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# Laser Wavelength Estimation Method Based on a High-Birefringence Fiber Loop Mirror

Ricardo I. ÁLVAREZ-TAMAYO[1*], Patricia PRIETO-CORTÉS[2], Manuel DURÁN-SÁNCHEZ[3], Baldemar IBARRA-ESCAMILLA[4], Antonio BARCELATA-PINZÓN[5], and Evgeny A. KUZIN[4]

[1]*Faculty of Physical-Mathematical Sciences*, *CONACYT – Universidad Autónoma de Nuevo León, San Nicolás de los Garza 66451, Mexico*

[2]*Faculty of Physical-Mathematical Sciences*, *Universidad Autónoma de Nuevo León, San Nicolás de los Garza 66451, Mexico*

[3]*Optics department*, *CONACYT – Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla 72480, Mexico*

[4]*Optics department*, *Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla 72480, Mexico*

[5]*Mechatronics division, Universidad Tecnológica de Puebla, Puebla 72300, Mexico*

[*]Corresponding author: Ricardo I. ÁLVAREZ-TAMAYO E-mail: rialvarez@conacyt.mx

**Abstract:** A simple method for the estimation of the wavelength of a fiber laser system is proposed. The method is based on the use of a high-birefringence-fiber loop mirror (HBFLM). The HBFLM exhibits a periodic transmission/reflection spectrum whose spectral characteristics are determined by the length and temperature of the high-birefringence fiber (HBF). Then, by the previous characterization of the HBFLM spectral transmission response, the central wavelength of the generated laser line can be estimated. By using a photodetector, the wavelength of the laser line is estimated during an HBF temperature scanning by measuring the temperature at which the maximum transmitted power of the HBFLM is reached. The proposed method is demonstrated in a linear cavity tunable Er/Yb fiber laser. This method is a reliable and low-cost alternative for laser wavelength determination in short wavelength ranges without the use of specialized and expensive equipment.

**Keywords:** Wavelength meter; fiber lasers; fiber optical loop mirror; high-birefringence fiber

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## 1. Introduction

Nowadays, wavelength meters have extensive applications in optical instrumentation devices and systems such as optical filters, fiber lasers, fiber sensors, optical communications systems, and medical instruments. Particularly, determination of the emission wavelength of coherent light sources is required for many fiber laser applications which commonly require expensive equipments such as an optical spectrum analyzer (OSA), monochromators, and Fabry-Perot spectrum analyzers. In this sense, laser wavelength measurement methods and techniques have been increasing interests since the first wavelength measurement review reported by Solomakha and Toropov in 1977 [1].

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Different methods for light wavelength measurement have been reported. In general terms, the methods are based on the use of wavelength-sensitive properties of materials, interference, and optical beating techniques [2]. The first group takes advantage of materials with wavelength-dependent optical properties where the optical response to a specific wavelength is related to signal intensity or polarization variations [3, 4]. The interference methods consider the space counting [5, 6] or the phase analysis [1, 7, 8] of the fringes between a reference and a testing wavelength due to an optical path difference in the interferometer. As to optical beating methods, a high-frequency photodetector is required to measure the difference between the frequencies of the tested laser signal and a reference laser source stabilized by saturated absorption [9, 10] or by using an optical frequency synthesizer [11, 12]. In this regard, the emergence of optical fibers and fiber coupled optical components allows the development of wavelength meters based on fiber interferometers [13, 14] and wavelength dependent properties of optical fiber devices [15, 16]. Particularly, all-fiber systems offer advantages such as simplicity of construction, low cost, free maintenance, simple calibration, stability, compactness, and portability. However, unlike the use of optical fiber wavelength-dependent properties, the use of all-fiber interferometers for the development of wavelength measuring methods has been underexploited. Besides, recently reported wavelength measuring methods tend to approaches including complexity on system design, measuring process, and data interpretation [6, 7, 17]. In this sense, an all-fiber wavelength meter promises to be a reliable option for wavelength estimation in optical systems.

