Temperature Sensor Based on Self-Interference of a Single Long-Period Fiber Grating

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SUMMARY A novel temperature sensor device based on a conventional long-period fiber grating but having an improved sensing resolution is presented. By forming a reflector at one cleaved end of the fiber embedding a long-period grating, a fine interference fringe pattern was obtained within the conventional broadband resonant spectrum of the grating. Due to the fine internal structure of the reflection spectrum of the proposed device, the accuracy in reading the temperature-induced resonant wavelength shift was improved. The formation of the self-interference fringe is analyzed and its properties are discussed in detail. The performance of the proposed device is analyzed by measuring the resonant wavelength shift of the device placed in a hot oven under varying temperature. The rate of the fringe shift is measured to be 55±1 pm/°C. The rms deviation is 10 pm over a 100°C dynamic range, which corresponds to 0.2°C in rms temperature deviation. The thermal variation of the differential effective index of the fiber is calculated to be (0.3 ±0.1)×10⁻⁶/°C by comparing the analytic calculations with the experimental results. The interference fringe shift is revealed to be inversely proportional to the differential effective group index of the fiber, which implies that the shifting rate strongly depends on the type of fibers and also on the order of the involved cladding mode.

Key words: fiber grating, long-period fiber grating, fiber sensor, cascaded fiber grating, temperature sensor

1. Introduction

Fiber gratings have been studied as sensor devices for temperature and strain measurements [1]–[4]. The optical and/or geometrical structures of the fiber that embeds the fiber grating are affected by strain or temperature variation, so that the resonant wavelength of the fiber grating is shifted. The amount of the measured-induced resonant wavelength shift and the accuracy in reading the wavelength shift depend on the type of fiber gratings. In a fiber Bragg grating (FBG), the resonant spectrum has a narrow bandwidth, in the order of sub-nanometer, but the induced wavelength shift is rather small [1], [4]. In comparison to the FBG, the bandwidth of the long-period fiber grating (LPG) is in the range of several tens of nanometers but the wavelength shifting rate is known to be much higher than that of the FBG [3]–[5]. Therefore, when the FBG is used as a sensor device, optical spectrum analyzing instrument with high-resolution is generally required. Whilst, with the LPG, a problem arises in accurate reading of the wavelength shift due to its wide bandwidth. If we can form an internal structure within the broad resonant spectrum of the LPG, we will get an improved sensing resolution in addition to the good readability of the LPG-based sensor. Recently, a cascaded LPG device composed of two in-series identical LPGs has been reported to have interference fringes within the broad stop-band of a conventional LPG spectrum [6]–[10]. However, making an identical LPG pair is practically complicated, and furthermore the reflection spectrum of the device, which is better than the transmission spectrum in installation convenience, is not available because a conventional LPG and a LPG pair have no appreciable reflection.

We present the self-interfering LPG (SILPG) device that exhibits a sinusoidal interference fringe pattern manifested as an internal structure within the broad resonant spectrum of a conventional LPG. The proposed device can be used in the reflection mode as FBG devices. Moreover, it has an improved sensing resolution over conventional LPG devices. It can be fabricated by coating a reflector on one cleaved end of the fiber that embeds a single conventional LPG. The SILPG fringe formation would be explained as the self-interference between the beams which are split by the grating and then recombined by the same grating after being reflected at the coated fiber end. An application as a novel temperature sensor is presented. Due to the finite interference fringe within the wide resonant spectrum of the LPG, the sensor device based on the SILPG inherently gives a better resolution than the one based on a conventional LPG. We also discuss the formalism that governs the temperature-induced resonant wavelength shift. It is also presented that the temperature sensitivity of the device is given as a function of the differential effective group index of the fiber, which is related with the first order dispersion of the fiber.

2. Self Interference in a Single LPG (SILPG)

Formation of interference fringes in a cascaded LPG pair has been well explained by the interference between the core mode and the cladding mode [6]–[9]. Part of the incident core mode is coupled to a cladding mode by the first grating and then, by the second grat-
Both the length and the effective index of the fiber are affected by temperature variation, and the effective index is also a function of the wavelength through dispersion (material and waveguide) of the fiber [12]. Therefore, the expression for the fringe shift induced by temperature variation is obtained by taking partial derivatives of Eq. (1) with respect to temperature and wavelength at $\lambda_{p0}$ and $T_0$:

$$p \cdot \frac{d\lambda_p}{dT} = \frac{d\lambda_{p0}}{dT} \frac{\partial}{\partial \lambda} \left( \Delta n_1 L_1 + \Delta n_2 L_2 \right) + \frac{\partial}{\partial T} \left( \Delta n_1 L_1 + \Delta n_2 L_2 \right).$$  

(2)

Rearranging the equation, we get

$$\frac{d\lambda_p}{dT} = \frac{\frac{\partial}{\partial \lambda} \left( \Delta n_1 L_1 + \Delta n_2 L_2 \right)}{p - \frac{\partial}{\partial T} \left( \Delta n_1 L_1 + \Delta n_2 L_2 \right)}.$$  

(3)

