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A cost-effective edge-filter based FBG interrogator using catastrophic fuse effect micro-cavity interferometers

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ABSTRACT

This paper proposed an inexpensive high contrast in-line micro-cavity interferometer for edge-filter strain and temperature interrogation of a fiber Bragg grating sensor. The simulation model is presented in order to describe the sensor behavior which strongly agrees with the experimental results with a mean error lower than 0.04%. The results show evidences of high repeatability and stability achieved in measurements of strain and temperature from 0 to 1440 μStrain and 5 °C to 50 °C, respectively.

1. Introduction

Optical fiber sensors (OFSs) have been developed and used broadly for physical and chemical measurement such as strain, temperature, pressure, and reflective index. OFSs bear important features such as intrinsic safety, resistance to chemical corrosion, immunity to electromagnetic interference, electric isolation, small size, lightweight sensing heads, high resolution, easy multiplexing, and capability for extremely remote monitoring [1,2]. Among the OFSs, fiber Bragg gratings (FBG) backscattered spectrum shifts are by far the most used for measuring temperature and/or mechanical strain [3,4]. Nonetheless, interrogation system are the most important drawback for their large commercial application, due to their high cost. Therefore, the development of new, and lower cost, interrogation alternatives are essential [5].

FBG sensor spectrum is usually monitored either by an optical spectrum analyzer (OSA) or a commercial FBG interrogator system. For real-time application in industry, the OSA is not suitable due to trade-offs between resolution and sweep frequency; not to mention OSA cost, volume and weight [6]. Commercial OFS interrogators (designed based on scanning laser or scanning filters) are able to probe the FBG spectrum with higher resolution. But, they become extremely expensive whenever hundreds scans per second are required [7,8].

An alternative technique for fast and inexpensive FBG interrogation is the frequency-to-amplitude conversion of edge-filtering, where the FBG spectrum goes through a slightly detuned broader filter. This role is usually performed by a Fabry-Perot filter. In this technique, FBG's spectral variations are straightforwardly translated into optical power variations [9,10]. Standard FBG used as edge-filter shows high sensitivity [7,11,12]. A fast interrogation technique based on the fusion of both time and wavelength division multiplexing is reported in [13], where matched FBGs-based technique is employed to interrogate several FBG sensors. The main advantages of this approach are no temperature cross-sensitivity and high sensitivity on the measurements however, very limited dynamic range is an inherent characteristic due to the limited bandwidth offered by the matched FBGs used as edge-filter. Tilted FBG (TFBG) required a special treatment in order to get a high visibility [14]. Chirped FBG (CFBG) has higher bandwidth than standard FBGs improving the interrogation dynamic range [15]. Long period gratings exhibit large dynamic range which would limit measurement accuracy and specially the number of sensors which can be multiplexed [16–18]. In [5], it is proposed an interrogation scheme based on Erbium doped fiber (EDF) edge-detection filter, where issues related with temperature dependence are avoided. However, 10 m of EDF is required to create the filter and the dynamic range is limited to a specific spectral region (1545–1555 nm), where the slope filter is around 1 dB/nm. A tunable Mach-Zehnder interferometer (MZI)-based technique is presented in [19] and 1.5 m of MMF allows a free spectrum range (FSR) of 6 nm, with a visibility of 2.8 dB. The above techniques present edge-filters with low visibility leading to low sensitivity translated into poor signal-to-noise-ratio (SNR). A simple approach is

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presented in [20], in which an optical whispering gallery mode edge-filter is performed. An etched standard SMF is bended in small radius coupling the core mode to the cladding modes leading to an interference pattern between them. In this method it is expected a high sensitive to external refractive index changes because the fiber cladding (without coating protection layer) is completely exposed to external environment, which would lead to erroneous measurements as variations on the surrounding environment induce a spectrum dip shift. In addition, low sensitivity could be achieved because the large slope.

A trade-off between dynamic range and sensitivity is an inherent characteristic in the edge-filter schemes. However, filters with high visibility enhance the filter slope improving both the sensitivity and the optical SNR. A Fabry-Perot interferometer (FPI) is a good candidate to lead with this issues, nevertheless, tunable FPI are an expensive alternative when compared with the aforementioned schemes. Different techniques have been proposed to construct FPIs [21,22]. Femtosecond (fs) laser micromachining method allows high accuracy but requires an expensive infrastructure. Diaphragm-based extrinsic FPI, or photonic crystal fiber-based fabrication are rather complicated and high cost methods. This paper presents a simple, compact, stable and inexpensive in-line solution based on catastrophic fuse effect micro-cavity interferometers [23,24]. FGB strain and temperature measurements are then presented to demonstrate, for the first time, the potential of these high contrast micro-cavities for building interrogation systems with high stability and repeatability.

This paper is organized as follows. Section 2 presents the operating principle, the sensor design and the mathematical model, also the spectra simulation of both the FPI and the FBG sensors and the interrogator system behavior simulation are reported. Section 3 describes the experimental setup used to evaluate the proposed sensor interrogator response. In Section 4 the experiments are performed and results for temperature and strain characterization are presented. Finally, the main conclusions are drawn in Section 5.