Moreover, different fiber sensors based on the use of a high-birefringence-fiber loop mirror (HBFLM) have been reported [18–24]. The HBFLM exhibits a wavelength periodic spectrum with high sensitivity to temperature and strain variations which make it suitable for detection and/or measurement of physical variables such as strain [18, 19], temperature [19–21], beat length [22], gas trace [23, 24], among others. Then, the wavelength modulated spectrum of the HBFLM with high sensitivity to temperature changes can be attractive for being used in laser wavelength estimation applications.

In this paper, we propose a reliable, simple, and low-cost method to estimate the laser wavelength based on the use of an all-fiber estimation device. The laser wavelength is obtained by measuring temperature at which the maximum transmitted power is achieved during a temperature scanning on the high-birefringence fiber (HBF) of the HBFLM fiber loop. The measurements are obtained by the synchronized use of a temperature controller/meter with a photodetector. Then, the laser wavelength is estimated by using an initial characterization of the HBFLM transmission spectrum by temperature variations on the HBF. We report, for the first time to our knowledge, a wavelength estimation method based on the use of the operation principle of a HBFLM. By using the interference spectrum of the HBFLM and the optical response to temperature changes of the HBF, the proposed wavelength estimation method encompasses the advantages of all-fiber optical systems combining characteristics of interferometer methods and wavelength-dependent material properties techniques in a simple and adaptable measuring process, without the use of a permanent reference source, specialized equipment/components, and complicated data acquisition/analysis. The reliability of the method is also proved by wavelength estimation of the laser lines generated by a homemade tunable fiber laser.

## 2. Wavelength estimation method

### 2.1 Principles

The proposed method is based on the use of an HBFLM as a wavelength spectral filter. The transmission/reflection spectrum of the HBFLM is a wavelength-dependent periodic modulation of the input signal, whose free spectral range (FSR) can be calculated as [25]

$$FSR = \frac{\lambda^2}{B \cdot L} \tag{1}$$

where $\lambda$ is the wavelength of the input light, and $B$ and $L$ are the birefringence and the length of the HBF, respectively. The modulated spectrum can be wavelength displaced by temperature changes on the HBF [25–27]. For an HBFLM constructed with a 50/50 coupler at temperature $t$ and input wavelength $\lambda$, its reflection can be described as [28]

$$R = \frac{\gamma}{2}\left[1 + \mathrm{A}\cos\left(\frac{2\pi}{\Lambda}(\lambda - \lambda_0) + \frac{2\pi}{T}(t - t_0)\right)\right] \tag{2}$$

where $\Lambda$ and $T$ are the measured wavelength and temperature periods, respectively; $\lambda_0$ and $t_0$ are the wavelength and temperature values where the HBFLM exhibits maximal reflection. The coefficient $\gamma$ stands for the insertion losses of the HBFLM, and the constant A is the fringe contrast between the maximum and minimal reflection.

## 2.2 Wavelength estimation device

Figure 1 shows the schematic of the wavelength estimation device used for the proposed method. The HBFLM is formed by a 50/50 optical coupler whose output ports (Ports 3 and 4) are interconnected forming a loop by a 28 cm long HBF segment with birefringence of $4.22 \times 10^{-4}$ [25]. By using (1), the calculated FSR of the HBFLM transmission/reflection spectrum at 1550 nm is of 20.33 nm. The HBF is placed on a Peltier cell which applies temperature variations by electrical current changes driven and monitored by a temperature controller/meter. In order to ensure the accuracy of the temperature controller, the entire length of the HBF is sandwiched between the Peltier cell and a temperature diffuser. Then, the temperature control system is placed inside a thermally insulated container. The splices between the output ports of the coupler and the HBF are attached to mechanical rotation Stages 1 and 2. The rotation of the splices leads to change of linear and circular birefringence by fiber twisting which allows adjusting the amplitude of the HBFLM transmitted power spectrum [25]. The rotation stages are fixed to the maximal amplitude in order to reach a higher measuring precision. An optical isolator (ISO) is connected to Port 1 of the coupler to avoid reflections of counter-propagated signals to the laser source. The signal of the laser wavelength under test is launched at the input port. The output port is used to measure the HBFLM transmission output power by a photodetector, recorded by a power meter console.

