

# Theoretical and Experimental Results of High-Birefringent Fiber Loop Mirror With an Output Port Probe

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(Invited Paper)

**Abstract**—Theoretical and experimental results of three different high-birefringent fiber loop mirrors with output ports are analyzed. For theoretical model, the Jones matrix analysis is used. The theoretical studies present similar results for all experimental configurations. The last configuration is tested as an interrogation system where the spectral response arises from the combination of the reference signal modulated by the sensor signal. The configuration is characterized in strain with the phase changes recovered from two quadrature phase signals, providing a sensitivity of 16 mrad/ $\mu\epsilon$  with a resolution of 1.9  $\mu\epsilon$ .

**Index Terms**—High-birefringent fiber loop mirror (Hi-Bi FLM), interferometer, optical fiber sensor, strain.

## I. INTRODUCTION

SINCE the end of the 1980s, the fiber loop mirror (FLM) has been shown to be an attractive device for optical fiber sensing [1]. The loop mirror is made up of a splice between the output ports of one directional optical coupler. In this case, the two waves travel with identical optical paths in opposite directions and a constructive interference is assured when the waves reenter the coupler. Afterward, all light is reflected back into the input port, while no light is transmitted to the output port. The reflectivity is limited by the losses of the splice, fiber, and coupler. When a section of highly birefringent (Hi-Bi) fiber is spliced inside the FLM, a path imbalance is introduced as

a consequence of propagation of light along different polarization eigenaxis, and thus, an interferometric channeled spectrum is observed. This configuration is an unbalanced Sagnac interferometer. The fiber birefringence and the fiber length inside the loop determine the channel separation of the pattern fringe [2]. Over the last decade, several high-birefringent fiber loop mirrors (Hi-Bi FLM) applications as sensors have been reported, through the inclusion of different types of Hi-Bi fibers [3]. Besides the gyroscope application [4], the Hi-Bi FLM has been used in temperature [2], [5] and strain [6] measurement, liquid level [7], displacement sensing [8], and refractometers [9], as well as a spectral filter for fiber Bragg grating demodulation [10]. Furthermore, the Hi-Bi FLM combined with other optical devices was also demonstrated for simultaneous measurement of strain and temperature [11]. Preliminary works using a Hi-Bi FLM with an output port probe were recently demonstrated [12]. These configurations presented similar sensitivities to strain when compared with the conventional Hi-Bi FLM. One of the configurations was used as refractometer using the Fresnel reflection [12].

In this paper, the authors present a theoretical model of three different Hi-Bi FLMs with an output port configuration. The last experimental setup is studied as a strain sensor using a reference signal to reconstruct the phase signal of the sensor.

## II. THEORETICAL ANALYSIS

Three configurations of Hi-Bi FLMs are schematically shown in Fig. 1. They consist of a loop of optical fiber formed between the output ports of two directional couplers along with an output port probe. The input light, constituted by one wave, travels from the optical source towards the first optical coupler (input port 1) and splits in two waves with half power, each traveling from output ports 3 and 4, following different optical paths. One arm of the FLM has a polarization controller (PC). The two waves couple into the second optical coupler for the output port 7 and reach the mirror. Afterward, they are reflected and arrive to the port 7, where the two waves are separated once more by the second optical coupler. Four waves are thus obtained at the output ports of the second coupler. Two waves are combined in the first coupler with opposite directions and the same optical path. Half of the light is then reflected back into the input port. This behavior is similar to the conventional Hi-Bi FLM [1]. The

