Interferometric temperature fiber sensor based on Hilbert Transform

Abstract: Implementation of the Hilbert Transform (HT) for temperature monitoring using an interferometric fiber sensor is presented. The method's effectiveness is confirmed through modeling, simulation, and experimental results. This approach simplifies the process of monitoring the phase of an interferometric signal from a fiber sensor. Using a Fabry-Perot interferometer as the sensing element, it is demonstrated that the HT method enables accurate temperature measurement. The results show a high sensitivity and precision, with an error margin of less than 0.1°C, demonstrating the method's reliability and potential for various applications.

1. Introduction.

Hilbert transform (HT) is a mathematical tool extensively used in telecommunications for signal processing [1]. In fiber sensors field, HT has been used to generate an analytic complex signal implemented for sensing signal processing in different applications. In [2], HT was used for demultiplexing of multiple fiber Bragg gratings (FBGs) using a broadband source and a single receiving interferometer. First, the fast Fourier transform was used to separate the signal from each grating, and then filtering and inverse Fourier transform were applied to obtain the analytic complex signal. Finally, phase calculation and slope of the change in phase were used to calculate the Bragg wavelength for each sensor. In [3], the analytic complex signal obtained by method of HT was used to reduce the nonlinearity in wavelength scanning. A wavelength-tunable laser was used to interrogate a sensing cavity. However, the laser produced a certain level of nonlinearity in the wavelength scanning. By calculating the phase from a signal coming from an auxiliary interferometer, the nonlinear change in the optical frequency of the laser was obtained. This nonlinear response was used to linearize the signal from the sensing cavity under test to demonstrate the proposed method. In [4], the analytic complex signal and its envelope was used in a white-light interferometric sensor for absolute position measurement from the tip of the fiber to a reflecting surface. To avoid possible singularities, the analytic signal was divided by its envelope. In [5], a polarimetric fiber sensor based on the analytic complex signal obtained by methods of HT was reported for calculation of strain-induced phase shift. In [6], a multipeak detection algorithm was reported for FBGs monitoring, there, the HT was implemented over the spectra containing all the FBGs spectrum, then the first derivative of the signal was calculated to improve segmentation of the spectrum containing each FBG. In [7], the reconstruction of the applied micro-displacement in a Fabry-Perot cavity based on HT was presented. There, the change in phase was used to calculate the change in length, and the proposed method was able to reconstruct the displacement movement.

On the other hand, interferometric fiber sensors used for temperature measurement are based on phase, amplitude or frequency monitoring of the interference signal, depending on the sensing head preparation [8-10]. In this sense, some interrogation techniques are based on phase or dip/peak tracking. In these works, after full temperature characterization of the sensor, each phase or dip/peak position in the interrogation signal is used to determine the temperature value [11-13]. Another popular technique is based on calculating the spatial frequency of the interference signal, where each frequency value is related to a temperature value, once again, after full calibration process [14,15]. Also, microwave photonic sensors have been reported [16]. An interrogation technique generating a single-bandpass filter has been reported for temperature monitoring. In this process, broadband light is transmitted through an interferometric fiber sensor. The resulting output light is modulated by a radio frequency (RF) signal and then passes through a dispersive medium before being detected by a photodetector. This process yields a bandpass filter, the central frequency of which changes with temperature variations due to the impact of temperature over the frequency of the interferometric fiber sensor [17]. Recently, Machine Learning (ML) has also been used as an interrogation method of temperature fiber sensors. Using ML algorithms, the range of temperature monitoring was extended beyond the 2-pi ambiguity [18]. Also, dual-point temperature sensing based on a synthetic database was reported in [19]. Another reported technique is based on intensity interrogation, using a diode laser and a photodetector [20]. In these works, the change in temperature modifies the intensity reflected/transmitted in the sensing system; however, most of these schemes are affected by any non-expected change in the laser intensity.

