# Strain and Temperature Discrimination Using High-Birefringence Erbium-Doped Fiber Loop Mirror With High Pump Power Laser

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***Abstract*—This work presents a method to tune the sensitivity of the sensor in a highly birefringent erbium-doped fiber loop mirror (FLM) when it is pumped. This concept was used for simultaneous measurement of strain and temperature. The FLM is sequentially pumped and unpumped by a high pump laser at 980 nm to change the erbium-doped fiber properties. The sensing head changes its sensitivity when subjected to strain and/or temperature variations due to thermal effects originated by the pump laser.**

***Index Terms*—Erbium-doped fiber, fiber loop mirror (FLM), high pump laser, optical fiber sensors.**

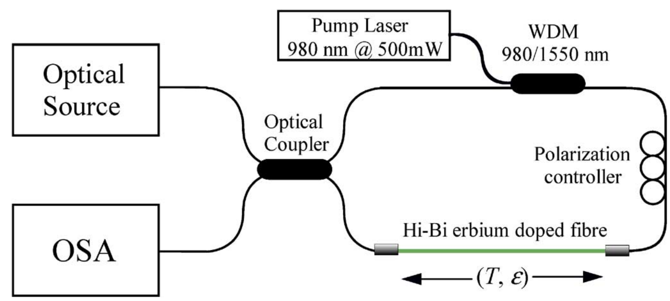


Fig. 1. Schematic diagram of the system using the Hi-Bi FLM.

## I. Introduction

THE highly birefringent (Hi-Bi) fiber loop mirror (FLM) is a device that can be used in optical fiber communications or as an optical fiber sensor [1]. The Hi-Bi FLM is formed by a 3-dB coupler connected to a polarization control and a section of Hi-Bi fiber. The use of Hi-Bi fiber brings some advantages over the traditional interferometer. One of them is the input polarization independence. Another one is the spectral filter periodicity, which depends only on the length of the Hi-Bi fiber and not on the total length of the FLM [1]. This last advantage can be explored for designing optical sensors with a small sensing head [2].

Optical fiber sensors capable of simultaneous strain and temperature discrimination are of considerable interest due to their potential applications in many fields. They are usually made by detecting two physical parameters. The techniques for strain and temperature discrimination based on fiber-optic technology using two devices in series have been extensively reported [3]. Recently, three works showed alternative and new possible configurations using Hi-Bi FLM. These configurations are based on a section of Hi-Bi fiber combined with long-period grating [4], two different types of Hi-Bi fiber [5], and two Hi-Bi FLM in series [6]. The first one presents two different types of optical sensors, in the second one the sensing head contains PANDA and elliptical core fibers, and in the last one the loops have photonics crystal fiber and internal elliptical cladding fiber. All these configurations need two sensors in series for strain and temperature discrimination.

In this letter, the authors present a configuration suitable for simultaneous measurement of strain and temperature using Hi-Bi erbium-doped FLM. A high-power pump laser (980 nm at 500 mW) was inserted in the FLM to change the properties of the Hi-Bi erbium-doped fiber. With the different sensitivity responses of the erbium-doped fiber to strain and temperature when the high pump laser is ON (maximum pump power) and OFF (unpumping), it is possible to simultaneously measure these two physical parameters.

## II. Experimental Results

Fig. 1 presents the experimental setup for simultaneous measurement of strain and temperature using Hi-Bi FLM. The configuration consisted of an optical broadband source, an FLM containing a section of erbium-doped fiber, a high pump laser at 980 nm with 500 mW of optical power, and an optical spectrum analyzer (OSA) with a resolution of 0.05 nm. The optical source is a broadband source with a central wavelength at 1550 nm and a spectral bandwidth of 100 nm.

