Strain Sensor based on a Hi-Bi Fiber Loop

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Abstract: In this work a strain sensor based on a Hi-Bi fiber loop mirror was build and a sensibility of $0.00448 \pm 0.00002 rad/\mu\epsilon$ was obtained. The strain was measured through the phase and for this a method of two laser signals in quadrature was used for an easy measurement of this. This work demonstrates that with an easy setup a high sensitivity in the measurements can be achieved.

I. Introduction

Sensing via fiber optics has began almost 50 years ago. The starting point of this field occurred with the development of the Fotonic Sensor in the mid 60s. This sensor was made by a bifurcated fiber where one end illuminated the surface and the other end measured the reflected light. When calibrated, this sensor was used to measure the relative position of the surface. Since then, this field of investigation has occupied many Research & Development groups and some important transitions into the commercial sector have been achieved [1]. One of these fiber sensors is the Fiber Loop Mirror (FLM). These sensors are more interesting when a section of highly birefringent fiber (Hi-Bi) is introduced in the loop. This configuration is interesting because is polarization independent and is sensitive only to changes on the Hi-Bi section [2]. In this work a Hi-Bi fiber loop mirror is constructed and characterized.

II. Theory

The FML under study has a birefringent section on it. This section is characterized for having a difference in the refractive indices along the fast and slow axis. The birefringent can be defined as $\beta = n_{fast} - n_{slow}$. Other way to define this property is as follows: $L_p = \frac{\lambda}{\beta}$, where the L_p is the beat length and is defined as the length for which the phase difference between the light that propagates in the fast and slow axis is 2π. The λ is the operational wavelength [2].

A standard Hi-Bi fiber loop mirror can be seen in the Figure 1.

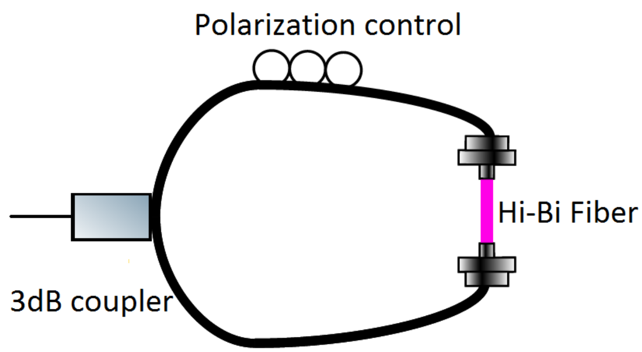


Figure 1: Schematic of a general Hi-Bi fiber loop mirror. All the credits of the scheme goes to [3].

A light signal is introduced in the fiber loop mirror and at the entrance, the 3 dB coupler splits the signal in two counter propagating beams which transverse the loop. While the beams propagates in the loop, their polarization changes and when they recombine an interference pattern is created. The visibility of the pattern can be modified by the polarization control section in the loop, as it can be seen in the Figure 1. The loop can also be seen as an unbalanced Mach-Zehnder interferometer. The phase difference between the fast and slow signal [2] is:

$$\Delta\phi = \frac{2\pi\beta L}{\lambda} \tag{1}$$

In the equation 1 the β and the L are the birefringent and the length of the Hi-Bi fiber, respectively. The λ is the operational wavelength. As said, the counter propagating beams recombine ate the 3 dB coupler and the relationship between transmission spectrum and wavelength can be shown [4] to be:

$$T(\lambda) = \left\{ sin\left(\theta_1 + \theta_2\right) cos\left(\frac{\pi L \beta}{\lambda}\right) \right\}^2 \tag{2}$$

where θ_1 and θ_2 are the angles between the light at the both ends of the Hi-Bi fiber and the fast or slow axis of the Hi-Bi fiber. This term is responsible for the visibility of the interference pattern. The reflectivity is simple given by: $R = 1 - T$. The spacing between wavelengths is inversely proportional to the length and birefringence of the Hi-Bi fiber [2], as it can be seen in the following equation:

$$\Delta\lambda = \frac{\lambda^2}{\beta L} \tag{3}$$

In this type of sensor one is interested in recover the phase to measure the displacement. If only on light source is used, the recovery of the phase is not straightforward. One elegant solution to overcome this problem is to use two light sources with different wavelengths [5]. The two wavelengths need to be close and the difference have to be less than the period of the transmission spectrum, equation 2. Thus, measuring the intensities of the two signals, the phase is easy recovered by the following equation:

$$\phi = tan^{-1}\left(\frac{V_1}{V_2}\right) \tag{4}$$

where V_1 and V_2 are the normalized and centered intensities of the two wavelengths. These wavelengths are chosen to be in quadrature. It's expected that the phase ϕ in equation 4 have a linear dependence on the length of the Hi-Bi fiber section.

