Microwave photonics filtering technique for interrogating long weak fiber Bragg grating sensors

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ABSTRACT

A system to interrogate photonic sensors based on long weak fiber Bragg gratings (FBGs) is presented and experimentally demonstrated, dedicated to measure the precise location of several spot events. The principle of operation is based on a technique used to analyze microwave photonics (MWP) filters. The long weak FBGs are used as quasi-distributed sensors. Several events can be detected along the FBG device with a spatial accuracy under 1 mm using a modulator and a photo-detector (PD) with a modest bandwidth of less than 500 MHz. The simple proposed scheme is intrinsically robust against environmental changes and easy to reconfigure.

Keywords: Fiber Bragg gratings, weak FBGs, fiber optics sensors, microwave photonics filters, discrete-time sensors.

1. INTRODUCTION

FBGs have been widely used and have rapidly developed in fiber optic-based signal processing systems and applications due to their excellent properties in terms of simplicity, low insertion loss, polarization independence, low cost and seamless integration in fiber optics systems. In addition, since FBGs are made of dielectric material, they result non conducting, immune to electromagnetic interference (EMI), chemically inert and spark free[1]. In the field of sensing application, several methods have been proposed in order to interrogate the Bragg-frequency distribution along a FBG with the aim of implementing distributed temperature/strain sensors such as frequency analysis[2] and discrete-time microwave photonic filtering technique[3], amongst others.

In this work, a technique for interrogating long weak FBGs and its potential applications to fiber sensing is described. The proposed configuration is specifically dedicated to the situation when one or more spot events must be precisely detected, such as hot spots or cracks in a structure. This technique offers several advantages since it relies on interference in the microwave domain, which is by far more stable and easier to control than optical domain methods. The fundamental concept behind the proposed technique is inspired from the operating principle of a discrete time MWP filter[4], in particular on the information on the delays between the different taps of the filter provided by measuring its radiofrequency transfer function given by the S_{21} parameter. In the previous proposed MWP filtering scheme[3], since the FBG has high reflectivity, the most important limitation arises from the fact that the system is not able to detect events having the same magnitude. In this scheme, a FBG sensing device able to detect one or more events having the same magnitude is described. The spot event positions can be evaluated with a spatial accuracy under 1 mm. To demonstrate the performance of the proposed technique two 10 cm-long weak FBGs have been fabricated as a sensing device able to detect one or more spot events located at discrete positions along the grating, with a modest bandwidth of only 500 MHz.

2. DESCRIPTION OF THE METHOD

The setup used to interrogate the sensor is depicted in Fig. 1. A continuous wave (CW) light is electro-optically modulated with a microwave signal. At the output of the electro-optical modulator (EOM) the modulated optical signal is split into N arms. Each arm contains a delay-line and an attenuator (or amplifier) in order to provide a delayed and weighted replica of the original signal. These time-delayed and weighted optical signals are combined together and photo-detected. In the detection process, the different taps can be mixed under either a coherent or an incoherent basis. In case of incoherent mixing, the tap combination at the PD is insensitive to environmental effects, stable and with a

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remarkably good repeatability. For these reasons, the experimental setup has been implemented under incoherent operation. The microwave signal is acquired and the electrical frequency response $H(\omega)$ of such a system is given by[4]:

$$H(\omega) = \sum_{k=0}^{N} a_k e^{-ik\omega T_k}. \tag{1}$$

where ω is the microwave frequency and a_k is the weight of the k-th replica that is delayed by T_k. If $T_k = T, \forall k$ Eq. (1) can be identified to a transfer function with a periodic spectral characteristic; the frequency period is known as *free spectral range* (FSR) and it is inversely proportional to the spacing T between samples[4]. This way, the response of the proposed sensor is described by Eq. (1) and the delay between two consecutive hot-spots is related to their spacing distance L by[3]:

$$T = \frac{2n_0 L}{c}. \tag{2}$$

where n_0 is the refractive index of the fiber and c is the speed of light in vacuum.

