

## Chapter 2: EFPI-based Sensor System

Fiber interferometric sensors have proved to be compact and highly versatile in the measurement of external disturbances. Since the measurement of extremely small phase shifts in the micro-radian range is possible in these sensors, extremely high sensitivities have been achieved [14]. Optical interferometers operate on the principle of interference between two or more light beams. Many fiber optic interferometers in general depend on the interference between two light beams obtained from reflections within or outside the fiber. These are the reference and sensing waves in the sensor. Secondary reflections do exist but are generally negligible. External parameters cause a change in the optical path length of the sensing wave, thus causing a phase difference between the two interfering waves. The output signal can be demodulated to obtain absolute or relative information about the external parameter.

### 2.1 Theory and Construction

The construction of the Extrinsic Fabry-Perot Interferometer (EFPI), first described by Murphy *et al.* [15], is shown in Figure 2.1. The Fabry-Perot (FP) cavity is formed by a single mode fiber and a multimode fiber sealed inside a hollow core tube. The single mode fiber acts as the input-output fiber whereas the multimode fiber is used solely as a reflector. The hollow core tube acts as a guide tube in addition to protecting the cavity from external elements. Light enters the single mode fiber and it is partially reflected from the first glass-air interface as  $R_1$ . The transmitted light travels through the cavity, is reflected from the second air-glass interface and enters the single mode fiber again as  $R_2$ . These reflections then interfere in the single mode fiber. The output depends on the difference in the optical path lengths traveled by the two interfering waves. The effect of subsequent reflections inside the cavity are negligible [16]. Output intensity is approximately given by Equation 2.1.

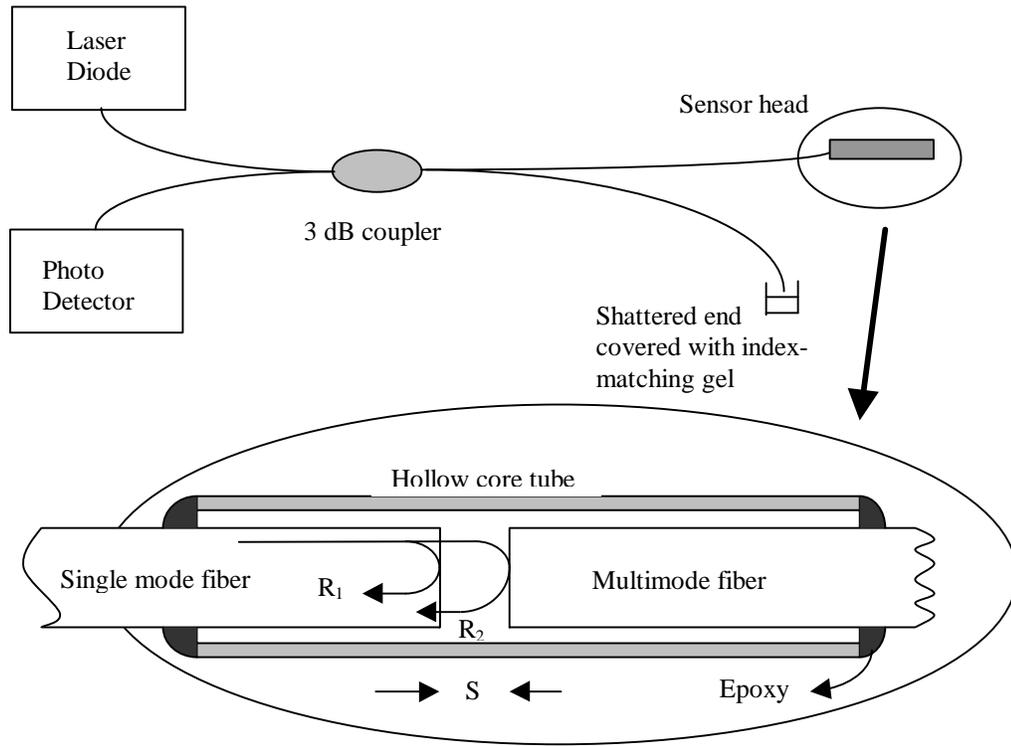


Figure 2.1 Schematic of an EFPI-based sensor.