III. Experimental setup

The Hi-Bi fiber that was used in this study had an internal elliptical clad, as it can be seen in the Figure 2. This fiber have a birefringence [2] of $\beta = 5.1 \cdot 10^{-4}$.

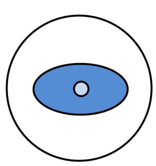
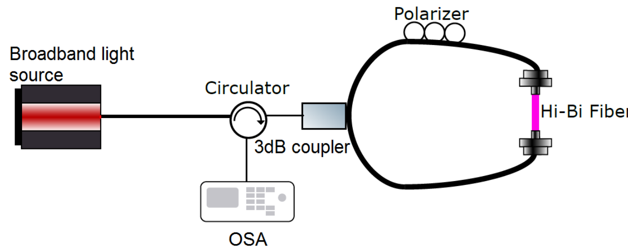
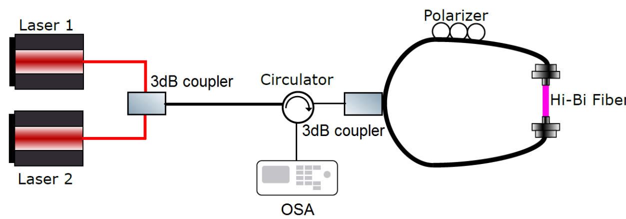


Figure 2: Cross section of an Hi-Bi fiber with an internal elliptical clad.

Two experimental setups were used. One for to determine the two wavelengths in quadrature and the other to characterize the sensor. The two experimental set ups can be seen in the Figure 3.



(a) Experimental setup to determine the two wavelengths in quadrature. The circulator lets the light from the broadband light source pass to the FLM and sends the light that comes from the FLM to the OSA.



(b) Experimental setup to characterize the dependency of the phase with the displacement. The first 3dB coupler joins the signals from laser 1 and laser 2.

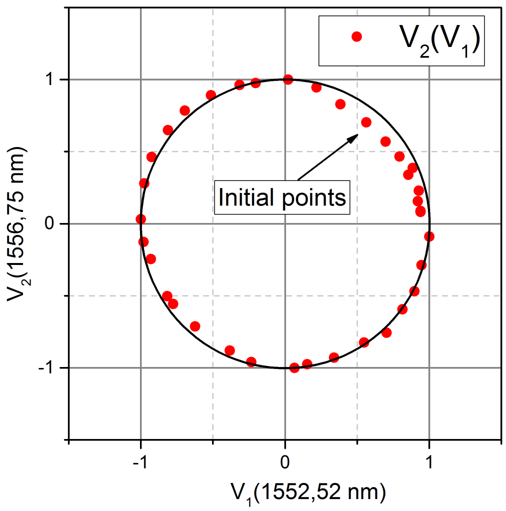
Figure 3: Experimental setups. All the credits of the schemes goes to [3].

The first scheme, in the Figure 3a, a broadband light source was used. The light from this source was introduced in the Hi-Bi fiber loop and an Optical Spectrum Analyzer (OSA) was used to measure the light that came out of the loop. With this configuration the aim was to obtain the best interference pattern and for this the polarizer was adjusted until the pattern was well defined. From this the value of $\Delta\lambda$ was measured and the value obtained was $\Delta\lambda = 16.61nm$. With this value the length of the Hi-Bi fiber can be calculated from the equation 3 and the value obtained was $L = 0.292m$, with the operation wavelength equals to $\lambda = 1573.36nm$. The $\Delta\lambda$ also allowed to determine the $\Delta\lambda^{quadrature}$ for the signals in quadrature and the value obtained was $\Delta\lambda^{quadrature} = 4.15nm$. With this, the next step was to assemble the scheme in the Figure 3b and for this two tunable lasers were used. The wavelengths that were used are the following: $\lambda_1 = 1552.52nm$ and $\lambda_2 = 1556.75nm$[1]. In the next part of the experiment the length of the Hi-Bi fiber was varied with a step of $\triangle L = 0.01mm$ and the intensities of the two signals were measured through the OSA.

