Quasi-distributed refractometer using tilted Bragg gratings and time domain reflectometry

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Abstract: Tilted fiber Bragg gratings (TFBGs) have been demonstrated to be accurate refractometers as they couple light from the fiber core to the cladding. Because they require spectral measurements on several tens of nanometers, demodulation techniques reported so far are not suited for quasi-distributed refractive index sensing using TFBGs cascaded along a single optical fiber. We demonstrate here that a commercial Optical Time Domain Reflectometer (OTDR) can be used to multiplex identical TFBGs refractometers written in the same optical fiber. Our solution is simple, relatively fast, cost-effective and is particularly interesting for the monitoring of long structures.

OCIS codes: (060.2310) Fiber optics; (060.2370) Fiber optics sensors; (230.1480) Bragg reflectors.

References and links

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1. Introduction

Refractometry is necessary in various areas including quality control in the food industry, process monitoring and biomedical applications. Nowadays, commercially available refractrometers are mainly derived from the Abbe configuration [1]. Such instruments determine the refractive index by computing the change in the total internal reflection angle of a prism on which the substance with the unknown refractive index is deposited. Although very accurate, these instruments present practical limitations due to their size and their power requirements. Moreover, the manner with which the prism has to be brought in contact with the substance often prevents their operation in situ. It is the reason why, due to the need for

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minimally invasive refractometers that can be interrogated remotely, optical fiber sensors, and more specifically fiber gratings sensors, have been widely developed during the last decade. 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 into the external medium to sense the SRI. Among the different configurations used to obtain such a mode distribution, tilted fiber Bragg gratings (TFBGs) appear very interesting. Indeed, contrary to long period fiber gratings refractometers [2], they provide intrinsically temperature-insensitive SRI measurements [3] and are much less sensitive to bending effects [4], which makes easier their use in practical applications.

TFBGs are short-period gratings (periodicity of the refractive index modulation of a few hundreds of nanometers) written at an angle with respect to the optical fiber cross-section. This angle breaks the symmetry of the fiber so that, in addition to the core mode coupling at the Bragg wavelength, TFBGs 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 contra-propagated in the fibre cladding [5]. Since they travel near the cladding-external medium interface, the cladding modes are sensitive to the SRI unlike the core mode. In practice, the simultaneous presence (at different wavelengths) of the core mode coupling (insensitive to SRI and bending) and several cladding mode resonances allows temperature-insensitive SRI sensing.

Up to now, two main techniques have been proposed to demodulate the TFBG transmitted spectrum evolution with respect to SRI changes and to determine the SRI value. The first one is based on the global monitoring of the area delimited by the cladding modes in the TFBG transmitted spectrum [3] while the second one involves the local monitoring of selected cladding mode resonance shifts with respect to the Bragg wavelength [6]. 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. In the context of quasi-distributed sensing, this complicates the wavelength division multiplexing of TFBGs sensors interrogated by such techniques along a single optical fiber. This is an issue since many practical applications such as the monitoring of water supply networks or large reservoirs require refractive index measurements at different locations with a low cost sensing system.

In this work, we provide a solution to this problem by means of a commercial OTDR (Optical Time Domain Reflectometer) used to interrogate identical TFBGs cascaded along a single optical fiber. The use of an OTDR, combined with spectral filtering, was initially proposed to increase the number of conventional FBG strain sensors that could be integrated along a single optical fiber [8]. Based on this pioneered demonstration, we report here that an OTDR can serve as a demodulation technique for TFBGs refractometers. Our solution, based on the computation of the insertion loss in the OTDR trace at the TFBG location, offers simple, relatively inexpensive and fast quasi-distributed SRI sensing, which is without equivalent for other demodulation techniques reported so far. In particular, our approach differs from the recently reported Ref. [9] that combines a multimode fiber OTDR with SRI sensors based on evanescent field absorption in coated, etched fibers: our system uses conventional single mode fibers at telecommunications wavelengths and the physical integrity of the fiber is maintained at the sensor locations. Experiments carried out to quantify the accuracy and sensitivity of our method are presented hereafter for refractive index measurements of sucrose solutions and calibrated liquids, and the temperature dependence of the system is quantified.

