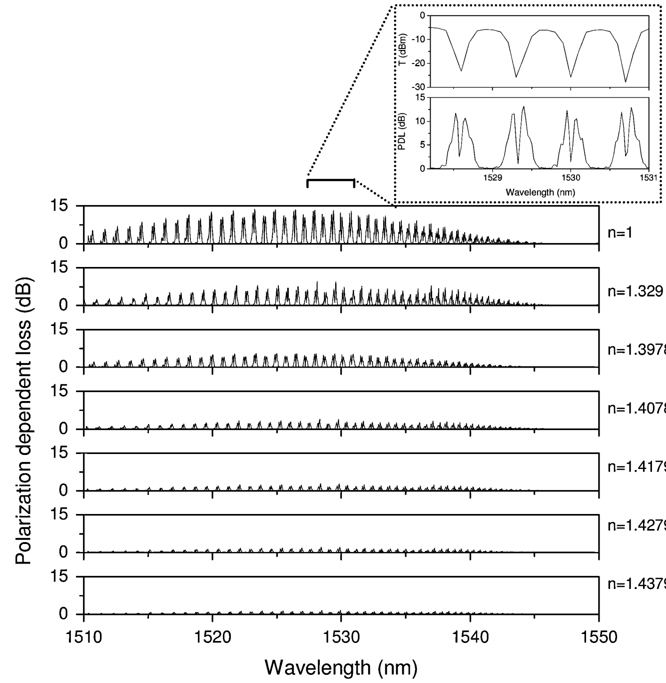

Fig. 3. PDL evolution of a 6° TFBG as a function of the SRI.

90°) while the polarimeter measures the state of polarization at the TFBG output in order to deduce its Jones matrix. At every wavelength during the measurements, the Jones matrix computed by the polarimeter was used to determine the PDL curve. During measurements, TFBGs were kept straight to avoid instabilities due to bending effects. With a wavelength sampling set to 10 pm, the PDL measurement in a 1-nm range takes only a few seconds.

To study the PDL sensitivity to the SRI value, we used a set of Cargille's oils whose refractive indices at 1530 nm are known with an accuracy of the order of 10^{-3}. To keep the strain on the TFBG constant during the experiments, it was attached to a microscope slide and small quantities of liquids with various refractive indices were deposited on the TFBG.

III. PDL Evolution With Wavelength

Fig. 2 presents the transmitted spectrum evolution of a 6° TFBG as a function of the SRI. To record the amplitude spectrum, the tunable laser whose polarization state varies with respect to the wavelength was passed through a linear polarizer, which explains the sine modulation in the measured spectra. The wavelength sampling was set to 100 pm. As the SRI increases, a progressive decrease of the peak-to-peak amplitudes of the cladding mode resonances is obtained in the transmitted spectrum, starting from the shortest wavelengths, as reported in [1] and [4].

Fig. 3 shows the PDL evolution with wavelength of the 6° TFBG as a function of the SRI. It can be seen that the PDL takes local maximum values at wavelengths corresponding to the edges of the cladding mode resonance bands. This comes from the fact that the PDL of a fiber grating can be defined as the absolute value of the difference between the amplitudes of the two transmitted signals corresponding to the eigenmodes, and at these particular wavelengths, this quantity is maximum [6]. The inset of Fig. 3 depicts a zoom of the PDL evolution for several cladding mode resonances around 1530 nm.

When the SRI increases, the PDL maximum amplitudes continuously decrease for all the cladding mode resonances. Moreover, from SRI $=$ 1.00 to SRI $=$ 1.33, while the transmitted spectrum remains practically unaffected by SRI changes, the maximum PDL amplitudes strongly evolve from about 14 to 10 dB. This PDL evolution can be explained as follows.

In practice, slight changes of the SRI value modify the resonances amplitudes in the transmitted spectrum through changes of the cladding mode profiles. For small SRI values, this perturbation is very weak since the cladding mode fields do not extend much in the cladding region. However, as the PDL curve is mainly caused by a resonance shift, its particular evolution can be attributed to the phase shifts undergone by the cladding modes during their total internal reflection at the cladding-surrounding medium interface (these phase shifts do not depend directly on the cladding modes penetration depth in the external medium but only on the index difference).

IV. Temperature-Insensitive SRI Sensing

To yield a good compromise between time and accuracy, PDL measurements were carried out in wavelength ranges of 1 nm with a sampling set to 10 pm. Within these wavelength regions, the maximum PDL amplitude was recorded and its evolution was tracked against the SRI value. The peak-to-peak amplitude of the transmission loss was also monitored for comparison. For the 6° TFBG used in our experiments, the best results in terms of SRI sensitivity were obtained for a 1-nm range centered around 1530 nm. Fig. 4 depicts the evolutions obtained in this wavelength range and confirms the results presented in Figs. 2 and 3.

