Heterodyne detection for Fiber Bragg Grating sensors

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Abstract

In this paper, we present a Fiber-Bragg-Grating-based temperature sensor. The technique employs heterodyne detection using two Fiber Bragg Gratings. One of the gratings is used as a reference (local oscillator) and the second as a sensing arm. This sensor uses a Folded Mach-Zehnder interferometer. As the temperature changes, the Bragg wavelength of the FBG shifts. The heterodyne detection is used to detect the frequency difference between the reference and sensing signals that is caused by the temperature change. The dynamic range and sensitivity of the sensor were analyzed and presented.

Optical fiber sensors became devices of choice for many applications over the years [1]. A wide range of fiber sensors have been introduced based on Fiber Bragg Gratings (FBG). Fiber sensors use a variety of techniques to detect the measurands. Some of these based on intensity [2], phase [3], polarization [4], or wavelength changes [5]. Phase sensors are usually based on Mach-Zehnder (MZ) interferometer. The MZ interferometer is an optical instrument capable of high-resolution phase analysis [6]. Recently, FBGs were developed, and enjoyed widespread applications in telecommunications and sensing. The Bragg wavelength of FBG is very sensitive to the environment. This property is exploited in the sensing applications.

It has been demonstrated that the use of interferometric detection of the wavelength shift of a Bragg Grating Sensors can yield very high sensitivity of grating temperature and strain [7,8]. FBG has become the most attractive intrinsic fiber sensor in recent years for various reasons [9]. One of the major advantages of this type of sensor is attributed to wavelength-encoded information provided by Bragg grating when affected by the measurands. Since the wavelength is an absolute parameter, signals from a FBG may be processed such that its information remains immune from power fluctuations along the optical path. Other advantages are the small size, rugged and intrinsic nature of these structures, as well as their multiplexing capabilities.

FBG temperature sensors have been developed with the characteristic advantages of wavelength encoding distributed sensing, and low cost. In this kind of sensors, as the sensed information is encoded directly into wavelength, the output does not depend on the total light levels, losses in the couplers, or light source power fluctuations.

In this paper, we present a new technique for measuring the Bragg wavelength shift using heterodyne detection. In such sensors, we detect the wavelength shifts $\Delta \lambda$ of the reflected light, induced by the temperature changes in the sensing FBG element.

The system used in this temperature sensor is shown in Fig. 1. It is in architecture we name Folded Mach-Zehnder (FMZ) interferometer. The FMZ is made of single-mode fibers with two inscribed identical Bragg gratings. One of these gratings is along the reference arm while the other is along the sensing arm. The light from the broadband source is launched into the single-mode fiber and split by a coupler into the two arms of the FMZ interferometer. The light waves will be reflected by the FBGs and are then combined by couplers C1 and C2 at the output. The phase difference between the two output waves is measured using heterodyne detection. This phase shift is caused by the change in the Bragg wavelength of the sensing arm caused by the temperature change.

The Bragg wavelength of the reflected beam from the FBG is given by

$$\lambda_b = 2nA_b,$$

(1)
where $n$ is the effective refractive index of the fiber grating, $A_b$ is the period of the grating.

The fractional change in the Bragg wavelength when the temperature of the grating sensor is raised by $\Delta T$ (we assume that the strain effect is absent) is given by

$$
\frac{\Delta \lambda_b}{\lambda_b} = \left( \frac{1}{n} \frac{\partial n}{\partial T} + \frac{1}{A_b} \frac{\partial A_b}{\partial T} \right) \Delta T,
$$

where $\Delta T$ is the temperature change, $\alpha_T$ is the coefficient of thermal expansion and $\Delta \lambda_b$ is the shift of the Bragg wavelength.

The thermal response of the FBG arises due to the inherent thermal expansion of the fiber material and the temperature dependence of the refractive index.

The Bragg wavelength shift, $\Delta \lambda_b$, is plotted as a function of temperature change, $\Delta T$, over the range from 0 to 100°C and is shown in Fig. 2. The variation is linear and $\Delta \lambda_b$ increases by the rate of 0.0078 nm/°C.

The relative phase of an optical beam depends on the optical pathlength and is given by

$$
\phi = \frac{2\pi n L}{\lambda_b},
$$

where $L$ is the length of the fiber.