2. Experiments

2.1 SRI influence on the TFBG transmitted spectrum

For TFBGs, the Bragg wavelength λ_{Bragg} and the wavelength $\lambda_{coupling,i}$ at which the discrete coupling to one particular i^{th} cladding mode occurs are given by [5]

$$\lambda_{Bragg} = 2n_{eff,core}\Lambda \tag{1}$$

$$\lambda_{coupling,i} = (n_{eff,clad,i} + n_{eff,core})\Lambda \tag{2}$$

where $n_{eff,core}$ and $n_{eff,clad,i}$ are the effective refractive indices of the core mode and the i^{th} cladding mode, respectively. Λ is the projection of the actual grating period Λ_g along the fiber axis due to the tilt angle θ and is such that $\Lambda=\Lambda_g/\cos\theta$.

Figure 1 presents the transmitted spectrum evolution of a 4° TFBG with respect to the SRI. This grating was written into hydrogen-loaded standard single mode fiber by means of a frequency-doubled argon-ion laser and a 1095 nm period uniform phase mask. To inscribe TFBGs, the phase mask was tilted in the plane perpendicular to the UV laser incident beam.

To modify the SRI around the TFBGs, we used both water-sugar solutions and a set of Cargille's oils whose refractive indices around 1550 nm are known with an accuracy of the order of 10^{-3}. To keep the strain on the TFBGs constant during the experiments, TFBGs were attached to a microscope slide and small quantities of liquids with various refractive indices were deposited on the TFBGs. The effect of strain will be addressed in more detail below.

As shown in Fig. 1, the cladding modes resonance strengths progressively decrease when the SRI increases. This results from the fact that, when the SRI rises and reaches $n_{eff,clad,i}$, the corresponding i^{th} cladding mode becomes weakly guided, reducing its resonance amplitude. When the SRI is equal to $n_{eff,clad,i}$, the i^{th} cladding is no longer guided but becomes radiated. Hence, as the SRI grows, a progressive smoothing of the transmitted spectrum is obtained, starting from the short wavelengths. Based on this evolution, it is readily conceivable that a straightforward demodulation technique for TFBGs refractometers consists in monitoring the changes in the cladding mode couplings through a precise measurement of the transmitted spectrum across a broad wavelength range, as used in [3-7]. However, because the cladding modes spectrum of each grating extends over several tens of nanometers, the main limitation of TFBG refractometers is that it is difficult to measure several TFBGs concatenated along a single optical fiber for quasi-distributed sensing. Wide band optical sources and detectors could be used but it would drastically increase the cost and response time of the interrogation unit. In the following, we demonstrate that using an OTDR to measure the total power *reflected* from a series of TFBGs removes this important limitation.

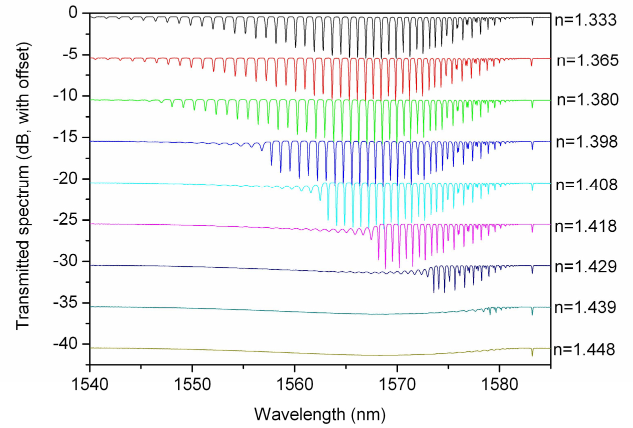

Fig. 1. 4° TFBG transmitted spectrum evolution as a function of the SRI (vertical axis in dB with offset).

2.2 Proposed demodulation technique

The OTDR is commonly used to analyze light loss mechanisms in fiber links. It injects optical pulse trains into the optical fibers under test and measures the backscattered and reflected light as a function of time. The signal is then analyzed to localize optical fiber discontinuities. As the OTDR returns the position of reflective events along an optical fiber, it can be used for quasi-distributed sensing purposes [8,9].