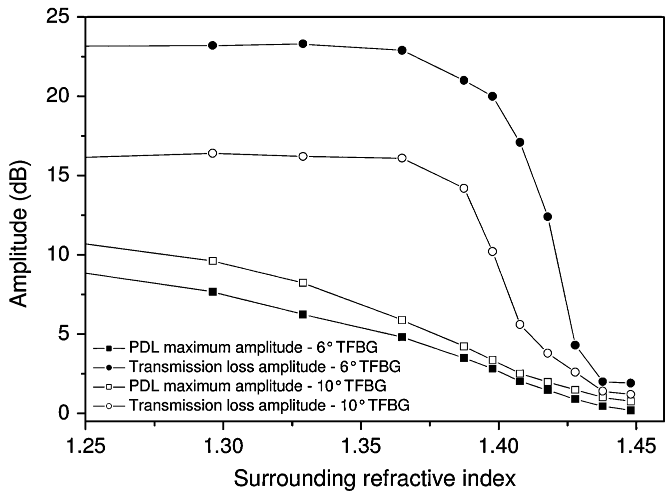

Fig. 4. Maximum PDL value and transmission loss around 1530 nm as a function of the SRI for a 6° and 10° TFBGs.

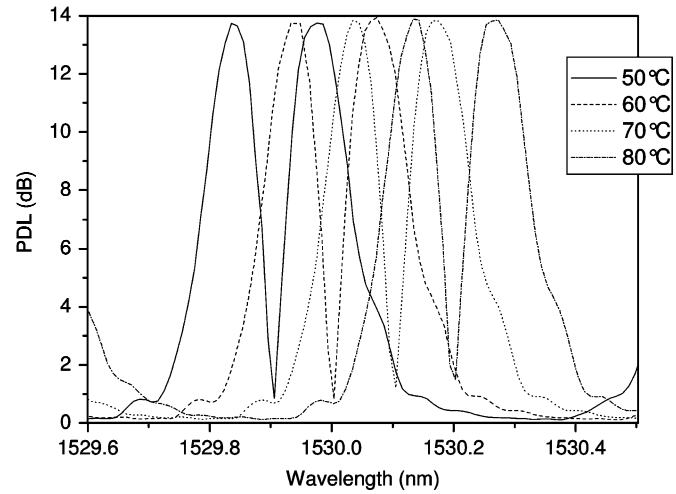

Fig. 5. PDL around 1525 nm as a function of temperature changes.

Because the transmission loss shape and amplitude vary slightly for SRI values smaller than 1.33, the amplitude of the transmission loss can only be used to sense SRI values higher than 1.33. Unambiguous SRI measurements in an extended SRI range are nevertheless possible by tracking amplitude changes in the PDL curve. In particular, for the 1-nm region centered around 1530 nm, a mean sensitivity equal to 1.1 dB per 0.01 of refractive index unit (RIU) is reported.

For comparison, Fig. 4 depicts the results obtained on a 10° TFBG written in the same experimental conditions as the 6° TFBG. The PDL maximum amplitude and cladding mode resonance loss evolutions against SRI were tracked in a wavelength window centered around 1520 nm. These results confirm those presented for the 6° TFBG since a monotonous decrease of the PDL is obtained in the investigated SRI range. The mean sensitivity is in this case computed equal to 1.3 dB per 0.01 of RIU.

Let us add that the maximum PDL amplitude decrease is accompanied by a wavelength shift of the resonance band when the SRI increases. This results from a cladding mode redistribution due to an external medium modification [1]. However, providing that the wavelength window includes a given cladding mode during its entire shift (this is the case with a 1-nm range), this wavelength shift does not affect the demodulation technique since it is based on the detection of the maximum PDL amplitude, whatever the wavelength is.

A repeatability test was carried out on the 6° TFBG by doing series of 100 measurements in the region centered around 1530 nm in well-defined experimental conditions (temperature and SRI value controlled and kept constant). The maximum error on the determination of the PDL maximum amplitude was computed equal to 0.1 dB. Taking into account the mean sensitivity of the demodulation technique, this is equivalent to an error on the determination of the SRI of a bit less than 10^{-3}.

The effect of temperature changes on the refractometer performances was also investigated. A thermal chamber accurate to 0.1 °C was used for that purpose. Fig. 5 shows the temperature influence on the PDL curve measured in air around 1530 nm. As expected from [7], the PDL maximum value is negligibly affected (less than 0.2 dB of variation) so that temperature-insensitive SRI sensing is possible using the maximum PDL amplitude as a demodulation technique.

V. Conclusion

Due to the manufacturing process in which UV light irradiates the optical fiber through only one side, some photoinduced birefringence is manifested in TFBGs and leads to PDL. We have demonstrated that this parameter can be advantageously used for refractometry purposes. Indeed, a novel demodulation technique based on the computation of the PDL maximum amplitude has been presented. Resolution of 1 10^{-3} in the determination of the SRI as well as temperature-insensitive response have been reported.

The main advantage of the technique reported in this letter lies in the greater range of SRI for which a given sensor remains useful and the reduced wavelength range of 1 nm to complete the measurement.

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