# High-birefringence fiber loop mirror sensor using a WDM fused fiber coupler

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An intensity-based highly birefringent (Hi-Bi) fiber loop mirror (FLM) sensor is proposed which uses a wavelength-division multiplexing (WDM) fiber coupler. The effect of integrating the WDM coupler in a FLM configuration is first studied. A section of Hi-Bi (bow-tie) fiber of length 0.26 m is then placed in the fiber loop, making the spectral response of the device simultaneously dependent on the Hi-Bi fiber section and WDM coupler characteristics. When strain is applied to the sensing head, the spectral signal is modulated in amplitude, in contrast with the conventional Hi-Bi FLM sensors in which there are wavelength shifts. The sensor was characterized in strain and a sensitivity of $(-2.2 \pm 0.4) \times 10^{-3}$ $\mu\varepsilon^{-1}$ for a range of 300 $\mu\varepsilon$ was attained. The self-referenced character of the sensor is noted. © 2013 Optical Society of America

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A conventional fiber loop mirror (FLM) is formed by splicing the output ports of a directional fiber coupler [1]. A typical FLM sensor configuration consists of placing a piece of highly birefringent (Hi-Bi) fiber inside of the fiber loop for use as sensing head [2]. The interfering clockwise and anticlockwise propagating optical fields in the fiber loop form a comb-like spectrum at the output port. The spectrum is dependent on the birefringence and the length of the Hi-Bi fiber. The peak wavelengths and the period of the spectrum are changed when the Hi-Bi fiber section is subjected to external physical parameter variation.

Several types of sensors based on this configuration have been developed over the last decade and applied to the measurement of different types of physical parameters, namely: strain [3], temperature [4], refractive index [5], and others [6]. Recently, different topologies were proposed for simultaneous measurement of strain and temperature [7] or temperature-independent strain measurements [8]. In the last year new interrogation systems were demonstrated for use in these types of sensors. One of them consists of reading an amplitude variation and a wavelength shift when two FLMs are concatenated and one is used as a reference signal and the other as a sensing head [9].

The fiber coupler used in these configurations is a fused bitapered fiber coupler fabricated in a region of parameters that make it essentially wavelength insensitive. For other applications, however, the wavelength dependence of the fused coupler is explored like in wavelength-division multiplexing (WDM) for optical communication networks. Here, the wavelength response of the coupler is the central feature and the fabrication is made with the purpose of providing narrow wavelength channels [10].

In this paper, such a wavelength-division fiber coupler is integrated in a Hi-Bi FLM configuration for sensing application. First, the WDM coupler is studied and analyzed as part of a FLM configuration. Then, after the insertion of a Hi-Bi fiber section, it is explored as strain sensor.

The WDM fiber coupler used was made by fusing and tapering two single-mode fibers over a small region where light from one fiber leaks partly into the other. The power output of a WDM coupler is given by the geometry of the coupling region (coupling length, the proximity of the fibers) and the operating wavelength.

The WDM device has two input ports (1, 2) and two output ports (3, 4). Optical power from a broadband light source was launched into one of the input ports (1) and measured at the output ports using an optical spectrum analyzer (OSA) with a resolution of 0.01 nm. The output signals are shown in Fig. 1. The signals observed in bar and cross states have a period of around 17.5 nm and a phase difference of $\pi/2$. A splice was performed between the two output ports forming a FLM configuration. The output signal is now measured at port 2 and is a combination of the two previous signals (Fig. 1). The period of the spectrum is now halved (8.7 nm), the visibility is approximately the same, and the loss increases. This signal is independent of the loop length and therefore of applied strain. When integrated in a sensor it can be used as a reference signal. The transmission maxima are obtained at the wavelengths corresponding to the bar and cross states maximum transmission. The transmission minima are located in the middle of the maxima and correspond to destructive interference. At these wavelengths the fiber loop acts as a mirror.

A simple interpretation of these results is made as follows:

if $E_1$ is the electric field generated at port 1, then at output ports 3 and 4 one obtains [1]

$$E_3 = E_1 \cos \kappa z, \quad E_4 = iE_1 \sin \kappa z, \tag{1}$$

where $\kappa$ and $z$ are the coupling coefficient and propagation distance. The coupling coefficient can here be taken as an approximately linear function of the wavelength. The corresponding optical powers in the two output ports are given by