In this work, we have cascaded identical TFBGs written at different locations along a single optical fiber. They were interrogated by a commercially available OTDR. The TFBGs were designed so that the amplitude spectrum of the OTDR optical source covers the cladding modes resonances in the transmitted spectrum of the TFBGs. In our case, 4° TFBGs allowed us to obtain such a feature: Fig. 2 shows the 4° TFBG transmitted spectrum and OTDR source amplitude spectrum measured by an optical spectrum analyzer.

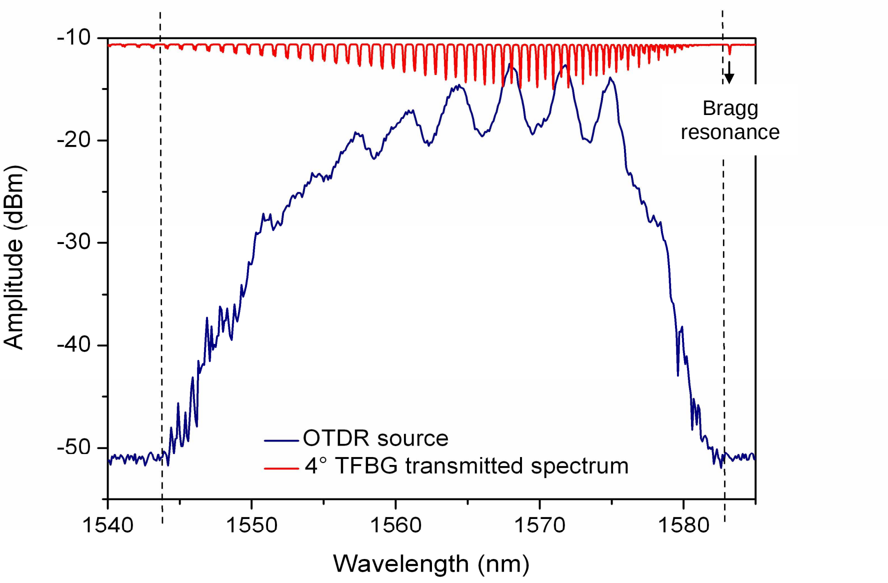

Fig. 2. 4° TFBG transmitted spectrum with the cladding mode resonances centred on the OTDR source.

Our demodulation technique is based on the monitoring of the insertion loss induced by the presence of the TFBG in the OTDR trace. Fig. 3 presents a typical OTDR trace for a 1 cm long 4° TFBG comprised between two single mode optical fiber sections of about 1 km length. The pulse duration of the OTDR source was set to 100 ns and the averaging time was chosen equal to 30 seconds. Apart from the important Fresnel reflection at the end of the fiber link, the remarkable feature of this trace is the reflection peak and associated downlink loss occurring at the location of the TFBG. The reflection is attributed to the strong core mode coupling at the Bragg wavelength while the insertion loss results mostly from the cladding modes couplings as they occur across the whole spectral range of the optical pulse source. As these couplings are influenced by the SRI, we demonstrate in the next section that a monitoring of the insertion loss in the OTDR trace can be used for refractometry purposes. For precise measurements, linear regressions were made at each side of the TFBG to determine its insertion loss, as schematized by the dotted lines in Fig. 3. The insertion loss is therefore equal to the difference of amplitude between the two regression lines at the location of the Bragg reflection in the OTDR trace.