In this letter, implementation of HT to obtain the analytic complex signal of a fiber interferometer used for temperature monitoring is presented. The reported system does not need full characterization, and only one measurement at the initial temperature is required. The fiber interferometer is made of a Fabry-Perot cavity, which is formed by two in-fiber mirrors generated by chemical attack to the core of the fiber. Manufacturing process of these mirrors was reported in [21]. Experimental results clearly illustrate the effectiveness of the implemented method while also demonstrating the ease of utilizing HT for temperature monitoring.

2. Description of the proposed method

The temperature fiber sensor is based on a low-reflectivity fiber Fabry-Perot interferometer, see Fig. 1a. This interferometer is constructed using standard single-mode fiber (SMF) and includes two low-reflectivity fiber-mirrors forming a 1.037 mm long cavity. The in-fiber mirrors reflect around 2% of light. Light reflected from these reflectors generates a two-wave interference, which produces an interference spectrum dependent on the wavelength. The cosine component of the sensing signal can be described by:

$$S(\lambda) = A \cdot cos\left(\frac{4 \cdot \pi \cdot n \cdot L_c}{\lambda} + \theta_0 + \Delta\theta_T\right), \quad (1)$$

where *A* is the amplitude of the interference signal, *n* denotes the refractive index of the fiber core, L_c is the length of the sensing cavity, λ is the wavelength, θ_0 is the initial phase of the sensing signal and depends on the manufacturing process of the sensing head, $\Delta\theta_T$ is the change in phase generated by change in temperature, which is defined as $\Delta\theta_T = 86.86 \cdot L \cdot \Delta T$ (see [21, 22] for more details), ΔT is the difference between an initial temperature in the fibre and the temperature of the fibre when the measurement is performed. Considering the cavity size of the implemented fiber sensor, a theoretical sensitivity of 0.09 rad/°C and a theoretical temperature-to-phase ratio ($\Delta T/\Delta\theta_T$) of 11.1 are obtained. It is worth mentioning that all the parameters of the mathematical model, used in Eq. (1), are adjustable, except for the initial phase (θ_0). Note that each sensor has a unique initial phase value related to the manufacturing process. However, it is important to emphasize that the phase value has no impact on the spatial frequency and amplitude of the signal. Implementation of the HT method is based on the determination of the initial phase value at a well identified initial temperature, allowing for immediate commencement of phase monitoring without necessitating any additional calibration procedures.

Changes in temperature will generate changes in the phase of the sensing signal. Here, the HT is used to easily obtain the phase value. The HT, $\mathcal{H}(S(\lambda))$, of the signal $S(\lambda)$ is used to obtain the complex analytic signal $z(\lambda) \in \mathbb{C}$, which can be expressed as:

$$z(\lambda) = S(\lambda) + i\mathcal{H}\big(S(\lambda)\big). \tag{2}$$

The imaginary component is in quadrature with the sensing signal, whereas the sensing signal is the real part of the complex analytic signal, see Fig 1b.

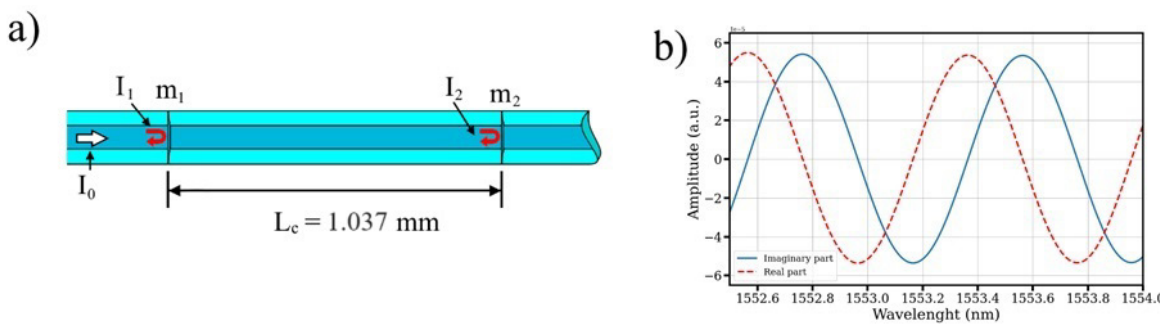

Fig. 1. a) Sensing head formed by two in-fiber mirrors (m_1 and m_2), I_0 represents the light intensity reaching the sensing head, and I_1, and I_2 represent the light intensity reflected at m_1 and m_2 respectively. b) Real (red line) and imaginary part (blue line) of the analytic complex signal.

