Asymmetric Fabry-Perot Cavity onto Optical Fiber Tip to Developing High Performance Sensing Devices

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ABSTRACT

Fabry-Perot interferometers are optical resonators used for developing high-resolution sensing devices. With the ability to detect and resolve the fine features of a transmission spectrum with high precision, these devices are commonly used to determine the resonant modes of a laser cavity, which often feature closely-spaced spectral peaks with narrow line widths. The most common configuration of a Fabry-Perot interferometer is a resonator consisting of two highly reflective, but partially transmitting, spherical mirrors that are facing one another.

In this work, we present an experiment of how the academic knowledge acquired can be applied to the development of technologies that improve the quality of life. We believe that the teaching of experiment-oriented topics, combined with a dynamic and dialogue-based classroom delivery, can encourage greater class participation. This experiment is designed around commonly used optoelectronic devices, such as LEDs, to engage students' interest. Additionally, students will learn to investigate non-trivial features of such devices, for example, that it is possible to relate the emission spectrum of a resonant cavity to physical parameters that affect the cavity, such as temperature or refractive index.

Keywords: Fabry-Perot interferometers, Optical fiber sensors, interferometry-based thermometer, High sensitive sensors

1. INTRODUCTION

The Fabry-Perot cavity (FPC) is named after Charles Fabry and Alfred Perot, who first developed and studied the concept in the late 19th century. It consists of a cavity created by placing two partially reflecting mirrors in close proximity to one another, which allows light to repeatedly bounce back and forth between them[1]. The operation principle behind of a FPC is based on the interference of light waves, which is determined by the relative phase shift and amplitude of the reflected waves. The multiple reflections cause interference patterns that produce a set of standing waves, which can be used to manipulate the properties of the light passing through the cavity. This technique is widely used in a variety of applications, including laser physics, spectroscopy, and telecommunications. Therefore, understanding the operation of this cavity is essential for students in the fields of optics, physics and engineering due to its widespread applications. However, the complexity of the cavity's operation can be challenging for students, particularly those without a strong background in optics.

One of the most common uses of FPCs is in laser systems, where they are used as resonators to amplify light and generate coherent radiation. However, Fabry-Perot cavities are also used in optical sensing and metrology, where their high sensitivity and selectivity make them ideal for detecting small changes in the environment.

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In recent years, researchers have developed FPCs using fiber optical fibers, which have enabled the development of various novel devices and applications[2,3]. In optical fibers, the cavities are created by splicing two sections of fiber together with a precise distance between them. The reflective surfaces can be created by coating the fiber ends with a highly reflective material or by etching a Bragg grating into the fiber. The length of the cavity is typically in the range of a few millimeters to a few centimeters, depending on the desired resonant frequency.

The use of optical fibers for the fabrication of FPCs has several advantages over traditional bulk optics[4,5]. First, optical fibers are highly sensitive to external perturbations such as temperature and strain, making them an ideal candidate for sensing applications. The high sensitivity of optical fibers allows for the detection of small changes in the environment, making them useful in various sensing applications, including temperature sensing, pressure sensing, and strain sensing. Second, optical fibers offer a compact and robust platform for the fabrication of FPCs. The small diameter of optical fibers allows for the fabrication of miniature cavities with a high finesse, which leads to enhanced resonant properties. The compactness of optical fiber-based FPCs makes them suitable for integration into small devices, which is particularly useful in portable sensing systems. Third, optical fibers offer ease of integration into existing optical systems. The small diameter and flexibility of optical fibers make them compatible with standard optical components, such as couplers and filters, allowing for easy integration into existing optical systems. Furthermore, the ability to use fiber-optic couplers to couple light into and out of the cavity allows for a straightforward and reliable method for tuning and monitoring the cavity resonance.

This work aims to emphasize the importance of explaining the FPC's operation to university students due to its numerous applications in modern technology. Here, we demonstrate the advantages of an asymmetric Fabry-Perot cavity (AFPC) fabricated onto optical fibers tip for sensing or monitoring applications. Specifically, this paper discusses the design, fabrication, and characterization of an AFPC for temperature and refractive index sensing, highlighting the advantages of using optical fibers for the fabrication of AFPCs.