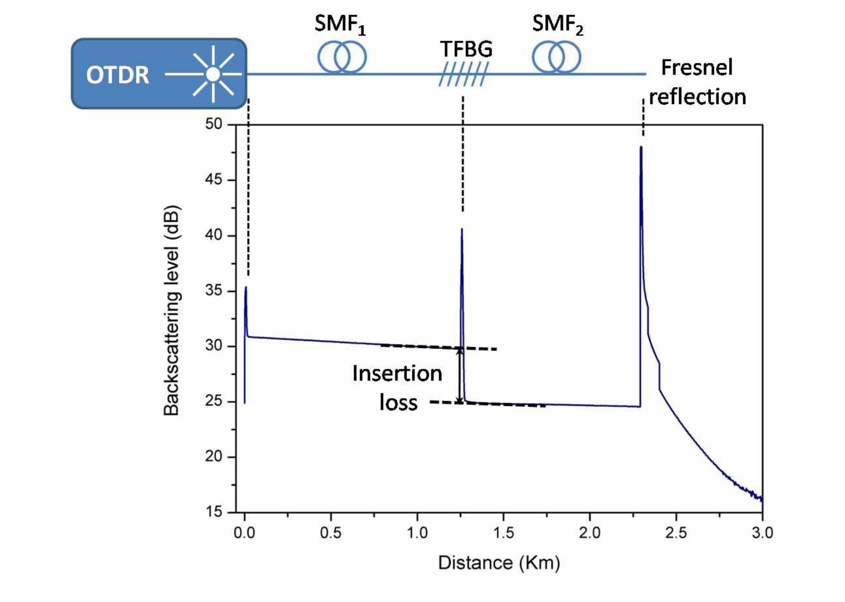

Fig. 3. Typical OTDR trace for a 1 cm long 4° TFBG inserted between two single mode optical fiber coils of approximately 1 km in length.

3. Results

Figure 4 shows the influence of the SRI on the OTDR trace for a 1 cm long 4° TFBG. As the SRI grows, the insertion loss at the TFBG location increases. This can be understood by careful examination of Fig. 1: as the SRI increases, narrowband and deep attenuation notches in the transmission spectrum are replaced by a broadband low level attenuation that gradually extends across the full spectrum of the source due to the progressive transformation of cladding modes into radiated modes. The result is a net increase in the total attenuation of the pulse as it travels through the grating. Taking into account the amplitude spectrum of the OTDR source and the transmitted spectrum evolution of the 4° TFBG with respect to the SRI (Fig. 1), simulations were carried out to compute the total transmitted power by the TFBG. A decrease was obtained for growing SRI values, confirming the experimental trend. Furthermore, the measurement of SRI by the increased transmission loss of a single TFBG sensor with growing external index was recently reported by Guo et al [10].

Figure 5 presents the evolution of the insertion loss measured in the OTDR trace at the 4° TFBG location as a function of the SRI value. The obtained data are compared to the normalized area evolution of the cladding modes spectrum computed conformingly to [3]. One can see that the two trends are opposite: while the normalized area evolution is monotonously decreasing for SRI values ranging between 1.33 and 1.45, the insertion loss evolution continuously grows. The insertion loss curve presents two inflection points, located at similar SRI values than those of the normalized area curve. This means that the sensitivities of these two demodulation techniques are not constant in the whole SRI range for which the TFBG sensor is useful. For the insertion loss monitoring, the sensitivity of the 4° TFBG is equal to 0.08 dB/0.01 RIU (refractive index unit) in the SRI ranges from 1.33 to 1.39 and from 1.43 to 1.45. The sensitivity increases to 0.65 dB/0.01 RIU in the SRI range 1.39-1.43. Given that the sensitivities of the two demodulation techniques are similar, we can thus conclude that the use of the OTDR to multiplex several sensors in the time domain does not result in a sensitivity penalty. The overall performances of the proposed demodulation technique are discussed in the following section.

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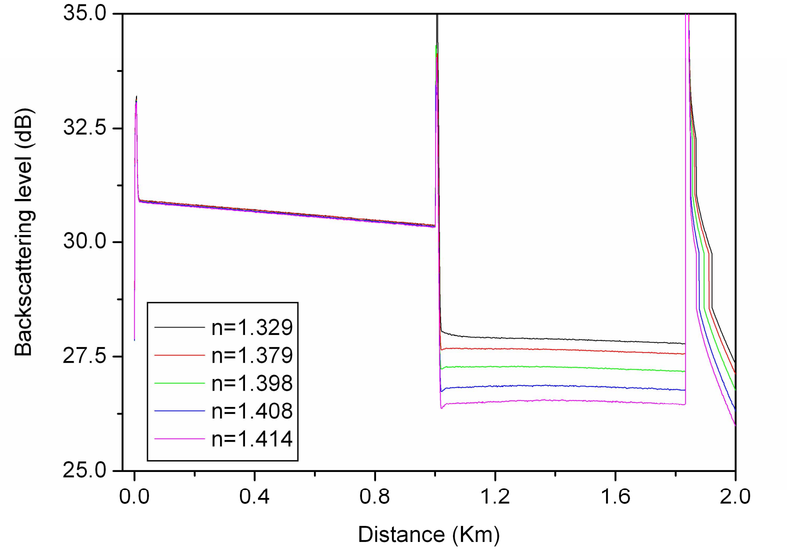

Fig. 4. Evolution of the OTDR trace for a 4° TFBG when the SRI is modified (pulse duration=100 ns, averaging time=30s).