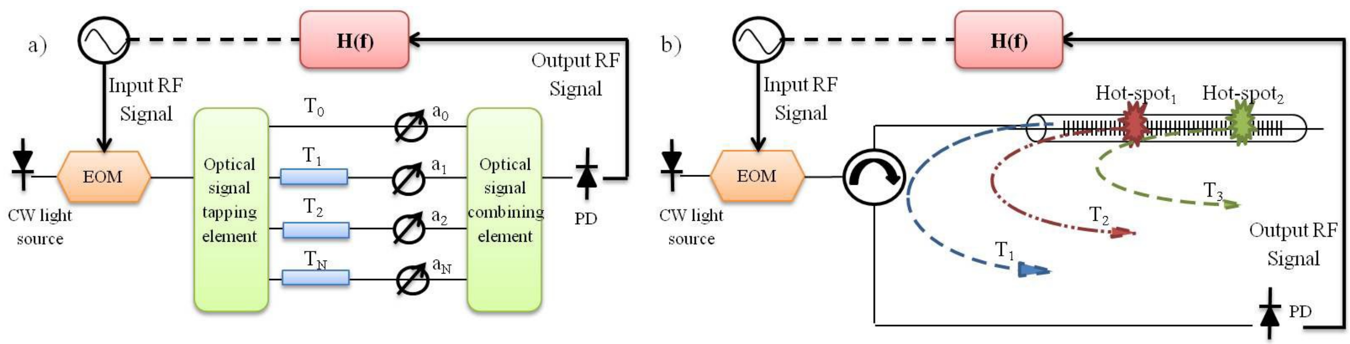

Figure 1. (a) Scheme of an N tap microwave photonic filter. (b) Schematic diagram of the proposed sensor interrogation.

3. SETUP AND EXPERIMENTAL MEASUREMENT

Experimental measurements have been performed used the setup illustrated in Fig. 2. A broadband signal provided by a semiconductor optical amplifier (SOA) is filtered using a tunable band-pass filter centered at the Bragg wavelength of the FBG sensing device, which is 1534.55 nm at room temperature. As the filter bandwidth is 1 nm, the time coherence of the filtered optical source is 8 ps[5], which dictates the smallest time spacing between hot spots to be ≈ 80 ps. This implies that the distance between spot events should be longer than 8.24 mm to maintain the conditions of the incoherent regime[5]. The output of the tunable filter is electro-optically modulated by a microwave signal generated by a vector network Analyzer (VNA), consisting of a radio frequency (RF) tone swept from 10 MHz to 500 MHz. At the output of the EOM, the signal is sent into the FBG sensor through an optical circulator. The signal reflected by the grating is photo-detected and the frequency response of the system is analyzed by monitoring the scattering parameter S_{21}, which relates the RF detected signal to the input modulating microwave signal.

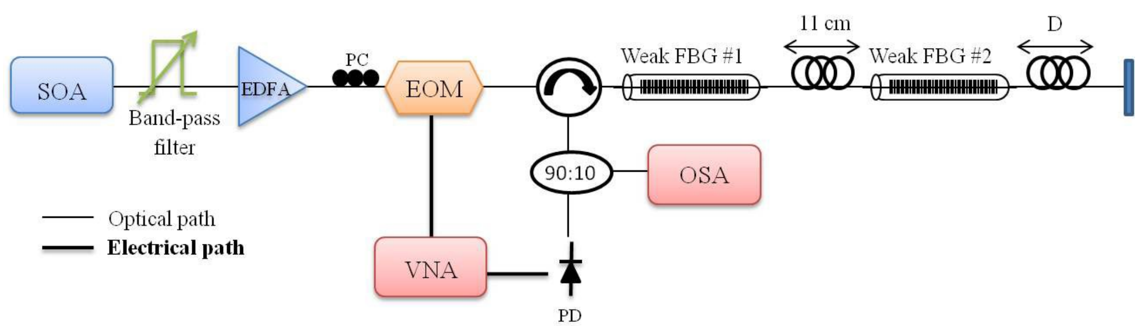

Figure 2. Schematic diagram used for interrogating a quasi-distributed sensor based on weak FBGs.