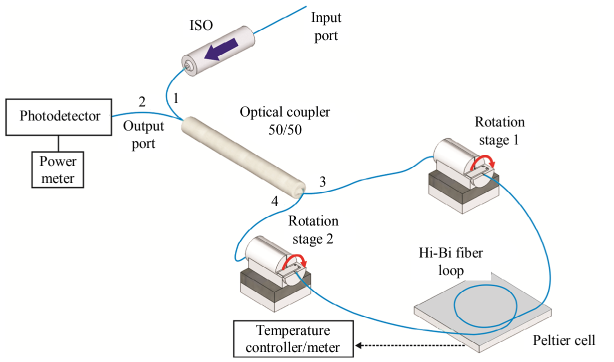


Fig. 1 Experimental setup of the laser wavelength estimation device based on an HBFLM.

## 2.3 Calibration and method description

Figure 2 shows the spectral response of the HBFLM to a wideband light source (from 1420 nm to 1620 nm) as the input signal. The transmitted power spectra for HBF temperatures of 21.24 ℃ and 20.31 ℃ are measured at the output port. The FSR of the HBFLM is of about 20 nm. As it can be observed, with an increase in the HBF temperature, the HBFLM transmission spectrum is wavelength shifted towards shorter wavelengths. The transmitted power of the HBFLM also exhibits a periodical dependence on HBF temperature changes, Figure 3 shows the measurement of the HBFLM transmitted power for a single temperature scanning from 24 ℃ to 40 ℃. The measurements are obtained for different input laser wavelengths launched at the input port by using a commercial wavelength tunable laser diode (Pirelli DLT C13-50). The output spectrum of each different input laser wavelength is previously measured directly with the OSA (Anristsu MS9740A) with a maximal resolution of 0.05 nm before the HBFLM characterization (see inset of Fig. 3). The transmitted power of the HBFLM is measured each 0.2 ℃ by using a photodetector and recorded by software. The HBF temperature scanning is controlled and monitored by using an electronic temperature controller/meter with the maximum resolution of 0.05 ℃. The HBFLM output spectrum depends on the HBF temperature with a modulation period of 14.15 ℃, which corresponds to the wavelength-dependent period of 20 nm (see Fig. 2).

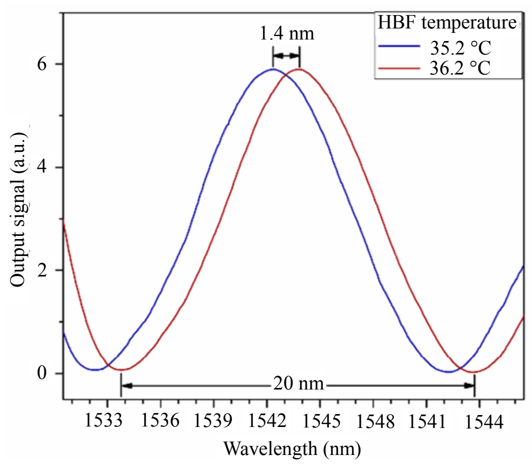


Fig. 2 HBFLM transmission wavelength displacement under HBF temperature variations.

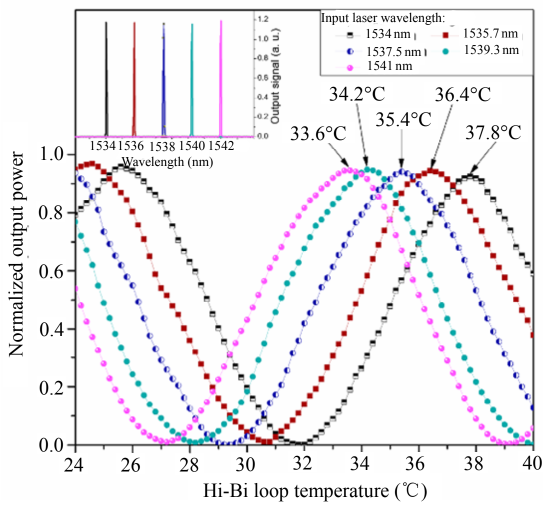


Fig. 3 HBFLM transmitted power for different input laser wavelengths on HBF temperature scanning.