The Hi-Bi FLM is formed by a 3-dB optical coupler with low insertion loss, an optical polarization controller, a piece of 0.28-m PANDA erbium-doped Hi-Bi fiber (INO) with an attenuation of 4.6 dB/km at 1200 nm (supported by the manufacturer) and a high pump laser at 980 nm. This erbium-doped

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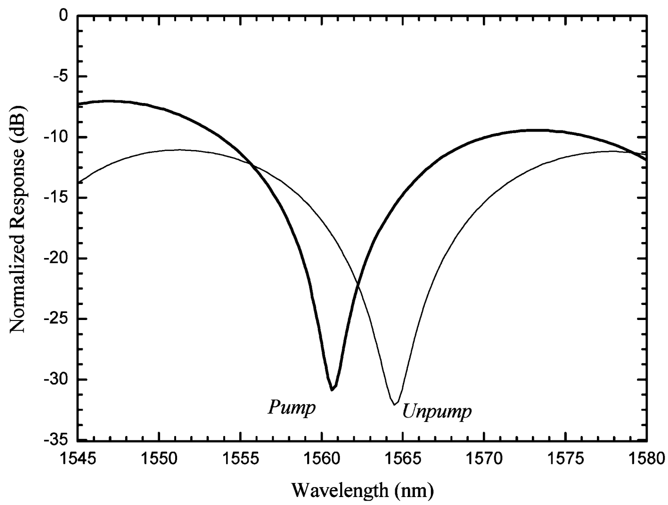


Fig. 2. Spectral response of the Hi-Bi FLM when is pumped and unpumped.

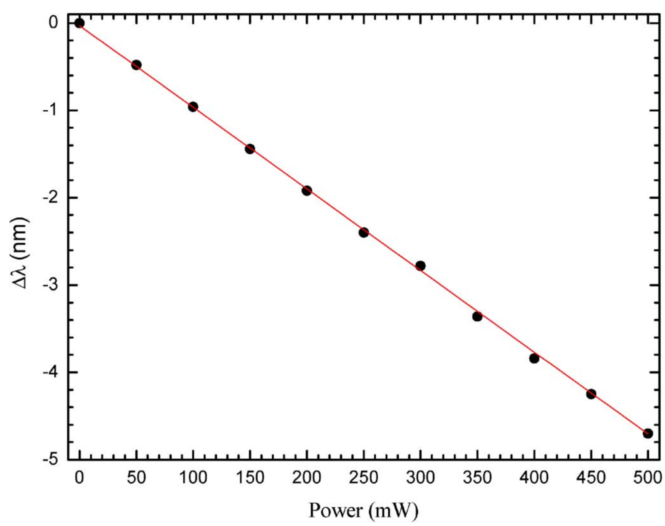


Fig. 3. Wavelength change of the Hi-Bi FLM with the pump power at temperature constant (25 °C).

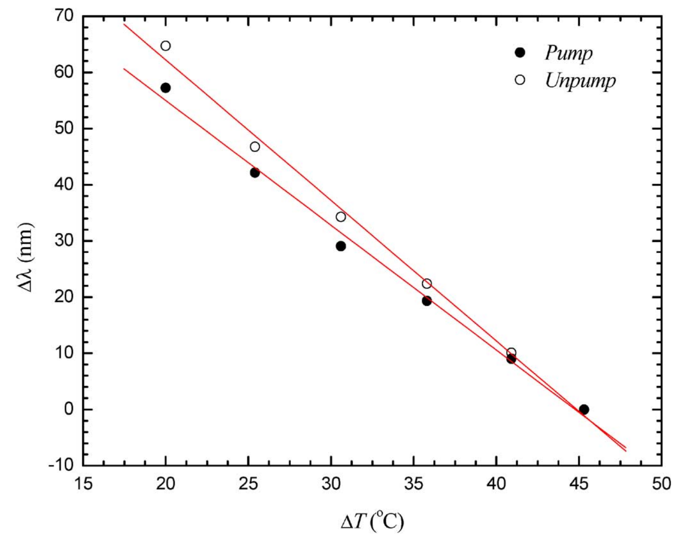


Fig. 4. Temperature response of the Hi-Bi FLM when is pumped and unpumped.