The initial idea of this experiment was to fabricate a very long weak FBG, but due to the limitations of our FBGs fabrication system, FBGs longer than 10 cm cannot actually be fabricated. Hence, as a proof-of-concept, the quasi-distributed sensor proposed is made by a pair of weak 10 cm-long FBGs (R < 6%) separated by 11 cm, while a piece of single-mode fiber (SMF) of length $D = 7.45\ m$ is appended after the second FBG. The other end of this fiber is left opened in the air to provide a reflection signal that will be used as reference tap.

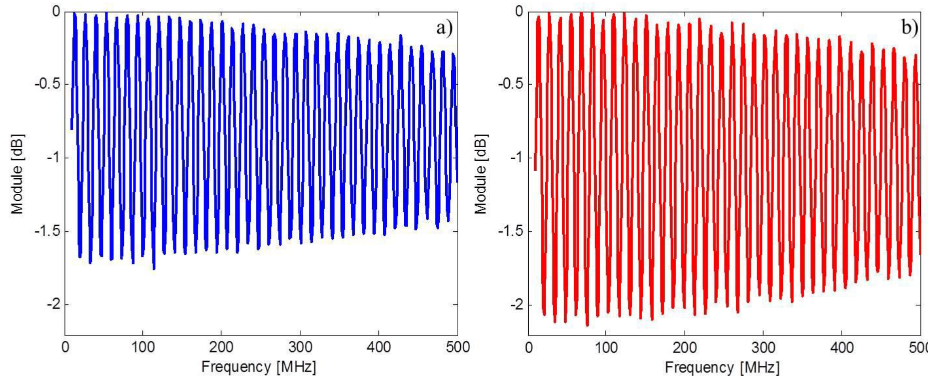

Figure 3. (a) MWP two tap filter obtained by the reference tap and the tap provided by the hot spot placed in the first FBG. (b) MWP two tap filter obtained by the reference tap and the tap provided by the hot spot placed in the second FBG.

If a 5 mm hot spot is placed in the middle point of the first grating, this will produce a local Bragg frequency shift and generate a reflected signal at the point where the hot spot is placed. At this point, by judiciously tuning the optical band-pass filter, the taps related to the original FBGs reflections are filtered out and a two tap MWP filter is actually obtained (see Fig. 3(a)) – resulting from the combination of the tap provided by the signal reflected by the hot spot and the reference tap. In the same way, if the hot spot is removed from the first FBG and placed in the middle of the second grating, another two tap filter is created, as shown in Fig. 3(b). The locations of the spot events can be obtained directly by evaluating the FSR of the filters as it is described by Eq. (2) with a spatial accuracy under 1 mm, or by using the inverse Fourier transform[3] (IFT). The distance between the end of the SMF and the hot spot placed in the first FBG is l_1=7.716 m, while the distance between the end of the SMF and the hot spot at the second grating is l_2=7.506 m.