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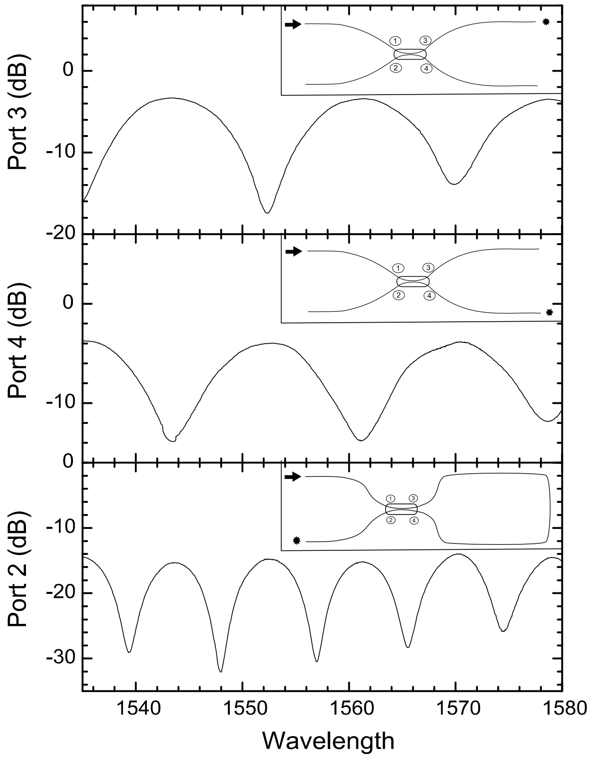

Fig. 1. Light is launched into port 1 and measured at ports 3 and 4. After forming a FLM, the transmissivity was measured at port 2.

$$P_3 = P_1 \cos^2 \kappa z, \quad P_4 = P_1 \sin^2 \kappa z. \tag{2}$$

The fields $E_3$ and $E_4$ from Eq. (1) now propagate through the loop, clockwise and counterclockwise, respectively, interfering on re-entering the coupler. The new output field and optical power are given by

$$E_2 = E_1[\cos^2 \kappa z + (i \sin \kappa z)^2] = E_1 \cos(2\kappa z), \tag{3}$$

$$P_2 = P_1 \cos^2 2\kappa z. \tag{4}$$

The previous equations describe the behavior of the WDM in an ideal case and show that the frequency of the spectrum in a fiber loop configuration is doubled when compared with those formed at the output ports 3 and 4.

The periods of these spectra are solely determined by the WDM coupler characteristics. There are some intrinsic losses to the coupler that are more relevant in the FLM configuration, since the light travels through the WDM coupler twice.

A Hi-Bi fiber section was spliced between the output ports of the WDM coupler, together with a polarization controller. This is the usual Hi-Bi FLM sensor with the single difference of the kind of coupler used. Figure 2 presents the sensor using the WDM. The Hi-Bi fiber section used was a bow-tie fiber of length $L = 25.5 \pm 0.1$ cm and a birefringence $\beta \sim 4.35 \times 10^{-4}$. Figure 3 shows the measured signal observed in the OSA equipment. In a conventional Hi-Bi FLM a well-defined comb-like spectrum would have formed due to the difference in phase imparted to different polarization fields crossing the bow-tie fiber. In this case, the signal presents the combination between the wavelength responses of the WDM (high frequency ~8.7 nm) and the Hi-Bi FLM (low frequency ~21 nm).

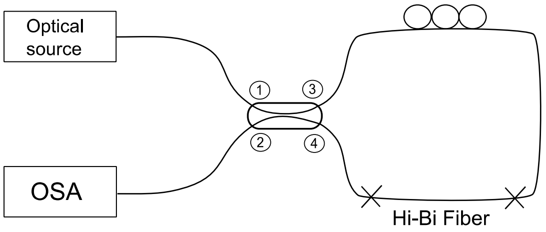

Fig. 2. FLM sensor with WDM, Hi-Bi fiber section, and a polarization controller.

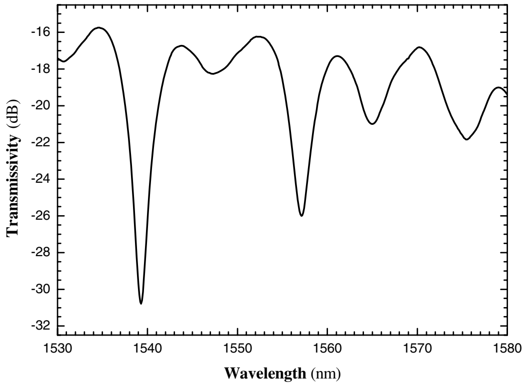

Fig. 3. Spectral response of the sensing configuration.

The spectral behavior of this new configuration was analyzed in the case of applied strain. The characterization was made by gluing the bow-tie fiber section to a micrometric translation stage with resolution of 2 μm. Figure 4 presents the response when the Hi-Bi fiber section is subjected to strain.

When strain is applied, the device presents an amplitude variation. At the spectra maxima the light is present at only one of ports 3 and 4 and no interference is possible. The traditional Hi-Bi FLM spectrum is thus sampled by the response of the WDM. The periodicity

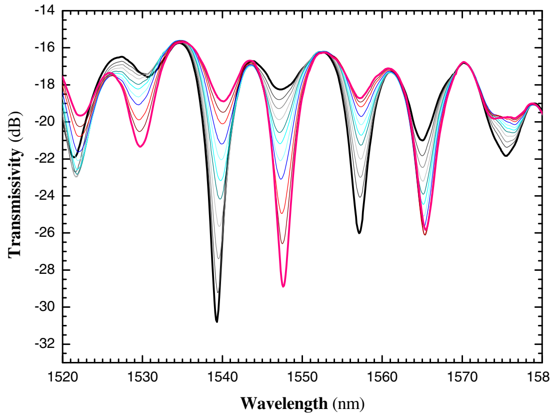

Fig. 4. Transmissivity of the FLM configuration as a function of the wavelength. Different color lines correspond to a difference in applied strain. From black to pink there is a gradual increase of strain with increments of about 25 με.