When the temperature change occurs, it affects the phase $\phi$, thus the relationship between the shift in Bragg wavelength, $\Delta \lambda_b$, and the phase shift, $\Delta \phi$, is given by

$$
\Delta \phi = \frac{2\pi n \Delta L \Delta \lambda_b}{\lambda_b^2},
$$

where $\Delta L$ is the optical pathlength difference between the interferometer arms, which is caused by the change in the FBG.

The output optical wave from the FMZ interferometer can be represented by the electric fields, reflected from the FBGs. These two optical waves can be represented by

$$
\Psi_1 = A_1 \cos(\omega_1 t + \phi_1),
$$

and

$$
\Psi_2 = A_2 \cos(\omega_2 t + \phi_2).
$$

Where $\omega_1$ and $\omega_2$ are the angular frequencies of the reflected signals from the reference and the sensing interferometer arms, respectively. $\phi_1$ and $\phi_2$ are the relative phases of the two signals ($\phi_1 = \phi_2$ and $\omega_1 = \omega_2$, when temperature effect is absent). $A_1$ and $A_2$ are amplitudes of the optical waves.

The output waves are detected with a photodiode which acts as a square-law detector. The photocurrent generated by the photodiode is given by

$$
I(t, T) = |A_1 \cos(\omega_1 t + \phi_1) + A_2 \cos(\omega_2 t + \phi_2)|^2.
$$

In Eq. (6) we dropped the effect of the photodiode responsivity. The photodiode will act as a low-pass filter for the optical frequencies. Therefore, the output current will contain only signals with frequencies lower than that of the optical signal. Therefore, the output current is given by

$$
I = A \cos(\Delta \omega t + \Delta \phi),
$$

where

$$
\Delta \omega = (\omega_2 - \omega_1),
$$

and

$$
\Delta \phi = (\phi_2 - \phi_1).$$

The amplitude $A$ depends on $A_1$, $A_2$ and the responsivity of the photodiode.

As the temperature changes, the frequency, $\Delta \omega$, and the phase, $\Delta \phi$, shifts change accordingly.
From Eq. (2), $\Delta \phi$ and $\Delta \omega$ can be expressed as a function of $\Delta T$ by

$$\Delta \phi = \left( \frac{2\pi n \Delta L}{\lambda_b} \right) \left( \frac{1}{n} \frac{\partial n}{\partial T} + \alpha_T \right) \Delta T,$$

and

$$\Delta \omega = \left( \frac{2\pi C}{\lambda_b} \right) \left( \frac{1}{n} \frac{\partial n}{\partial T} + \alpha_T \right) \Delta T.$$

The instantaneous output current, given by Eq. (6), is plotted as a function of temperature as shown in Fig. 3. We have considered two cases for $\Delta L$, namely $\Delta L = 1$ mm and 2 mm, these are shown in Figs. 3(a) and (b), respectively. The dynamic range of the sensor depends on $\Delta L$. As $\Delta L$ increases, the range of temperature that can be measured using this sensor without any ambiguity decreases. In the case of $\Delta L = 1$ mm, the dynamic range is 100°C while for $\Delta L = 2$ mm it is only 50°C, as shown in Fig. 3. For a wider dynamic range one needs to use a smaller value for $\Delta L$. It is obvious that the measurement sensitivity decreases by the increase of dynamic range.

In many applications, the steady-state value of temperature is to be measured. In this case the root mean square (rms) values are to be used for the measurement. Therefore the output current, from Eq. (7), can be rewritten as

$$I = A[\cos(\Delta \omega t) \cos \Delta \phi - \sin(\Delta \omega t) \sin \Delta \phi].$$

Since $\Delta \phi \ll 2\pi$, then

$$I \approx A[\cos(\Delta \omega t) - \Delta \phi \sin(\Delta \omega t)].$$

The rms of the output current is

$$I_{\text{rms}} = A \sqrt{\frac{1}{2} + \Delta \phi^2}.$$

The rms output current, Eq. (14), is a function of $\Delta \phi$ which depends on the temperature change. This relationship is plotted in Fig. 4. The change in rms output current is linearly dependent on the temperature change. So by measuring the current we can determine the temperature change $\Delta T$. At the system level the detector can be connected to a current-to-voltage converter with the proper gain. The reading of a voltmeter can be made to reflect the temperature reading.

In conclusion, we have introduced a new technique for measuring temperature using FBG based fiber sensor. The system is based on the FMZ interferometer. The temperature measurement can be made for instantaneous or average values. The simulated results indicate a wide dynamic range with improved sensitivity.

References