$$I_{det} = A^2 \left\{ 1 + \frac{2ta}{a + 2s \tan(\sin^{-1}(NA))} \cos\left(\frac{4ps}{I}\right) + \left(\frac{ta}{a + 2s \tan(\sin^{-1}(NA))}\right)^2 \right\} \quad (2.1)$$

where  $I_{det}$  is the detected signal intensity,  $A$  is the reference reflection coefficient,  $s$  is the length of the air gap,  $t$  is the transmission coefficient of the air-glass interface,  $a$  is the core-radius of the fiber and  $NA$  is the numerical aperture of the single mode fiber [17]. Figure 2.2 shows the variation in the detected intensity as a function of air gap length.

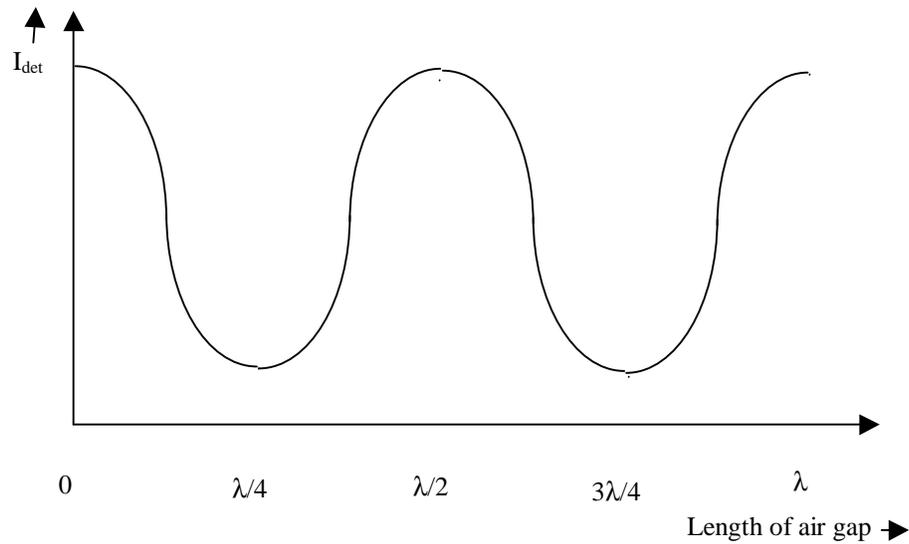


Figure 2.2 Detected intensity as a function of air gap length.

## 2.2 Advantages and Limitations

A small interaction length is the major advantage of an EFPI [17]. This gives it the ability to effectively monitor various external parameters as a point sensor. Since the single mode fiber carries the light signal both to and from the sensor, no separate electrical biasing is required. Hence an EFPI can be used in environments not suitable for other kinds of active sensors and can be deployed at larger distances from the laser source and demodulation circuitry without having to worry about EMI. It can be easily bonded to other materials for measurement applications and can also be embedded in composite materials. The ability of being embedded makes it an ideal candidate for smart structure and smart highway applications. A typical EFPI can have a gage length of 2-3 mm with an air gap separation of about 30-40  $\mu\text{m}$  [17]. It is relatively easy to fabricate, compact and light weight. An EFPI has a wide frequency response, limited only by the signal processing circuitry at the detector end.

As can be seen in Figure 2.2, the variation in the output signal of an EFPI with change in the length of the air gap, is sinusoidal. Thus when the length of the air gap is any multiple of  $\lambda/4$ , the output is at the maximum or minimum and the sensitivity (slope of the curve at that point) is zero. The sensor thus exhibits varying sensitivity to external perturbation depending on the operating point. This phenomenon is common to all interferometric sensors and is known as ‘signal fading’. Figure 2.3 shows the signal fading phenomenon in detail.