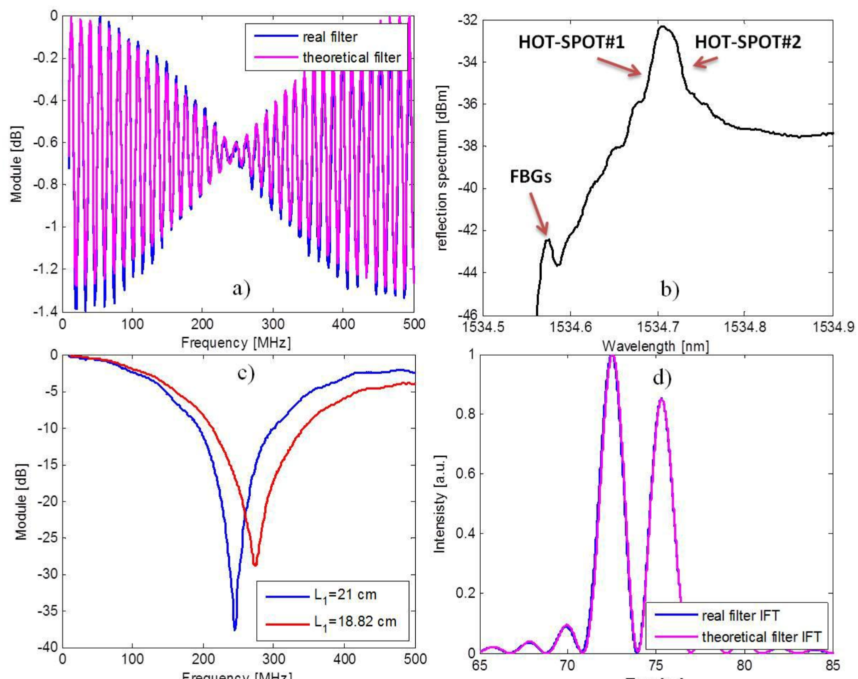

Figure 4. (a) Frequency response of three tap filters (real and theoretical). (b) Reflection spectrum acquired with the OSA. (c) Frequency response of the filters due to the presence of two hot spots. (d). IFT of the three tap filters shown in Fig. 4(a).

When two hot spots are placed in the middle of each FBG and the band-pass filter is properly tuned in order to eliminate the original FBG reflections, a three tap filter is obtained, as shown in Fig. 4(a). The positions of the two hot spots referred to the end of the SMF, evaluated by using Eq. (2), are l_1=7.716 m and l_2=7.506 m, which means that the separation between the two spot events is L_1= l_1–l_2= 21 cm, as anticipated. In order to estimate the temperature of the hot spots an optical spectrum analyzer (OSA) is used (see Fig. 3). Since a 10 pm shift in Bragg wavelength correspond to 1°C shift in temperature, the temperature shift in the hot spot zone is calculated to be ΔT= 16°C (see Fig. 4(b)).

Furthermore, the distance between the two hot spots, L_1, can be measured with more precision evaluating the FSR of the two tap filter, obtained if the reflection at the end of SMF is suppressed, as illustrated by the blue curve in Fig. 4(c). In order to eliminate this reference tap, an angled polished connector (APC) and an index-matching fluid (IMF) are now applied at the end of the SMF. This way, if the second hot spot is moved, the FSR of the two tap filter changes, as shown by the red curve in Fig. 4(c). Once calculated the FSR, the positions of the hot spots can be evaluated by using Eq. (2).

Finally, the position of the hot spots can be also measured by using the IFT[3] of the filter transfer function, as shown in Fig. 4(d). In this regard, since the filter formed by the taps concerning the spot events has just one replica (see Fig. 4(c)), the minimum detectable distance between two hot spot is more than 20 cm, if the IFT calculation method is used. Even so, it is possible to reduce this value if the number of replicas of the MWP filter is increased, either by extending the frequency range or by mathematically improving the algorithm used to calculate the IFT of the MWP filter.

4. CONCLUSION

A technique for estimating the position and number of spot events along a FBG sensor is proposed and demonstrated, based on the principle of operation of a MWP filter. The hot spot positions can be simply evaluated by using an EOM and a PD of only 500 MHz bandwidth, while the magnitude of the hot spots can be measured by means of an OSA. A pair of weak 10 cm-long FBGs is employed as a quasi-distributed temperature/crack sensor. By evaluating the FSR of the resulting MWP filter the location of two hot spots along the FBG sensor can be detected with a remarkable accuracy. In the scheme proposed, the location of the event is calculated with a 1 mm spatial accuracy, which can be potentially further improved using a higher range instrument. The former value simply indicates the potential of the method in term of accuracy that is certainly attractive in some research areas such as bio and chemical fields, among others.

The proposed configuration allows the detection and estimation of several spot events by using the IFT of the measured RF transfer function (S_{21} parameter). In this regard, since the filter formed by the taps provided by the hot spots has just one replica, the minimum detectable distance between two events should be more than 20 cm if an accuracy under 1 mm is desirable. Even so, it is possible to release this issue if the number of replicas of the filter is increased, either by extending the frequency range or by mathematically improving the algorithm used to calculate the IFT. The latter point is actually a complementary research under study going beyond the scope of this manuscript.

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