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[INVITED] Cascade FBGs distributed sensors interrogation using microwave photonics filtering techniques ☆

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ABSTRACT

Systems to interrogate photonic sensors based on long fiber Bragg gratings (FBGs) are illustrated and experimentally validated. The FBGs-based devices are used as quasi-distributed sensors and have demonstrated their ability to detect and 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 overall idea beyond this work has been borne out and demonstrated step by step starting from preliminary test that have led to the development of a very-long distributed sensor based on an array of 500 equal and weak FBGs. Firstly, we have demonstrated the feasibility of the MWP filtering technique to interrogate a 10 cm-long high reflectivity ($\approx$ 99%) FBG. Then, a pair of low-reflectivity ($<$ 6%) FBGs has been employed as sensing device. The latter has laid the foundation for the development and implementation of a 5 m-long fiber optic sensor based on 500 very weak FBGs. Spot events have been detected with a good spatial accuracy of less than 1 mm using a modulator and a photo-detector (PD) with a modest bandwidth of only 500 MHz. The simple proposed schemes result cost effective, intrinsically robust against environmental changes and easy to reconfigure.

1. Introduction

Over the years, fiber optic devices and components have became one of the core technologies in a variety of fields due to their advantageous features such as simplicity, small size, light weight, low insertion loss, low cost, and the ability to make multiple distributed measurements along the fiber length. Furthermore, since optical fibers are made of dielectric material, they prove to be non conducting, immune to electromagnetic interference (EMI), chemically inert, spark free and extraordinarily resistant to corrosive surroundings [1]. All these attractive characteristics are highly desirable for remote interrogation from long distance and/or in harsh environments. For these reasons fiber optic based devices have been broadly implemented in many sensors applications.

In the fiber optic sensing area, fiber Bragg gratings (FBGs) have been playing a key role owing to their fast response, high sensitivity, distributed and multiplexing capability of measuring different kinds of physical and mechanical parameters [2]. Furthermore, the systems employed to interrogate FBG sensors do not require very complicated setup and/or high pump power to be launched in the sensing fiber, resulting in very simple and cost-effective interrogation systems.

Different methods have been proposed and implemented in order to interrogate the Bragg-frequency distribution along a FBG with the aim of implementing distributed temperature/strain sensors. Some of these salient techniques include optical low-coherence reflectometry (OLCR) [3], synthesis of optical coherence function (SOCF) [4] and optical frequency domain reflectometry (OFDR) [5], amongst others. In this context, OLCR technique has demonstrated very good performance in terms of spatial resolution. Anyway, this scheme presents a limited measurement range and a slow response time. On the other hand, SOCF allows a point-by-point characterization of the grating properties by simply tuning the modulation frequency of the optical source. Anyway, this technique requires a very complicated setup and hence expensive devices. Finally, OFDR enables temperature and strain measurements over long ranges with very good performance but comprising a sophisticated post processing scheme and an auxiliary interferometer used to avoid any non-linearity. Moreover, the system results polarization dependent and thus requires the presence of a polarization beam splitter and two separate photodetectors (PDs) to mitigate signal fading.

FBG sensors normally only supply information at discrete point, hence FBGs-based devices have been usually employed to perform highly sensitive discrete point sensing. Nevertheless, practical applications require fully distributed sensing in which the entire length of the fiber generates information [6,7]. Regarding this, fiber distributed sensing based on very-weak reflectivity FBG has been demonstrated using optical time-domain reflectometry

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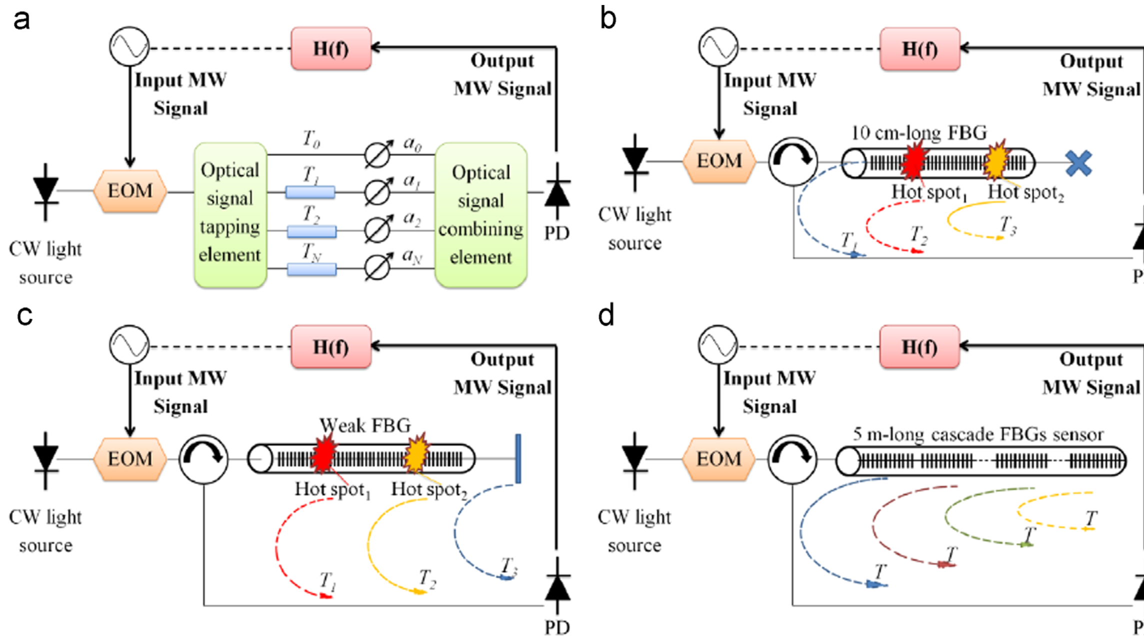