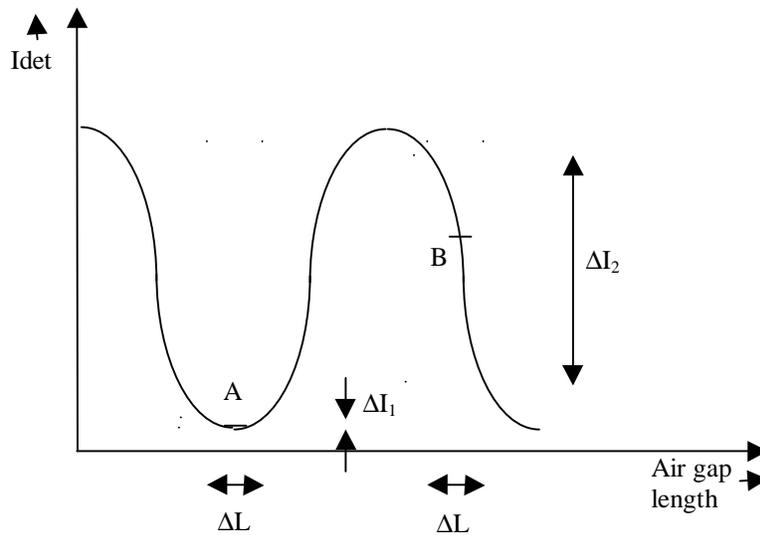


Figure 2.3 Signal fading in fiber interferometers.

As can be seen from the above figure, at operating point A, an air gap change of  $\Delta L$  causes an output variation of  $\Delta I_1$ . However at operating point B, the same change in air gap length causes a much larger output variation of  $\Delta I_2$ . Thus, the EFPI has to be biased at the quadrature point to achieve maximum sensitivity. Moreover, this operating point has to be maintained at all times during the actual operation of the sensor. This limitation can be eliminated using the Quadrature Phase Shifted (QPS) demodulation scheme and is explained in the following section. Source intensity fluctuation is another important factor since it causes a change in the EFPI output

without any change in the air gap length. This limitation however, can be overcome using the split-spectrum based approach to loss compensation proposed by Wang *et al.* [18]

## 2.3 Signal Demodulation Schemes

Various signal demodulation schemes have been developed for EFPI-based sensors. Some of these are explained below.

### 2.3.1 Quadrature Phase Shifted (QPS) EFPI

The QPS EFPI demodulation scheme allows relative measurement of the change in air gap length. Thus the measurement is independent of the initial operating point. However, complex signal processing is involved. In this scheme, two different sensors with outputs  $90^\circ$  out of phase or ‘in quadrature’ are fabricated. Figs. 2.4 and 2.5 show the sensor arrangement and signal outputs in this scheme.



Figure 2.4 Sensor arrangement in a QPS EFPI sensor scheme.

The system consists of two different EFPI sensors in quadrature with each other. Thus at any given instant, at least one of the sensors operates in its most sensitive region. By monitoring the phase lead-lag of the two signals, information about the direction can be unambiguously obtained [19]. The disadvantages of this scheme include the necessity of complex fringe counting methods, the difficulty in the fabrication of the sensors and the maintenance of the quadrature phase shift under repeated strain conditions.