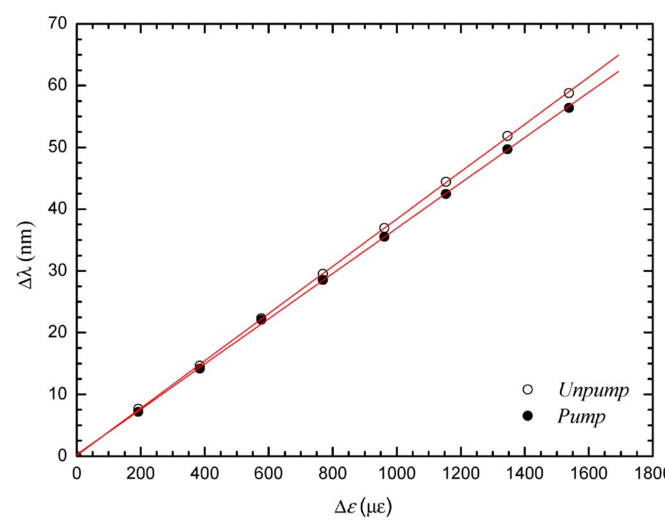


Fig. 5. Strain response of the Hi-Bi FLM when is pumped and unpumped.

Hi-Bi fiber also has an inner cladding codoped with fluorine and phosphorus.

The sensing head was characterized in strain (temperature constant) and temperature (strain constant). The wavelength values are obtained by switching the pump laser ON and OFF.

Fig. 2 shows the Hi-Bi FLM spectral response in the pumped and unpumped states. This Hi-Bi erbium-doped fiber showed a negative displacement (left displacement of the spectrum) with approximately 4.7 nm. The result is expected due to the strong effects that arise from the birefringence changes caused by the increase of the temperature that are usually observed in Hi-Bi fibers [7]. In this case, the temperature variation is caused by the high pump laser. Fig. 3 presents the behavior of the wavelength variation of the sensing head with the pump power injected in the Hi-Bi erbium-doped fiber at room temperature. The slope coefficient obtained is −9.35 pm/mW. Fig. 4 shows a linear and different temperature response of the sensing head when subjected to unpumped/pumped laser. In the first case, the Hi-Bi erbium-doped fiber is only sensitive to external temperature, while in the pumped case, the Hi-Bi erbium-doped fiber is sensitive to two effects: external temperature and the heating caused by the high-power pump laser. One can observe that the heating effect caused by the pump laser with the increase of temperature is small. For high temperatures, the thermal effect caused by pump laser is negligible. The difference between unpumped/pumped sensitivities is around 13%. Fig. 5 shows a linear (right displacement of the spectrum) and different strain response of the sensing head. When the sensing head is unpumped, the Hi-Bi erbium-doped fiber presents more sensitivity for a constant temperature. In other hand, when the Hi-Bi erbium-doped fiber is pumped, the sensing head is sensitive to two effects: strain applied and also the thermal effect caused by the pump laser. The last one produces a sensitivity reduction around 4% of the sensing head. This behavior is expected due to the temperature applied on the Hi-Bi erbium-doped fiber that reduces the birefringence originated by the stress effect and hence a negative displacement (see Fig. 2) of the spectrum is observed.

When the strain and temperature applied to the sensing head vary, the wavelengths of the Hi-Bi FLM are shifted according to

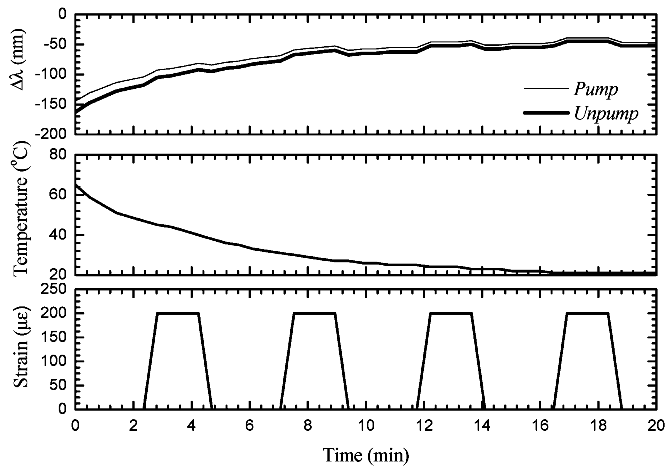


Fig. 6. Simultaneous measurement of strain and temperature using (2).