The monitored temperature at which the maximum recorded power is measured is also shown. When the input laser signal is tuned to longer wavelengths, the maximum power shifts toward lower temperatures. Then, during a HBF temperature scanning, the temperature at which the maximum transmitted power is recorded allows an estimation of the input laser wavelength.

The extended characterization of the monitored HBF temperature for the maximum recorded power as a function of the input laser wavelength is depicted in Fig. 4. The results are obtained for input laser signals wavelength tuned each ~1.7 nm in a range from 1534 nm to 1549.4 nm. The carrying out of a single temperature scan leads to a high wavelength estimation error (Fig. 3) which can be minimized by performing multiple measurements. Then, in the extended characterization each input wavelength is estimated as the mean value from a set of 20 alternated (back and forth) temperature scans, which also allows discard hysteresis effect. The error bars represent the temperature error, which is calculated as the standard deviation of the mean value for each input wavelength. The maximum temperature error of ± 0.1217 ℃ is obtained at 1546 nm. The input wavelength as a function of the HBF temperature at the maximum HBFLM transmitted power can be linearly fitted with a slope of 1.405 nm/℃ (see Fig. 5). With the calibration obtained, the input wavelength can be estimated in a range of ~20 nm, restricted by the HBFLM FSR. An input signal exceeding the characterized wavelength range leads to incorrect wavelength estimation, since the power maximum corresponds to a different HBFLM wavelength period but in the same HBF temperature range. It is worth to mention that the characterization of the HBFLM with reference input signals measured by the OSA represents an initial calibration of the wavelength estimation device, performed only once if the HBF length and the contrast adjustment remain unaltered.

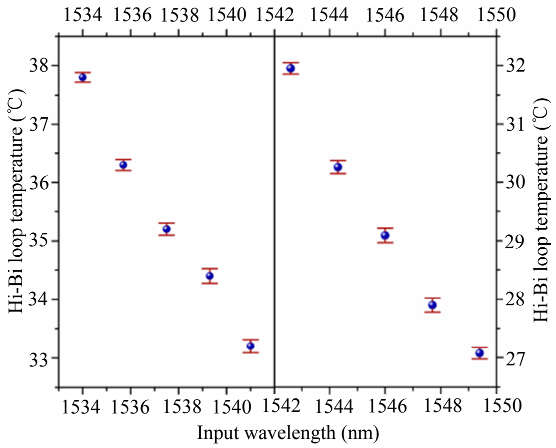


Fig. 4 HBF temperature for the maximum transmitted power measured for different input laser wavelengths.

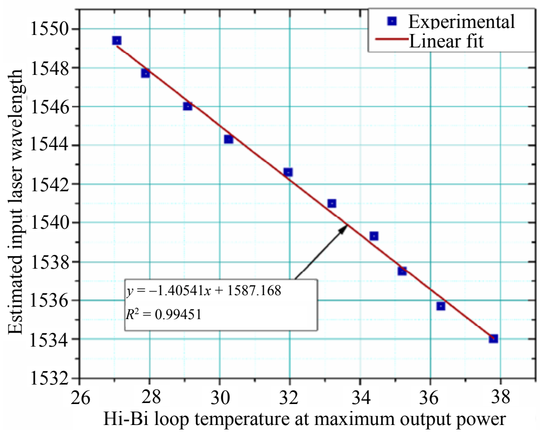


Fig. 5 Input laser wavelength as a function of HBF temperature at the maximal measured transmitted power.