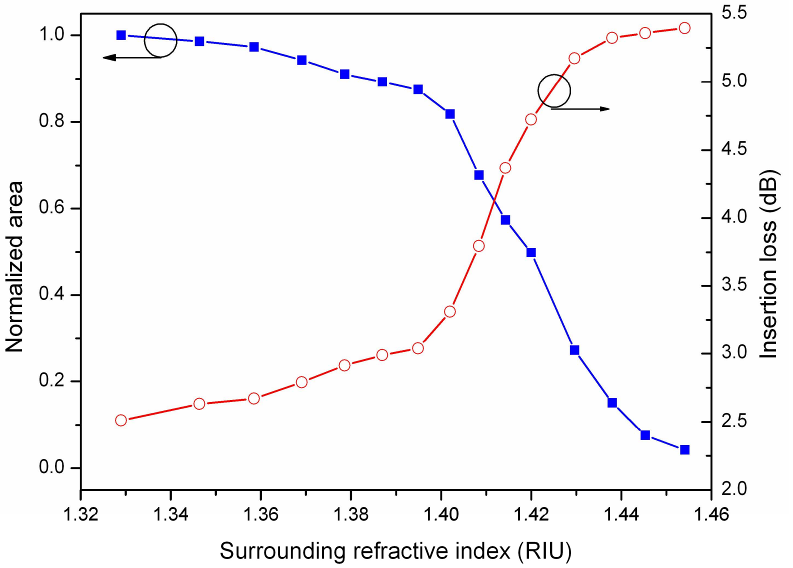

Fig. 5. Evolution of the insertion loss in the OTDR trace as a function of the SRI – Comparison with the normalized area.

4. Sensing performances

The performances of our demodulation technique are both related to the TFBGs coupling characteristics and to the OTDR parameters. With the OTDR used in this work, the measurement error on the insertion loss is equal to 0.05 dB/dB (i.e. when the measurement loss is 1 dB or less, the accuracy is within ± 0.05 dB), which directly affects the SRI value. To improve the precision on the SRI determination, we did a series of 10 measurements averaged for 30 seconds each (total measurement time equal to 5 minutes) and we computed the mean value of the insertion loss in the different OTDR traces. In this way, the maximum error on the SRI value was computed equal to 2 10^{-3} in the ranges 1.33-1.39 and 1.43-1.45. It was equal to 3 10^{-4} in the range 1.39-1.43 where the maximum sensitivity is obtained.

Note that one can play on the tilt angle to modify the sensitivity to the SRI in a given range, as reported in [3]. For instance, with a 10° TFBG that preferentially couples the core mode to high order cladding modes characterized by small effective refractive index values, the range of maximum sensitivity can be moved to SRI values slightly above 1.30.

The pulse duration of the OTDR source dictates the number of TFBGs that can be cascaded along a single optical fiber and the fiber length that must be present between the TFBGs for a proper determination of the insertion loss. Indeed, when the pulse duration increases, as the OTDR receives more optical power, the dead zone (distance for which the OTDR is blind after having measured a strong reflection) related to the presence of the Bragg reflection in the OTDR trace increases. For that reason, more fiber length has to be present between the TFBGs for increasing pulse widths. The benefit of increasing the pulse duration is to offer the possibility of cascading more TFBGs since the dynamic range grows with the pulse duration.