To reduce the variability in the phase calculation, the complex analytic signal is first normalized by its magnitude defined by $M = \sqrt{Re(z)^2 + Im(z)^2}$. And the phase is calculated as:

$$\theta(\lambda) = arctan\frac{[Im(z_n)]}{[Re(z_n)]} = \frac{4 \cdot \pi \cdot n \cdot L_c}{\lambda} + \theta_0 + \Delta\theta_T, \tag{3}$$

where z_n represents the normalized analytic signal, $z_n = z/M$. In Eq. 3, the phase obtained still includes the wavelength-dependent phase and the initial phase; in this sense, a reference phase measurement is needed to remove these phases components and only extract the change in phase generated by the temperature change. By subtracting this reference phase measurement from the current measurement phase and considering that the only difference between the two is the temperature phase components, the temperature phase difference, $\Delta\theta_T$, can be determined as:

$$\Delta\theta_T = \theta(\lambda) - \theta_R(\lambda). \tag{4}$$

The change in temperature by the change in phase, can be expressed as follows:

$$\Delta T = \frac{\Delta\theta_T}{86.86 \cdot L_c}, \tag{5}$$

This allows for easy calculation of the sensing signal phase and straightforward determination of temperature changes.

3. Experimental setup and results

To demonstrate the effectiveness of implementing the HT for temperature monitoring, an interferometric fiber sensor was implemented as a temperature sensor and its signal being processed using the methodology described in Section 2. In the experimental setup, a broadband source (BBS) is used as the optical source, a low-reflectivity fiber Fabry-Perot interferometer is used as the fiber sensor and an optical spectrum analyzer is used for sensing signal recording, as shown in Fig. 2. The interferometric fiber sensor is made of standard fiber SMF-28, and has a cavity length of 1.037 mm. In this sensor, a two-wave interference pattern is generated by the light reflected from two fiber mirrors forming the cavity.

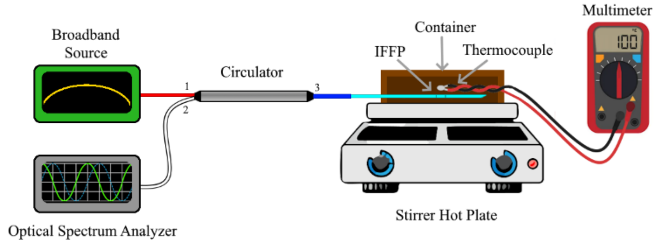

Fig. 2. Experimental setup for temperature monitoring.

In our experiments, the sensor was initially exposed to a known temperature to determine its initial phase using the HT method (see Section 2). A heat-plate was used to apply temperature changes to the fiber sensor, which has been covered with a tunnel-type aluminum protector to ensure temperature stability, as shown in Fig. 2. Using this setup, a series of experiments were conducted, varying the temperature from 50 to 115 °C in steps of 5 °C. The sensing signal was processed using the HT method for temperature determination at each applied temperature. Experimental results showing the spectrum red-shift generated by the increase in temperature are presented in Fig. 3a. Both phase and temperature, calculated using Eq. 4 and Eq. 5 respectively, are shown in Fig. 3b.