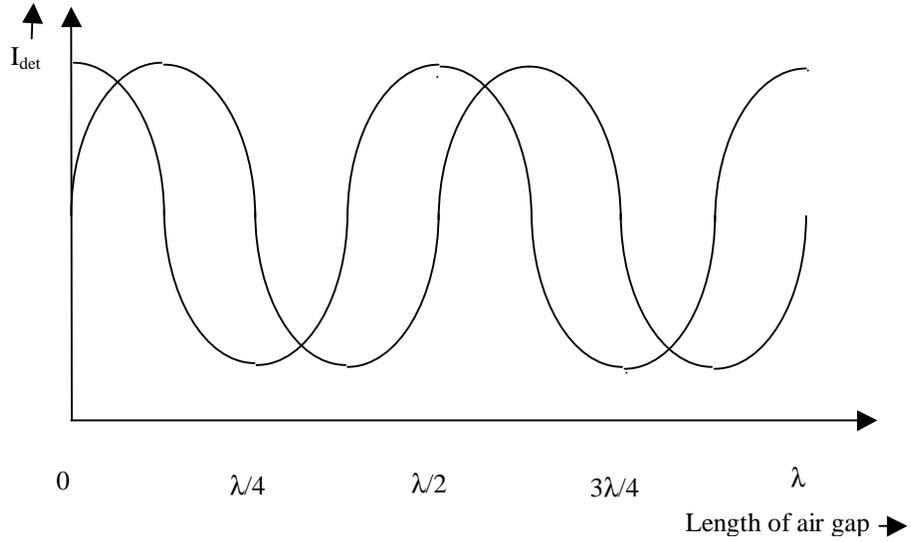


Figure 2.5 Signal output in a QPS EFPI sensor scheme.

### 2.3.2 Dual Wavelength Method

This is another scheme for detecting the change in air gap length. Unlike the quadrature phase shifted EFPI, this scheme utilizes only a single sensor but two different source wavelengths and hence the name, ‘Dual Wavelength’. If an EFPI is illuminated using two sources at wavelengths  $I_1$  and  $I_2$ , the change in the output signal phase corresponding to each source wavelength is given by Eqs. 2.2 and 2.3 respectively [20].

$$\Delta\Phi_1 = \frac{4pL}{I_1} \quad (2.2)$$

$$\Delta\Phi_2 = \frac{4pL}{I_2} \quad (2.3)$$

where  $L$  is the length of the air gap. The relative phase difference between the two signals is then,

$$\Delta\Phi = 4pL \frac{\Delta I}{I_1 I_2} \quad (2.4)$$

where  $\Delta I = I_1 - I_2$ . The dynamic range is limited to  $0 < \Delta\Phi < p$  radians. The typical dynamic range for this scheme is 40  $\mu\text{m}$ . For a given dynamic range, monitoring the phase lead-lag of the two signals yields directional information.

### 2.3.3 White Light Interferometry Technique

This technique allows the measurement of absolute gap length, not possible with the earlier techniques. The EFPI in this case is illuminated with a broadband source, such as a light emitting diode (LED). The output is fed to an optical spectrum analyzer (OSA). Wavelengths for which the phase difference between the reference and sensing reflections is a multiple of  $2\pi$ , interfere constructively and show up as peaks on the output spectrum. The gap length is then determined using Equation 2.5 [21].

$$L = \frac{I_1 I_2}{2(I_1 - I_2)} \quad (2.5)$$

where  $I_1$  and  $I_2$  are the wavelengths of any two subsequent peaks in the optical spectrum. One of the many advantages of this technique is the elimination of complex fringe counting methods. Another major advantage is the absolute gap length detection. The use of the OSA slows the frequency response of the system to 5 Hz. In addition, to obtain accurate information, the system has to be operated in a transmissive mode with a high finesse EFPI cavity which complicates fabrication. The system described above had a dynamic range of 0 to 500  $\mu\text{m}$  with a resolution of 1  $\mu\text{m}$  [21].

## **2.4 Applications of EFPI Sensors**

An EFPI basically measures the change in gap length. Thus it can be used to measure any parameter that causes a change in the gap length of the EFPI. The ability to measure change in gap length makes the EFPI a highly versatile sensor. It can be used to measure strain, pressure, temperature, magnetic fields and many other physical, chemical or electrical parameters using modified geometries and innovative temperature compensation schemes. Commercial EFPI-based sensors measuring strain and temperature have been available for quite some time.