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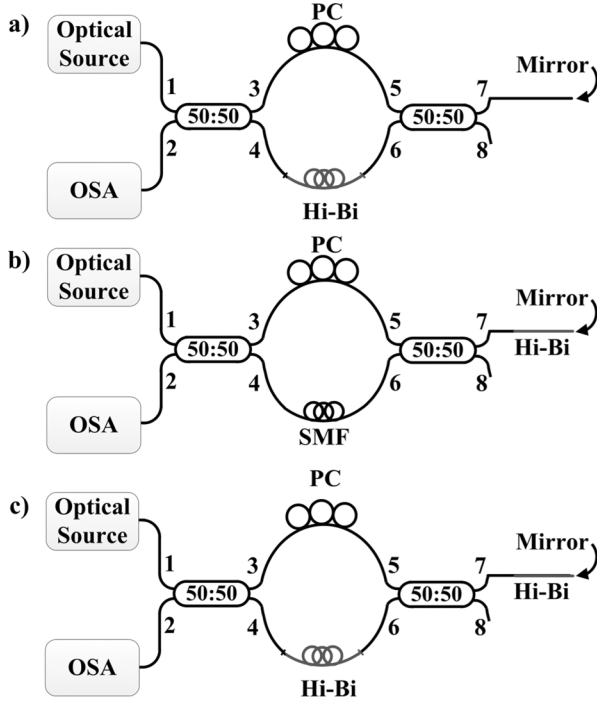


Fig. 1. Schematic setup for the (a) first, (b) second, and (c) third new Hi-Bi FLM configurations.

other two waves have a different optical path resulting into a channeled spectrum with a short periodicity not resolved by the optical spectrum analyzer (OSA), which reads only the averages powers of these waves. The difference between the three configurations was the localization of the Hi-Bi fiber section. In the first configuration [see Fig. 1(a)], it was placed between the two couplers, while in the second one [see Fig. 1(b)], in the output probe. The last configuration consisted on the combination of the first and second setups.

In this study, the Jones matrix analysis was used to calculate the transmission field. The Hi-Bi fiber section used in the first configuration [see Fig. 1(a)] had a length of 0.36 m. An equivalent optical circuit of the first configuration proposed is shown in Fig. 2(a). The Jones matrix analysis of the transmission field of the first configuration is expressed as

$$E_{\text{OUT}} = \{[K_I][J_{\text{HB}}][K_C] + [K_C][J_{\text{PC}}][K_I]\} \times [J_M] \times \{[K_C][J_{\text{HB}}][K_C] + [K_I][J_{\text{PC}}][K_I]\} E_{\text{in}} \quad (1)$$

with

$$[J_{\text{HB}}] = \begin{bmatrix} e^{j\beta_e L} & 0 \\ 0 & e^{j\beta_o L} \end{bmatrix}, \quad [J_M] = \begin{bmatrix} 10 & \\ & 0 - 1 \end{bmatrix} \quad (2)$$

$$[J_{\text{PC}}] = \begin{bmatrix} \cos \theta - \sin \theta & \\ \sin \theta \cos \theta & \end{bmatrix} \begin{bmatrix} e^{j\Gamma(\lambda)/2} & 0 \\ 0 & e^{j\Gamma(\lambda)/2} \end{bmatrix} \times \begin{bmatrix} \cos \theta \sin \theta & \\ -\sin \theta \cos \theta & \end{bmatrix} \quad (3)$$

where  $[J_{\text{HB}}]$ ,  $[J_M]$ , and  $[J_{\text{PC}}]$  are the Jones matrices of the Hi-Bi fiber, the mirror, and the PC, respectively. Here, the propagation constants along the  $e$  axis and  $o$  axis of the Hi-Bi fiber are represented by  $\beta_e$  and  $\beta_o$ , respectively, and the length of the Hi-Bi fiber is expressed as  $L$ . Based on the birefringence of the

Hi-Bi fiber  $B = (n_e - n_o)$ , the difference between the propagation constants is  $\beta_e - \beta_o = 2\pi B/\lambda$ .  $\Gamma$  is the retardance and  $\theta$  is the orientation of the wave plate axes with respect to the laboratory coordinates. The others matrices are given by

$$[K_I] = [K_{1,3}] = [K_{5,7}] = [K_{4,2}] = \begin{bmatrix} \sqrt{0.50} & \\ & 0\sqrt{0.5} \end{bmatrix} \quad (4)$$