We studied the impact of the pulse duration on the number of sensors that can be simultaneously addressed and on the minimum distance between the sensing points within the fiber. Fig. 6 shows the data obtained from OTDR traces measured with different pulse widths and from simulations carried out with the coupling characteristics of the 4° TFBG taken in high SRI liquid (worst case in terms of insertion loss value). It can be seen that, for a pulse duration of 100 ns as used in our experiments, 6 TFBGs can be readily cascaded between fiber sections of about 125 meters. To determine the minimum distance between the gratings, fiber lengths of 10 meters were considered at each side of the OTDR dead zone occurring at the TFBG locations. In our case, this distance yields 10 measurement points, which is sufficient to make a linear regression with an error on the determination of the slope of the order of 1 %. In practice, this does not fix the distance between the sensing points to this value since the optical fiber can be easily coiled between the TFBGs so that the sensing points can be placed close to each other. To illustrate the quasi-distributed sensing possibility, Fig. 7 shows an OTDR trace with 5 concatenated identical 4° TFBGs measured in different SRI environments.

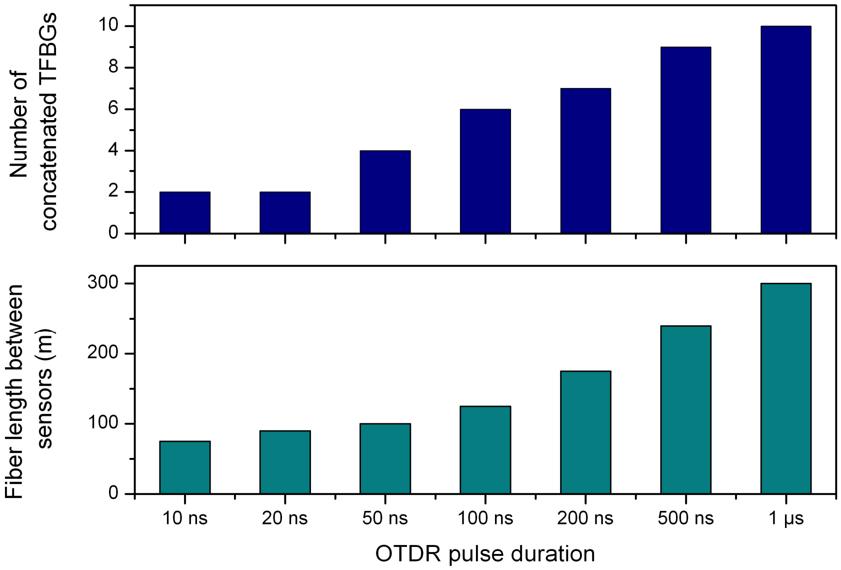

Fig. 6. Influence of the OTDR pulse duration on the quasi-distributed sensing performances.

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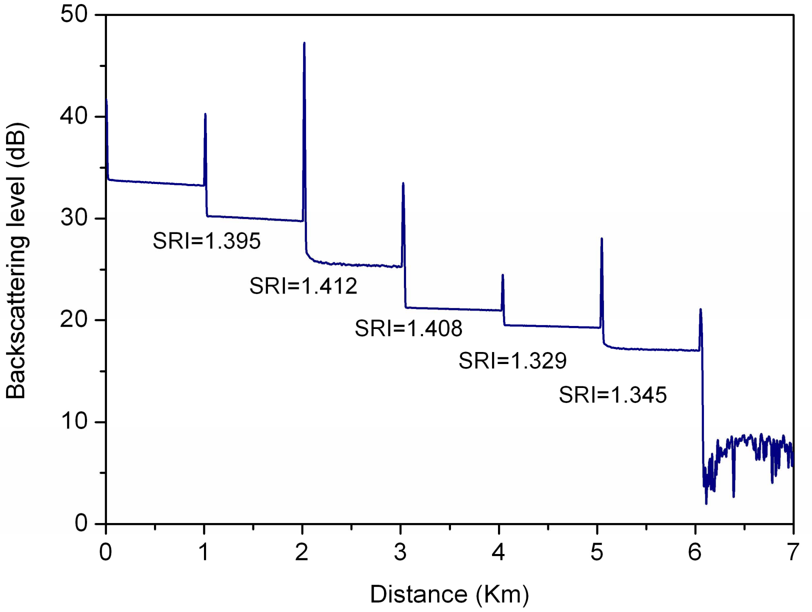

Fig. 7. OTDR trace with 5 cascaded 4° TFBG (pulse duration=100 ns, averaging time=30s, fiber length between gratings=1 km).