Fig. 1. (a) Schematic diagram representing an N tap MWP filter configuration. (b) Schematic layout implemented for interrogating the 10 cm-long high reflectivity FBG. (c) Schematic layout for interrogating the fiber optic sensor based on a pair of weak FBGs. (d) Schematic diagram for interrogating the 500 weak FBGs cascade sensor.

(OTDR) [8]. By scanning the laser frequency a distribution map of the reflectivity along the fiber has been obtained, demonstrating very good performance in terms of accuracy and signal response.

In this contribution, a technique to interrogate long FBGs and its potential applications to distributed fiber sensing is proposed and demonstrated. The fundamental concept for this approach is inspired on the operation principle of a discrete time microwave photonic (MWP) filter [9–11]. MWP is a discipline which collects together the field of microwave engineering with optoelectronics. Both microwave and optoelectronics obey to the same electromagnetic laws and then presents common features but also significant differences. In microwave domain, due to the large wavelength of microwave, construction of an interferometric structure does not require a precision as high as that needed by an optical interferometer. Moreover, microwave interferences can be more easily resolved than the optical interference in which the detecting devices are not fast enough to follow the very high optical frequency. For these reasons, the proposed technique brings several advantages derived from the fact that it relies on interference in the microwave rather than optical domain. Microwave interferometry is by far more stable and easier to control and, if suitably combined with photonics, provides a remarkable spatial accuracy. Furthermore, the system spectral performance can be easily reconfigured, since the sensor is based on a discrete time filter configuration. Thus, the methodology presented involves exploiting the best advantages brought by two symbiotic technologies: microwaves and photonics. Relying on microwave interferometry and working under incoherent operation, the configuration proposed is intrinsically robust against environmental changes, stable and with good repeatable performance [9–11]. Finally, this technique is potentially low cost as it is based on low bandwidth radio-frequency and off-the-shelf photonic components rather than on ultra-short pulses, optical interferometry or OFDR techniques.

The proposed technique is specifically suited when a spot event must be precisely identified and located, such as hot-spots or cracks in structures. The overall idea beyond this work has been borne out and demonstrated step by step starting from preliminary test that have led to the development of a very-long distributed sensor based on an array of weak FBGs. To get started, we have demonstrated the feasibility of the MWP filtering technique to interrogate a grating by using a 10 cm-long high reflectivity FBG as sensing device. Such a system proved to be able to detect several spot events with spatial accuracy less than 1 mm [12]. However, in this case since the FBG used as a quasi-distributed sensor has high reflectivity ($\approx 99\%$), the most important limitation arises from the fact that the system is not able to detect events having the same magnitude. Thus, to overcome this limitation a pair of low-reflectivity ($< 6\%$) FBGs has been employed as sensing device. With this configuration, several events have been detected with a spatial accuracy of less than 1 mm using a modulator and a photo-detector (PD) with a modest bandwidth of less than 500 MHz [13]. The latter has laid the foundation for the development and implementation of a long fiber optic sensor based on very weak FBGs (reflectivity ≈ 0.001). Hence, we have proposed and validated a distributed sensor consisting of a 5 m-long fiber, containing 500 equal 9 mm-long Bragg gratings. The detection of spot events along the sensor has been demonstrated with remarkable accuracy under 1 mm, using a PD and a modulator with a bandwidth of only 500 MHz [14]. All these sensors prove to be simple, robust, polarization insensitive and allow a lowering of the instrumentation complexity for distributed sensing applications.

2. Description of the method

The fundamental concept beyond the proposed methodology is inspired on the principle of operation of a MWP filter and is depicted in Fig. 1(a). The output of a continuous wave (CW) light source 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 has 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 according to 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 remarkably good