$$[K_C] = [K_{1,4}] = [K_{6,7}] = [K_{3,2}] = \begin{bmatrix} j\sqrt{0.50} & \\ & 0j\sqrt{0.5} \end{bmatrix} \quad (5)$$

where  $[K_I]$  and  $[K_C]$  are the in-coupling and cross-coupling matrices, respectively, for the 3 dB optical coupler. The theoretical result of the first configuration is shown in Fig. 3(a) and is in concordance with the experimental results. At the second configuration, as shown in Fig. 1(b), the Hi-Bi fiber with the same length of the first configuration was laid in the output probe. There were 2 m of single-mode fiber (SMF) instead of Hi-Bi fiber, when comparing with the first configuration. The equivalent optical circuit of the second configuration is shown in Fig. 2(b), where the Jones matrix analysis is expressed as

$$E_{\text{OUT}} = \{[K_I][J_{\text{SMF}}][K_C] + [K_I][J_{\text{PC}}][K_I]\} \times [J_{\text{HB}}] \times [J_M] \times [J_{\text{HB}}] \times \{[K_C][J_{\text{SMF}}][K_C] + [K_I][J_{\text{PC}}][K_I]\} E_{\text{in}} \quad (6)$$

$$[J_{\text{SMF}}] = \begin{bmatrix} 10 & \\ & 01 \end{bmatrix} e^{i\Delta\varphi} \quad \text{and} \quad \Delta\varphi = \frac{2\pi n\Delta L}{\lambda} \quad (7)$$

where  $n$  is the fiber core refractive index of the SMF and  $\Delta L$  is the difference of fiber length between the two arms of the loop. The simulated Hi-Bi fiber effect in the second configuration is shown in Fig. 3(b). Similar theoretical and experimental results were obtained. The simulation results of the visibility variation using the PC in the second experimental setup are shown in Fig. 4.

In Fig. 2(c), an equivalent optical circuit is presented for the proposed FLM interferometer shown in Fig. 1(c). This configuration is practically the same as the second one, only  $[J_{\text{SMF}}]$  and  $[J_{\text{HB}}]$  are replaced with  $[J_{\text{HB}_R}]$  and  $[J_{\text{HB}_S}]$ , respectively. The  $\text{HB}_R$  and  $\text{HB}_S$  correspond to the reference and sensor Hi-Bi fibers, respectively. The transmission spectra simulation results are shown in Fig. 5(a) for the sensor without the reference signal. Fig. 5(b) exhibits the spectral response for the sensor combined with the reference signal. Comparing the two first results, the theoretical model is in good agreement with the two experimental results obtained. The last configuration presents some discrepancy due to the experimental setup is not optimized with a polarization control in the second Hi-Bi fiber section.

### III. EXPERIMENTAL DETAILS

The last configuration [see Fig. 1(c)] was characterized as an interrogation setup for strain measurement. In this case, two Hi-Bi fiber sections were used as sensor and reference. An optical broadband source with a bandwidth of 100 nm and a central wavelength of 1570 nm was used. The setup was formed by two simple couplers with low insertion loss, where the two output ports of the first coupler were spliced to the two input ports of the second one. In one of the splices, a Hi-Bi fiber section (reference) was inserted, while in the other arm a PC was placed, in