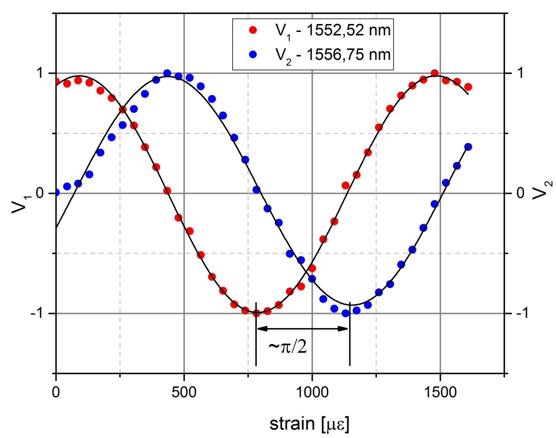
IV. Results and discussion

After the measurements, the two signals were centered and normalized and the plots of the signal for $\lambda_1 = 1552.52nm$ versus the signal for $\lambda_2 = 1556.75nm$ can be seen in the Figures 4a and 4b.

[1]Noticing that $\Delta\lambda = \lambda_2 - \lambda_1 = 4.23nm$, approximately the desired.



(a) Plot of the signal V_2 as function of V_1.



(b) Plot of the variation of the signals V_1 and V_2 as function of the strain applied to the Hi-Bi fiber.

Figure 4: Experimental results.

From the Figure 4a it can be seen that the signals are almost in quadrature. The data is, approximately, coincident with the black circle. The first points differ a little bit and this could be caused by the fiber not being fully stretched. The other points are approximately coincident with the black circle, but some deviations are still visible. This can be due to the fact that the fiber was held in the micro-metric car with tape and this could introduce some plastic effects in the deformation of the fiber. Furthermore, the conditions in the lab were not the best; the fiber was on the table and sometimes it was touched; the power measurement was also not the best, because the values floated a lot and the the signals were not in perfect quadrature. This can also be seen in the Figure 4b.

Even so, the obtained results are in good agreement with the expected, as it can be seen in the Figure 5.

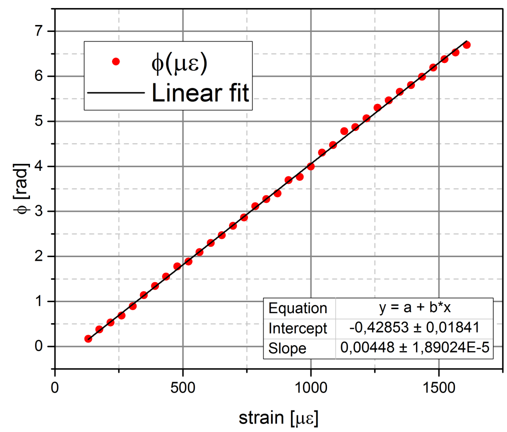


Figure 5: Plot of ϕ, equation 4, as function of the stain applied to the Hi-Bi fiber. The inset in the figure are the results from the linear fit.

The relation between the phase and the strain is linear, as expected. Notice that after applying the equation 4, the data needs to be adjusted to obtain the linear relation as obtained in the Figure 5. This adjustment corresponds to the correction of the periodicity of the function tan^{-1}. The sensibility was calculated and the value obtained was $0.00448 \pm 0.00002 rad/\mu\epsilon$. Although difficult to see, the data in the Figure 5 shows some oscillation. This oscillation is due to the fact that the two signals were not in perfect quadrature, as stated at the end of section 3. From this it can be concluded that for a good linear relation the signals need to be in perfect quadrature.

V. Conclusion

A strain sensor based on a Hi-Bi fiber loop was build and a sensibility obtained was $0.00448 \pm 0.00002\ rad/\mu\epsilon$. For measuring the phase the method of two signals in quadrature was used. This method facilitates the phase measurement, however, some data processing is needed before the calculation and this could present some difficulties for automated systems. Also, if the two signals are not in perfect quadrature, a modulation is obtained when the phase is plotted against the strain. Even so, this system presents an high sensitivity and an easy assembly, thus making this sensor of great applicability. Some applications of this sensor are: strain, temperature and displacement measurements; in dispersion compensation; and many others, as found in the literature. The introduction of Bragg gratings can be used for measure the strain and temperature at the same time. It is expected that new advances with this sensors are made to be applied to biochemical sensing and environmental monitoring.

References

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