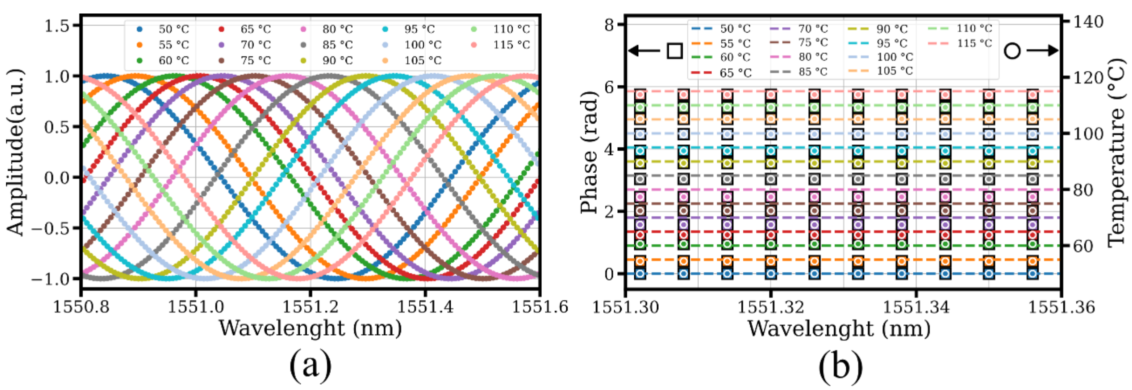

Fig. 3. (a) Comparison of measured sensor signals from 50 to 115 degrees Celsius with 5-degree intervals. (b) Phase and temperature calculated using the proposed method at each interrogated wavelength.

In Fig. 4a, the linear relationship between the applied temperature and the calculated temperatures is shown. The experimental sensitivity of the sensor is 0.09 rad/°C. These results demonstrate that temperature monitoring was effectively performed by using HT method with an error of less than 0.1°C, as shown in Fig. 4b.

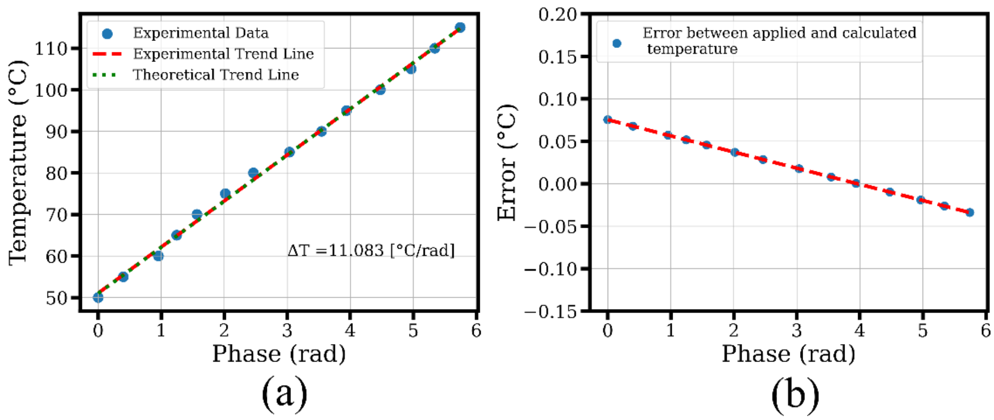

Fig. 4. (a) Phase shift of the temperature sensor signal. The red dashed trend line represents a linear regression of the experimental data points (blue dots), while the green dotted trend line corresponds to the theoretical data trend; (b) Error between the applied temperature and the calculated temperature. The red dashed trend line indicates the linear regression of the experimental data points (blue dots).

The experimental results demonstrate the effectiveness of the fiber optic sensor in temperature monitoring. By using the HT method described in Section 2, the initial phase was accurately determined and subsequent temperature changes were effectively monitored. The setup, which included the thermal plate and the tunnel-type aluminum shield, ensured stable temperature conditions, allowing accurate measurements. The results, shown in Fig. 4a, indicate a clear linear relationship between the applied and calculated temperature, with an error margin of less than 0.1°C, highlighting the reliability of the method. These results suggest that the HT method is a reliable solution for accurate temperature monitoring.

4. Conclusions

The implementation of the HT for temperature monitoring using a fiber interferometer has proven to be highly effective. Results from modeling, simulation, and experiments confirm that the HT method simplifies interferometric phase monitoring. Using an interferometric fiber sensor, the HT method achieves temperature measurement with an error margin of less than 0.1°C. This approach eliminates the need for full sensor characterization, requiring only an initial temperature measurement, facilitating its application in various conditions. The reliability and accuracy of the HT method suggest its potential for numerous temperature monitoring applications. Furthermore, the proposed method can be used in any other interferometric sensor based on two-wave interference.

5. References

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