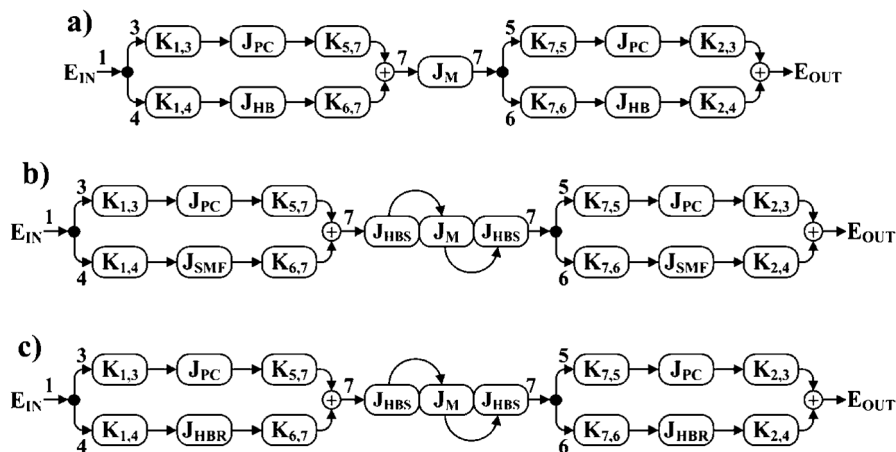


Fig. 2. Equivalent optical circuit of the proposed three configurations: (a) first, (b) second, and (c) third new Hi-Bi FLM configurations.

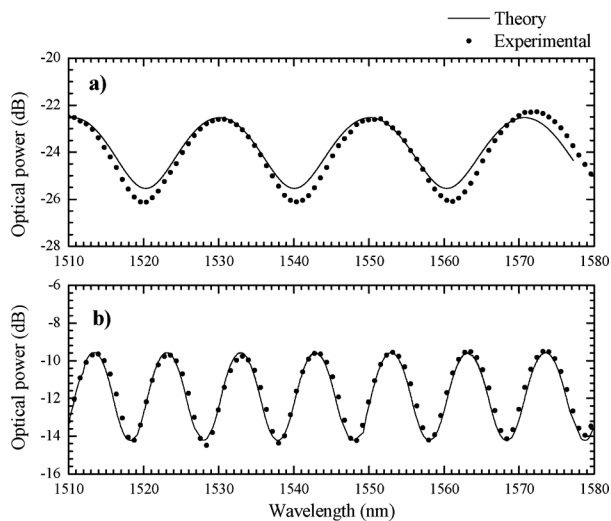


Fig. 3. Simulation and experimental results of the spectral response for the (a) first and (b) second configurations.

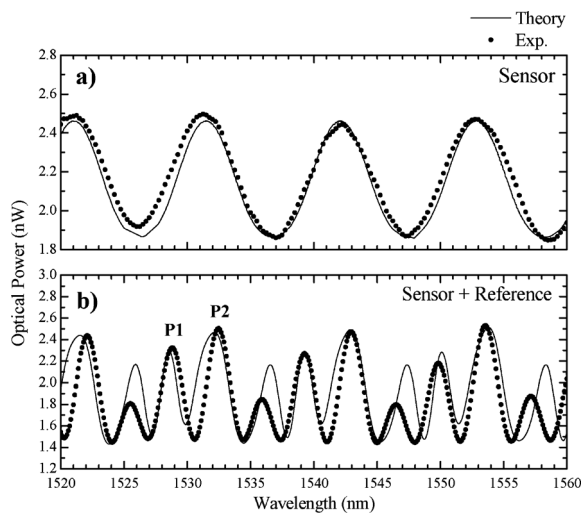


Fig. 5. Simulation and experimental result of spectral response of (a) sensor and (b) signals combined (sensor + reference).

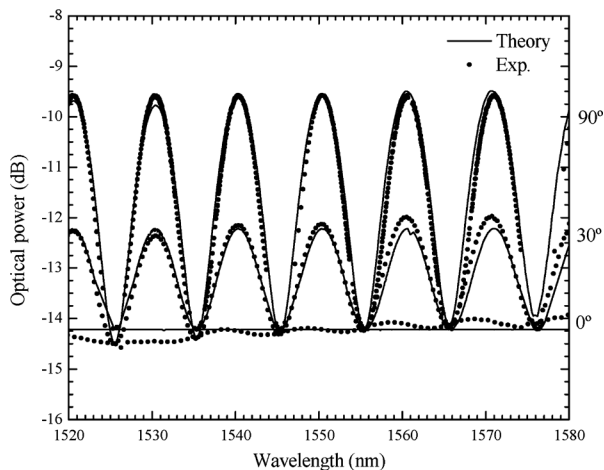


Fig. 4. Simulation and experimental results of the interferometric visibility variation of the second configuration using only a PC.