2. Operation principle

The principle of operation of the low cost FBG interrogator is depicted in Fig. 1. The proposal setup is based on an amplified spontaneous emission (ASE) broadband light source (BBS) from 1520 nm to 1580 nm, one optical splitter 90/10, two optical circulators, one Peltier with its temperature controller (TEC), and two optical power meters (OPMs). The ASE signal is launched to the splitter, where 10% of the optical power is acquired by the first OPM which is used as a reference signal to compensate the ASE's fluctuations. The other 90% of optical power is launched into the FBG by using an optical circulator. The backscattered spectrum from the FBG is coupled to the in-line FPI by using a second optical circulator. Thus, the resulting optical power (Output), after crossing both the FBG and FPI, is detected by a second OPM. The in-line FPI micro-cavity is housed in a cooper structure to reduce external mechanical deformation and vibration. This special micro-cavity conveniently shows low temperature sensitivity compared

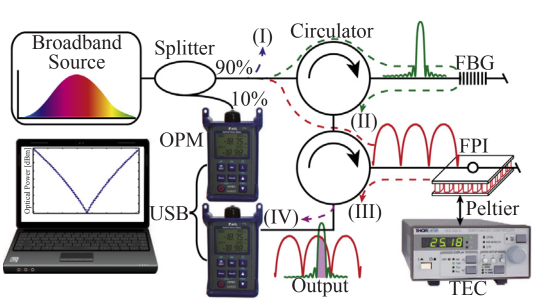

Fig. 1. Setup for FPI-based low cost FBG interrogator. OPM: optical power meter, USB: universal serial bus, FBG: fiber Bragg grating, FPI: Fabry-Perot interferometer, TEC: thermoelectric controller.

to FBG's [23] regarding wavelength shift features. However, a temperature control is used to improve the interrogation accuracy of this FPI-based method. Therefore, only the FBG will be exposed to external perturbations, which induces fiber Bragg wavelength shifts, which will be translated into output optical power variation by the FPI.

3. Interrogator experimental implementation and analytical modeling

A photosensitive single mode fiber (ThorLabs GF1B) was used to record the uniform FBG sensor using the phase mask technique with a KrF UV Excimer laser emitting at 248 nm (BraggStar Industrial model from Coherent). The FBG was inscribed with 5 mJ energy pulses and a repetition frequency of 500 Hz. A 10 mm length FBG was selected to get more than 90% of reflectivity [25]. The FPI micro-cavity was fabricated with a similar process presented in [23]. A commercial fusion splice machine (Fujikura FSM-40S), a standard single mode fiber (Corning SMF-125/9) and a fiber previously destroyed by the catastrophic fiber fuse effect (Corning SMG-652), were used to make the micro-cavity [26,23]. In order to produce the fiber fuse effect, a Raman fiber laser (IPG, Model RLR-10-1480) at 1480 nm with 3 W of optical power was used. The parameters used in the splicing machine to fabricate the micro-cavity have been optimized to an arc power of 20 mA (20-bits), during 3 s. The fabrication process is simple and inexpensive when compared with other FPI micro-cavities production methods [21,22].

The fabrication process is divided into 4 steps. First, the fusion splicing between a standard SMF and a fiber damaged by the fuse effect is performed (see Fig. 2(a)). As a result, a large cavity with drop shape is obtained (see Fig. 2(b)). The next step is to cleave this cavity and splicing it with a second standard SMF as depicted in Fig. 2(c). In order to facilitate the identification of the location bubble and its cleaving process a microscope was used. This step has a big influence over the resulting micro-cavity shape (see Fig. 2(d)). Thus, if the cleaved bubble is small, as a result, a small micro-cavity will be obtained. However, the micro-cavity size can be increased by exposing the bubble to additional arcs, thus the FSR can be controlled. On the other hand, the visibility is strongly dependent on the mirrors shape (transversal walls of the cavity) which usually are concave structures, thus, for maximum visibility the cavity length L needs to be approximatively equal to the curvature radius of the two surfaces on the ellipsoidal cavity [27]. By

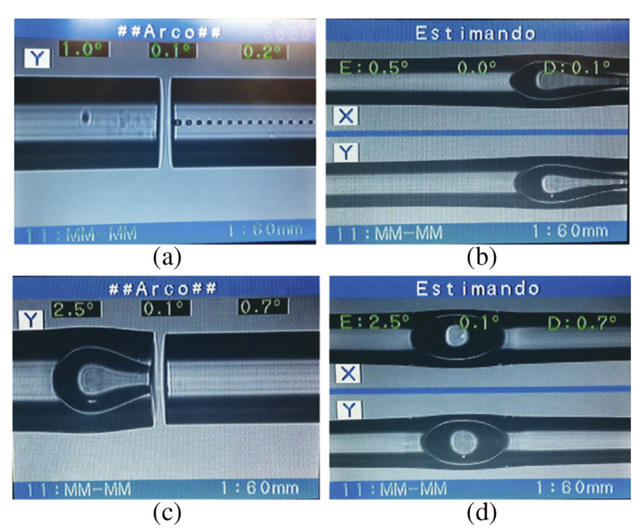

Fig. 2. FPI micro-cavity fabrication process. Pictures took from the splicing machine FSM-40S. (a) Splicing process between a standard SMF and a fiber destroyed by the catastrophic fuse effect, (b) a cavity with drop shape after fusion splicing between the SMF and the recycled fiber, (c) splicing process between the cleaved cavity with drop shape and a standard SMF, and (d) typical resulting FPI micro-cavity after splicing process.