Let us also add that the total number of TFBGs that can be addressed simultaneously is determined in the worst case, i.e. when all the gratings are immersed in the SRI environment yielding the maximum insertion loss (SRI=1.45). This number is computed so that the last sensor of the chain fits within the dynamic range of the OTDR for a given pulse width.

The quasi-distributed sensing performances can also be tailored through the modification of the TFBGs coupling strengths by playing on the UV laser fluence received by the optical fiber during the TFBGs fabrication process. It is indeed possible to cascade more TFBGs if their coupling efficiency is reduced. A simulation has shown that up to 10 TFBGs can be observed with a pulse duration set to 100 ns if they are characterized by maximum cladding mode resonances of 3 dB (the maximum cladding mode amplitude was about 5 dB for the TFBGs used in our experiments). However, reducing the cladding modes resonances drastically affects the SRI sensitivity. Indeed, in the SRI range 1.39-1.43 (range of maximum sensitivity), the sensitivity was computed equal to only 0.36 dB/0.01 RIU. To avoid this limitation, an efficient mean to increase the number of sensing points without altering the sensitivity consists in enhancing the OTDR source power. A further improvement of the demodulation technique could be to use a long period fiber grating filter in front of the cascaded TFBGs to suppress their Bragg reflection and the corresponding dead zones in the OTDR trace. In this way, reduced fiber lengths could be used between sensing points.

During our experiments, we also verified that, under normal operating conditions, our demodulation technique is intrinsically insensitive to temperature fluctuations since the cladding modes resonances shift so slightly (~ 10 pm/^{o}C) and without modification of the shape of the envelope of the resonances [6,7]. A typical temperature-dependent measurement is shown in Fig. 8 for which the TFBG immerged in water has been measured at different temperatures. One can see that the insertion loss remains practically constant when the temperature evolves in the range between 20°C and 80°C. The maximum variation due to the temperature change has been measured equal to 0.02 dB and results from the measurement accuracy. Let us also add that, apart from very high strain values, the effect of an axial strain on the OTDR trace would be the same as for the temperature dependence.

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Finally, our technique presents the additional benefit that the measurement is inherently single-ended while most other demodulation techniques for LPG or TFBG refractometers require access to both fiber ends.

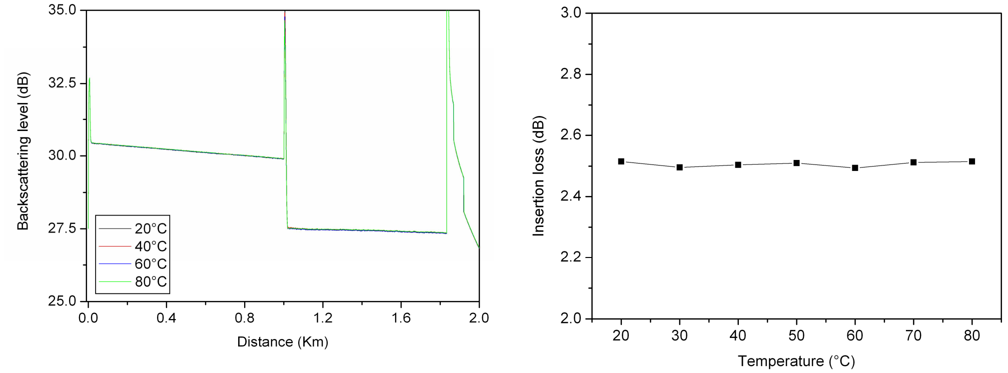

Fig. 8. Temperature influence on the OTDR trace of the 4° TFBG immerged in water (left) and evolution of the insertion loss with respect to temperature (right).

5. Conclusion

We have presented the first in-line quasi-distributed refractometer using TFBGs. In this sensor configuration, identical TFBGs are cascaded along a single optical fiber and remotely interrogated by a commercial OTDR. As the cladding modes spectrum is designed to match the OTDR source amplitude spectrum, the demodulation technique is based on the monitoring of the insertion loss at the TFBG locations in the OTDR trace. This parameter is monotonously increasing when the refractive index grows. Using a simple and low cost sensing system, up to 10 TFBGs can be cascaded along a single optical fiber, yielding SRI measurements in the range between 1.33 and 1.45 with an accuracy of the order of 10^{-3} and relative temperature insensitivity.

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