order to optimize the spectral response of the fringe pattern. The sensor was located at the output port of the second coupler and consists of the same type of Hi-Bi fiber. With the insertion of

two Hi-Bi fiber sections, the configuration will have two combined unbalanced Sagnac interferometers. The Hi-Bi fiber used was a PANDA fiber (PM-1550-HP) with a length of 1.34 m and 0.34 m for the reference and sensor signal, respectively. All results were monitored using an OSA with a maximum resolution of 0.05 nm. The LabVIEW software was used to process the data acquired through the OSA. A real-time signal processing was applied based on the generation of interferometric quadrature signals from the reference. The glue used to fix the fiber sensor was cyanoacrylate adhesive and its properties remained the same over the range of the applied physical parameters that were considered.

Fig. 5(a) shows the transmission spectrum of the sensor, which was obtained without the reference signal included in the experimental setup. The sensor wavelength periodicity was  $\sim 11.2$  nm, corresponding to a group birefringence of  $3.3 \times 10^{-4}$ . Fig. 5(b) shows a fringe pattern for the sensor signal combined with the reference signal. Two different frequencies were observed. The higher frequency corresponds to the reference signal and has a wavelength periodicity of  $\sim 4$  nm. The lower frequency, shown from the amplitude modulation of the reference signal, was due

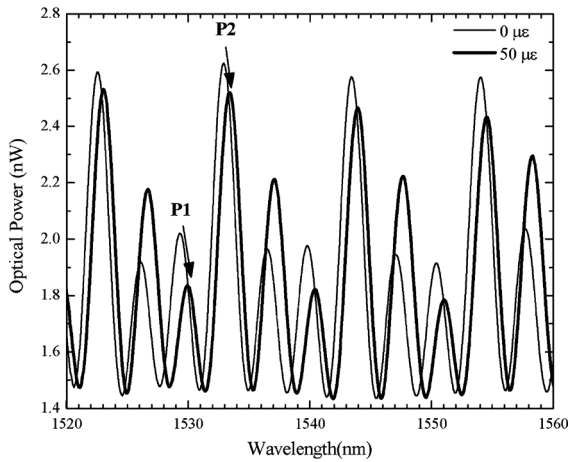


Fig. 6. Spectral response when the sensing head is subjected to strain.

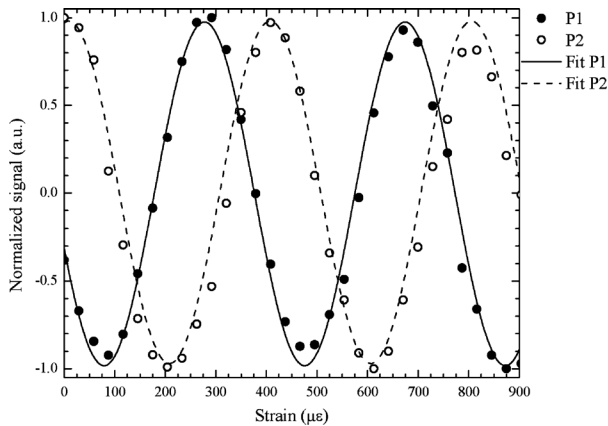


Fig. 7. Normalized output signals versus the strain, and the respective fits made to the experimental data.

to the sensor response. For strain characterization, the sensing head was attached to a translation stage with a resolution of  $1 \mu\text{m}$ . Fig. 6 shows the response of the sensor when it was unstrained and when it was subjected to  $50 \mu\epsilon$ . An amplitude variation of the reference signal can be observed due to the fringe pattern wavelength shift of the sensor when strain was applied. Peaks  $P_1$  and  $P_2$  evidenced in the figure were in quadrature and their spectral variation is a consequence of the strain induced optical path difference change in the Hi-Bi sensing section when strain was applied. Using the two peaks variation, it was possible to reconstruct the pattern fringe of the sensor signal. In this case, the two peaks in quadrature were enough to measure the phase variation of the sensor. The normalized amplitude outputs represented in Fig. 7 were obtained from both peaks. Besides the amplitude variation of the peaks when strain was applied, their fits are also represented. A quadrature phase-shifted relation can be observed between these two signals, which allows the phase recovery from