## 3. Laser wavelength estimation from a homemade tunable fiber laser

### 3.1 Tunable fiber laser experimental setup

In order to demonstrate the reliability of the proposed method, the wavelength estimation device is proved with a homemade tunable fiber laser, as shown in Fig. 6. The linear cavity fiber laser is formed by a 3-m-long Er/Yb double-clad fiber (EYDCF), used as a gain medium, which is pumped by a multimode high power laser source at 976 nm through a beam combiner. The cavity is limited at one end by a Sagnac fiber loop (SFL) which consists of a 50/50 optical coupler whose output ports are interconnected. At the other end, a fiber Bragg grating (FBG) with ~90% reflection at 1548 nm acts as a wavelength-tunable narrow-band reflector. The laser wavelength is tuned by mechanical strain applied on the FBG which is attached to a flexible metal sheet. A mechanical tuning stage shifts the Bragg wavelength by micrometric linear displacement on the metal sheet which compresses the FBG by curvature [28–30]. Then, the wavelength of generated laser line is tuned. The unconnected end of the FBG and the unconnected port of the SFL provide the laser Outputs 1 and 2, respectively.

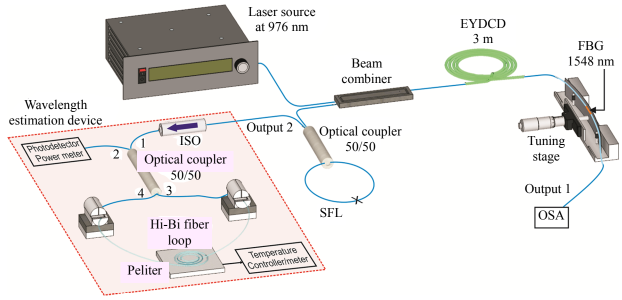


Fig. 6 Schematic of the homemade tunable laser with the wavelength estimation device connected.

### 3.2 Results

Although it is not required as part of the proposed method, the spectrum of the generated laser wavelength is measured with the OSA at Output 1 as a reference to verify the accuracy of the wavelength estimation. The wavelength estimation device is connected to laser Output 2.

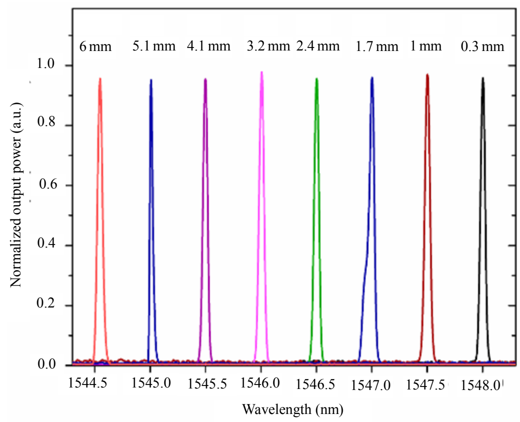


Fig. 7 Generated laser wavelength spectra for different FBG tunings.

Figure 7 shows the output spectrum of each tuned laser line used as the input laser signal for wavelength estimation. The laser spectra are measured for a pump power of 1 W, in a wavelength range from 1544.5 nm to 1548 nm, tuned each 0.5 nm. The value of micrometric linear displacement of the tuning stage to achieve each wavelength tuning is shown for each laser line. An increase in curvature compression on the FBG leads to laser line tuning toward shorter wavelengths. Figure 8 shows the comparison between the reference value of the input laser wavelength and the estimated wavelength value. The estimated laser wavelength is shown as a function of the HBF temperature at the maximum HBFLM transmitted power recorded. The calculated error of the HBF loop temperature is ±0.116 ℃ which corresponds to a wavelength estimation uncertainty of ±0.16 nm. A simple accuracy analysis of the estimated wavelength compared with the reference value is shown in Fig. 9.

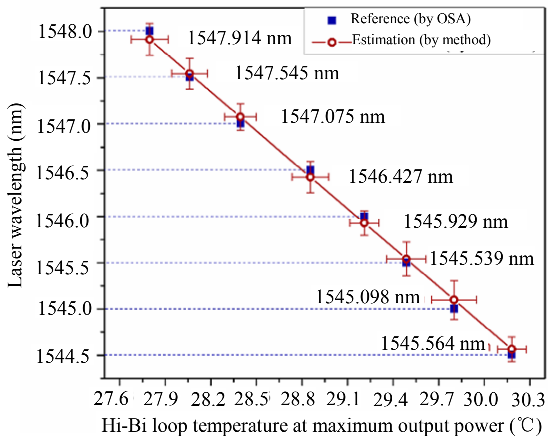


Fig. 8 Laser wavelength: comparison between the reference value measured by the OSA and the estimated value by the proposed method.