2. PHYSICAL PRINCIPLE

To fabricate the cavity of the AFPC we used a micro-sphere made of polymer. Its operating principle is explained as follows. Let us assume that a wave with amplitude E_0 propagates without attenuation in the core of the SMF, see Fig. 1(a). When such a wave reaches the SMF-polymer interface, it is partially reflected, the rest is transmitted to the polymer. The amplitude of the reflected wave (E_{r1}) can be expressed as[6] :

$$E_{r1} = r_1 E_0 \tag{1}$$

where r_1 is the amplitude reflection coefficient which depends on the refractive indices of the polymer (n_p) and the fiber core (n_c), as $r_1 \approx (n_p - n_c)/(n_p + n_c)$. It is important to point out that the expression for r_1 is valid for perpendicular incidence (symmetric cavity) and random polarized light. The wave that propagates in the polymer reaches the polymer-external-medium interface with an accumulated phase of $\phi = 2\pi n_p d/\lambda$, being d the height of the polymer microcap and λ the wavelength of the optical source. Such a wave suffers Fresnel reflection from the polymer-external-medium interface if the index of the polymer, n_p, and the refractive index of the external medium (n_e) are different. In an AFPC, not all the reflected wave from the polymer-external medium interface is coupled into the SMF core. Due to the small angle of the SMF face, the fiber facet and the curved surface of the polymer microcap are not parallel (see Fig. 1(a)); that is the reason we do not treat our devices as a Fabry-Perot interferometer.

The amplitude of the reflected wave (Er_2) can be expressed as $Er_2 = E_0 r_2(1- r_1)\exp(-i\phi)$ where r_2 is the amplitude reflection coefficient which is expressed as $r_2 \approx (n_e-n_p)/(n_e+n_p)$. The reflected wave that is coupled back to the SMF core is expressed as:

$$E_c = \eta r_2 E_0 (1-r_1)^2 \exp(-i2\phi). \tag{2}$$

In Eq. (2), η is the coupling coefficient, that depends on the angle of the SMF face, d, n_p, λ, spot size of the output beam of the SMF, etc. The amplitude of the total reflected field (E_T) is the sum of Er_1 and E_c:

$$E_T = E_0\left[r_1 + \eta r_2 (1-r_1)^2 \exp(-i2\phi)\right]. \tag{3}$$

Thus, the total reflected intensity that can be measured is $(E_T)^2$. By defining $I_r = (E_T/E_0)^2$ we get:

$$I_r = r_1^2 + \eta^2 r_2^2 (1-r_1)^4 + 2\eta r_1 r_2 (1-r_1)^2 \cos(2\phi). \tag{4}$$

From Eq. (4) it is possible to deduce that the maximums of the I_r will be given when $\phi = 2m\pi$ and the minimums when $\phi = (2m+1)\pi$, m being a positive integer. So, the wavelengths of the interference pattern where I_r takes maximum values will be located at:

$$\lambda_m = \frac{2n_p d}{m} \tag{5}$$

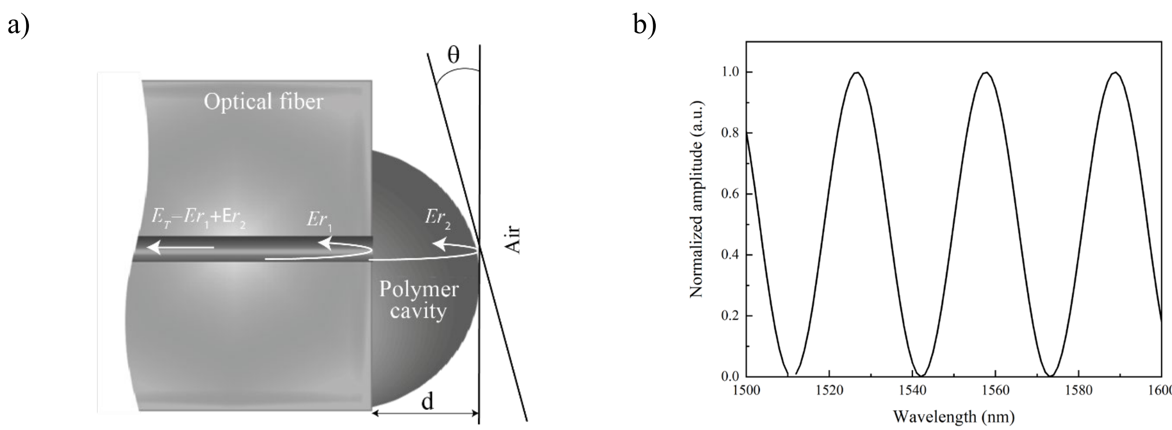

Figure 1: a) Illustration of the AFPC. b) Theoretical spectrum calculated from the Eq. (4).

The visibility (V) of an interference pattern is defined as the difference over the sum between the maximum and minimum of such a pattern. Thus, from Eq. (5), we can derived V as:

$$V = \frac{4\left[(1-r_1)\sqrt{r_1 r_2}\right]}{2r_1 + 2(1-r_1)r_2} \tag{6}$$

3. RESULTS

Experimentally, our interferometer was assessed as a thermometer and it was compared with a commercial resistance temperature detector (RTD). The Fig. 2(a), shows the observed spectra of the device at different temperatures. The Fig 2(b) shows the experimental test which consists in temperature increments from ~ -25 to ~ +100 ºC in steps of 25 degrees. Then, the temperature was decreased to initial temperature. An additional experimental text consisted in exposing them repeatedly to several temperature cycles (Fig 2(c)). In Fig. 2(d) it can be see the calibration curve. The theoretical fitting was calculated by considering η = 0.18. From the plots, the device sensitivity was found to be 265 pm/ºC.