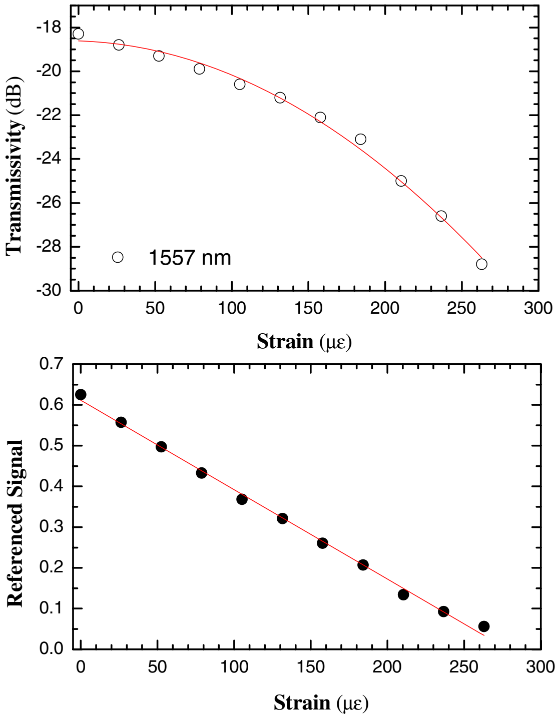

Fig. 5. Response of the sensing head at 1557 nm and the referenced signal.

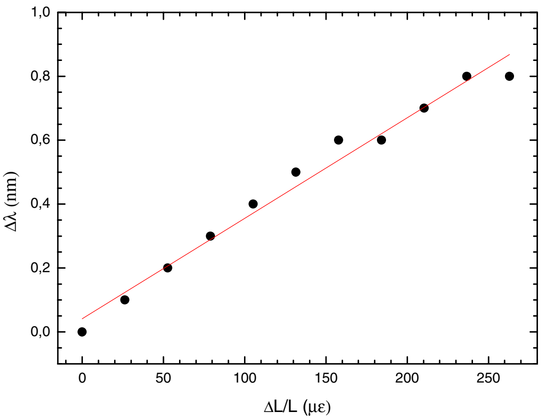

Fig. 6. Wavelength shift of the transmissivity minimum at 1359 nm as a function of applied strain.

is the same as in the FLM of Fig. 1. In a conventional 3 dB coupler FLM the applied strain would result simply in a wavelength shift of the spectrum. With the inclusion of the WDM, such shift is translated to a change in intensity at a specified wavelength. No appreciable output fluctuations were observed during the repeated measurements. The signal amplitude measured at 1557 nm wavelength was selected and displayed as function of the applied strain (Fig. 5). It is then referenced to the optical power of the peak at 1553 nm and plotted on a linear scale. The sensor then presents a linear sensitivity of $(-2.2 \pm 0.4) \times 10^{-3}\ \mu\varepsilon^{-1}$ for a range of 300 με. In this case, the source fluctuation is eliminated. However, for a large range of strain measurement it is expected to present a sinusoidal response typical of the pattern fringe obtained by the sensing head. This response was observed in the literature concerning the use of two FLMs concatenated [9] or in figure-eight configuration [11].

Despite the maxima of transmissivity being fixed, the minima have a measurable shift. The minima at 1539 nm presented a linear behavior with a sensitivity of $3.15\ \mathrm{pm}\,\mu\varepsilon^{-1}$ (see Fig. 6). This means that the sensor may allow for both kinds of measurement. The immediate advantages of a WDM FLM come from the transition from a sensor involving the measurement of shifts in the spectrum to a simpler intensity-based sensor.

The other clear advantage is the provision of an incorporated reference signal. Further applications of the concept should make clearer its potentialities.

In summary, a strain sensor based on a Hi-Bi FLM configuration using a WDM coupler was demonstrated. The WDM coupler in a FLM configuration was analyzed and it was shown that the period of the formed spectrum is half of the one at the ports 3 or 4 of the coupler. The substitution of the usual wavelength-insensitive fused coupler for a WDM coupler leads to an amplitude variation and a low-cost, intensity-based Hi-Bi FLM sensor. The combination of two components (WDM and Hi-Bi FLM) allows one to have a reference signal, provided by the WDM. The substitution for a WDM coupler can be done on any type of FLM configuration for the measurement of physical parameters with a reference signal.

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