$$\phi = \tan^{-1} \left( \frac{P_{1n}}{P_{2n}} \right) \quad (8)$$

where  $P_{1n}$  and  $P_{2n}$  are the normalized optical powers of  $P_1$  and  $P_2$ , respectively [13]. The strain induced phase change is shown in Fig. 8. Strain was applied between 0 and  $900 \mu\epsilon$ , resulting in a linear slope with a sensitivity of  $16 \text{ mrad}/\mu\epsilon$ . Fig. 9 illustrates

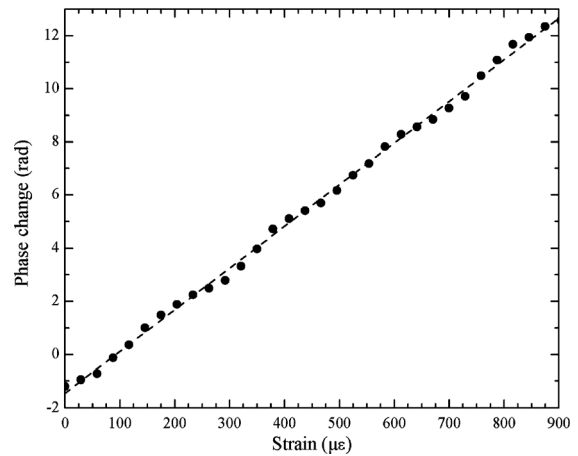


Fig. 8. Relationship between the phase signal change and the strain variation.

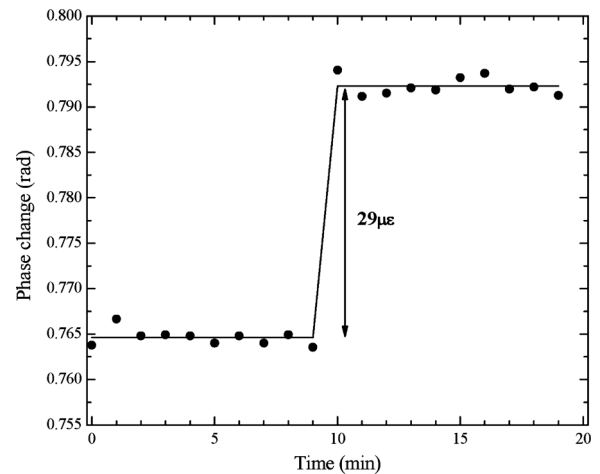


Fig. 9. Strain sensor resolution of sensing head.

the system response for a strain step variation of  $29 \mu\epsilon$ . From the phase step change and noise level, it turns out a system resolution of  $1.9 \mu\epsilon$ .

#### IV. CONCLUSION

A theoretical analysis based on Jones matrix formalism addressing three new FLM configurations was performed. The results obtained confirm that the three setups presented a behavior of an FLM. The first configuration, where the Hi-Bi section was spliced between the two couplers, can be used as reference setup to interrogate other interferometric sensors. The second setup can be used to interrogate different Hi-Bi fiber sections subjected to different physical or chemical interactions. The last configuration was experimentally analyzed in this paper when applied to strain measurement. It was observed that with the two Hi-Bi fiber sections in the FLM, the spectrum of the reference signal was modulated by the sensing head spectral response. The amplitude variation of the reference signal was due to the change on fringe pattern wavelength of the sensing head. The phase change of the sensing head was monitored through the two peaks power response in quadrature phase shift of the reference signal, resulting into values for the sensitivity and resolution of  $16 \text{ mrad}/\mu\epsilon$  and  $1.9 \mu\epsilon$ , respectively. Comparing with a traditional Hi-Bi FLM,

this setup provides the elimination of the phase fluctuations that can occur between the sensor and reference signals, increasing its potential for remote sensing applications.

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