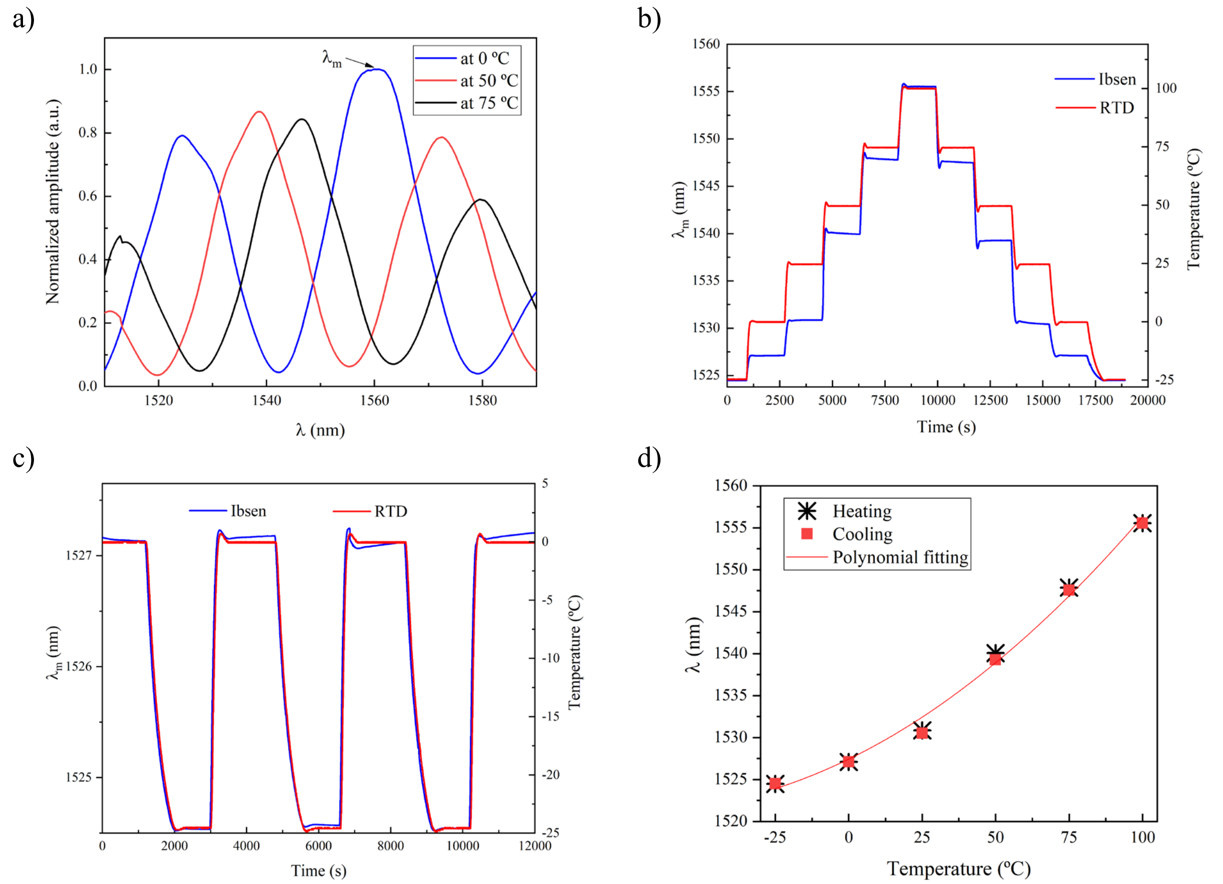

Fig. 2. (a) Spectra of the temperature sensor at different temperatures. λ_m is the maximum of each spectrum. (b) and (c) Comparative of our temperature sensor with a commercial thermometer during several temperature cycles. (d) The calibration curve was found to be λ_m(nm)= 1,527.44+0.17·x +0.00118x^2.

CONCLUSIONS

The fabrication of our proposal is simple and reproducible. An important advantage of our devices is that they operate at the well-established telecommunications wavelength bands. The cavities made of polymer present high temperature sensitivity and resolution and respond fast to temperature changes.

The AFPCs proposed could be useful in several applications that demand high sensitivity thermometers. For example, they could be useful to explore temperature inside micro-fluid channels or other small spaces or to monitor temperature of tiny objects. Their fast thermal response time makes them attractive to monitor temperature in environmental or biomedical applications.

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