$\Delta\lambda_i = K_{Ti}\Delta T + K_{\varepsilon i}\Delta\varepsilon$, where $\Delta T$ and $\Delta\varepsilon$ are temperature and strain variation and $i = \mathrm{pump}, \mathrm{unpump}$ corresponds to the Hi-Bi FLM in pump and unpump states, respectively. This allows writing a well-conditioned system of two equations for $\Delta T$ and $\Delta\varepsilon$, given in a matrix form as

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} = \frac{1}{D} \begin{bmatrix} K_{\varepsilon\ \mathrm{unpump}} & -K_{\varepsilon\ \mathrm{pump}} \\ -K_{T\ \mathrm{unpump}} & K_{T\ \mathrm{pump}} \end{bmatrix} \begin{bmatrix} \Delta\lambda_{\mathrm{pump}} \\ \Delta\lambda_{\mathrm{unpump}} \end{bmatrix} \tag{1}$$

where the determinant is $D = K_{T\mathrm{pump}}.K_{\varepsilon\mathrm{unpump}} - K_{\varepsilon\mathrm{pump}}.K_{T\mathrm{unpump}}$. The strain sensitivity $(K_{\varepsilon\mathrm{pump}}, K_{\varepsilon\mathrm{unpump}})$ and thermal sensitivity $(K_{T\mathrm{pump}}, K_{T\mathrm{unpump}})$ are the sensor head sensitivity coefficients. The matrix coefficients are obtained from the experimental slopes shown in Figs. 3 and 4, resulting in

$$\begin{bmatrix} \Delta T \\ \Delta\varepsilon \end{bmatrix} = 149.34 \begin{bmatrix} 0.038 & -0.036 \\ 2.50 & -2.22 \end{bmatrix} \begin{bmatrix} \Delta\lambda_{\mathrm{pump}} \\ \Delta\lambda_{\mathrm{unpump}} \end{bmatrix} \tag{2}$$

With $\Delta\lambda$ in nanometers (nm), $\Delta T$ in degrees Celsius (°C), and $\Delta\varepsilon$ in microstrain ($\mu\varepsilon$). Fig. 6 shows a real-time experimental demonstration of simultaneous measurement of both physical parameters. The system was heated until, approximately, 60 °C and gradually cooled down to 20 °C during 20 min. At the same time, a periodic step strain of 200 $\mu\varepsilon$ was applied. The system output response for simultaneous changes of temperature and strain was expected. From this data and using (2), it was possible to discriminate the evolution of the temperature and strain with time.

## III. Conclusion

A technique for tuning the sensitivity of fiber sensors based on a pumped erbium-doped fiber was presented. To demonstrate this principle, a sensing head based on a high pump power laser combined with Hi-Bi erbium-doped FLM was described. It was possible to demonstrate that the simultaneous measurement of strain and temperature using this configuration could be achieved. Due to the high pump power laser injected in the FLM, the erbium-doped fiber had its properties changed. The principal effect is the erbium absorption causing the fiber heating. In this experience, the different slope between the sensitivities of the physical parameters is small. A possible solution to improve the sensitivities is to increase the erbium doping in the Hi-Bi fiber and/or increasing the optical power of the pump laser. This technique presents some advantages, namely, it reduces the number of sensing heads and allows a fast solution to adjust the sensitivity only by changing the power of the pump laser. The maximum errors for temperature and strain measurements were found to be $\pm 1.8$ °C and $\pm 26\ \mu\varepsilon$, respectively. The error uncertainty was measured and is approximately half the maximum error values obtained by the matrix method. This uncertainty is limited by the maximum resolution of the OSA.

In addition, this configuration setup allows different kinds of multiparameter measurements that can be made by tailoring the pump laser characteristics. This method can also be used for other types of sensing heads based in erbium-doped fiber with high power pump laser.

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