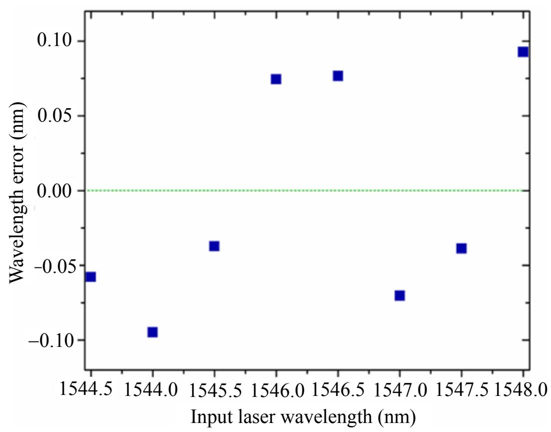


Fig. 9 Plot of the residual error between the estimated wavelength and the input laser wavelength measured by the OSA.

The residual wavelength error is shown for each input wavelength. The worst-case error observed over the testing wavelength range is 0.0949 nm, obtained at the input laser wavelength of 1545 nm. For the estimated wavelengths, the calculated mean absolute error is 0.0069 nm.

## 4. Discussion

The linear dependence between the input laser wavelength and the temperature at which the maximum recorded power is measured allows the estimation of the input laser wavelength. This method is useful to determine the laser line wavelength in a range depending on the FSR of the HBFLM. Changing the physical length of the HBF the FSR is modified, so the wavelength detection range can be easily extended by carrying out the same method proposed. However, with a shorter HBF length, the wavelength period and thus the measurement range will increase, at the expense of a proportional decrease of the estimation resolution.

The proposed wavelength estimation method combines wavelength-dependent materials properties methods and interferometer-based techniques. The wavelength estimation is obtained without a reference source or the use of expensive equipment (such as an OSA), once the initial HBFLM characterization is carried out. Besides, specialized optical components and instruments are not required, compared with optical beating techniques in which a high-resolution and high-frequency photodetector is needed, or compared with other interferometer wavelength meters where a charge-coupled device (CCD) camera, expert data acquisition systems, and complicated algorithms for fringe analysis are often needed. Considering the simplicity of the proposed method, unlike the current trend toward complexity in systems or data interpretation, the uncertainty of wavelength estimation proves the effectiveness of the method [5, 17].

The proposed method comprises the advantages of all-fiber optics systems. Hence, it allows intuitive, straightforward, and reliable wavelength estimation by using a maintenance-free, low-cost, portable, and robust optical system with a long-term operation. In addition, the wavelength can be estimated in different wavelength bands supported by the fiber components without changes on the wavelength estimation device. The minimum input laser wavelength variation experimentally detected by using the proposed method is ~0.2 nm. Therefore, further improvements can include the optimization of synchronization between the temperature scanning and the output power recording, the enhancement of the temperature measurement resolution, and the optimization of the temperature controller. The proposed method exhibits a resolution of 0.163 nm measuring a range of ~20 nm in the 1.55 μm wavelength range with estimation mean absolute error of ±0.0069 nm.

## 5. Conclusions

In this paper, we demonstrate a simple method to estimate the laser wavelength with an all-fiber wavelength estimation device based on the operation characteristics of an HBFLM. With a previous HBFLM characterization, the laser wavelength is estimated by measuring the temperature at which the maximum transmitted power of the HBFLM is reached during a temperature scanning on the HBF. The measurements for wavelength estimation are obtained by the synchronized use of a photodetector and a temperature controller/meter. The proposed wavelength estimation device is demonstrated as a reliable, low-cost, and compact all-fiber system to estimate the laser wavelength at a specific adaptable wavelength range with ease of implementation, measurement process, and data analysis; without the use of a permanent reference source and specialized equipment.

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