Since the length of fiber is not a function of wavelength and the mode order $p$ was given in Eq. (1), Eq. (3) becomes

$$\frac{d\lambda_p}{dT} = \frac{\lambda_{p0}}{\Delta m_1 L_1 + \Delta m_2 L_2} \cdot \left( \frac{\partial \Delta n_1}{\partial T} L_1 + \frac{\partial \Delta n_2}{\partial T} L_2 + \Delta n_1 \frac{\partial L_1}{\partial T} + \Delta n_2 \frac{\partial L_2}{\partial T} \right),$$  

(4)

where $\Delta m_1$ and $\Delta m_2$ are the differential effective group indices of the grating region and the grating-free region, respectively, and they are defined by

$$\Delta m_{1,2} = \Delta m_{1,2} - \lambda \frac{\partial \Delta n_{1,2}}{\partial \lambda}.$$  

(5)

For weak grating, we can approximate the differential effective indices $\Delta n_1$ and $\Delta n_2$, to be equal $\Delta n_{eff} = \Delta n_{1} \approx \Delta n_{2}$. In this case, we obtain the simplified expression for the temperature-induced fringe variation [9], [12],

$$\frac{d\lambda_p}{dT} = \lambda_{p0} \left( \frac{\partial \Delta n_{eff}}{\partial T} + \Delta n_{eff} \cdot \alpha_T \right),$$  

(6)

where $\alpha_T$ is the thermal expansion coefficient of the fiber. Equation (6) indicates that the wavelength shifting rate is inversely proportional to the differential effective group index of the fiber. Therefore, the first order dispersions not only of the core mode but of the cladding mode affect the temperature-induced wavelength shift as well.

The grating part of the SILPG device, when used as a sensor device, is also under temperature variation, thus the spectral center of the envelope spectrum would be also shifted by the temperature variation. The expression of the resonant wavelength of a LPG, $\lambda_{env}$, is well known and given by [5], [11]

$$\lambda_{env}(T) = \Delta n_1(T, \lambda) \cdot \Lambda(T),$$  

(7)

where $\Lambda(T)$ is the periodicity of the grating under temperature variation. By taking partial derivatives of $\Lambda(T)$,
Eq. (7) with respect to temperature and wavelength, we obtain
\[
\frac{d\lambda_{en}}{dT} = \frac{\Lambda}{1 - \Lambda \frac{\partial \Delta n_1}{\partial \lambda}} \left( \frac{\partial \Delta n_1}{\partial T} + \Delta n_1 \cdot \alpha_T \right). \tag{8}
\]
Equation (8) is valid for the FBGs as well, in which the differential effective index $\Delta n_1$ is replaced with the effective index of the core mode $n_{c_{core}}$. Due to the long periodicity of a LPG compared with a FBG, the wavelength shifting rate of the LPG is generally larger than that of the FBG. Furthermore, it is also possible to get reduced thermal sensitivity by selecting a proper cladding mode through adjusting the LPG periodicity, and even negative sensitivity has been reported [3].

By substituting Eq. (7) into Eq. (8), we get the expression,
\[
\frac{d\lambda_{en}}{dT} = \frac{\lambda_{en}}{\Delta m_1} \left( \frac{\partial \Delta n_1}{\partial T} + \Delta n_1 \cdot \alpha_T \right), \tag{9}
\]
which is similar to Eq. (6). The only difference is that the effective index of the fiber might be affected by the grating itself and by the UV irradiation during the grating fabrication process. These effects, however, have been reported to be negligible within the first order approximation when the grating strength is weak and/or the unperturbed length of a LPG pair is much larger than the grating length [9, 12]. Therefore, it is expected that the interference fringe of the SILPG under temperature variation is shifted with its envelope curve at a similar rate. The experimental confirmation will be described in the following section.

In Eqs. (6) and (9), the wavelength shifting rate is inversely proportional to the differential effective group index of the fiber that is not generally provided with other fiber parameters. Fortunately, the differential effective group index of the fiber can be obtained by measuring the spectral spacing between adjacent interference fringe peaks, which is given as [9, 12]
\[
\Delta\lambda_{\text{spacing}} = \frac{\lambda_p^2}{\Delta m \cdot (L_1 + L_2)}. \tag{10}
\]

3. Experiments and Results

The LPG was made in a hydrogen-loaded DSC-type (dual shape core) dispersion-shifted fiber (DSF) of Mitsubishi by illuminating KrF excimer laser beam through an amplitude mask of 500 μm periodicity. The length of the grating was 20 mm, and the grating strength was controlled to have around 3 dB peak loss at the center of the stop-band positioned around 1.55 μm. The reflector was made by cleaving one end of the fiber embedding the LPG and then coating it with gold using a DC sputter. The distance between the grating end to the fiber end was 24 ± 1 mm.

Figure 2 shows the reflection spectrum of the proposed SILPG device. It is observed that each stop-band has interference fringes and the contrast of the fringe in the higher order stop-band is worse than the one in the lower order band. Within the stop-band positioned around 1.55 μm, the fringe contrast is very weak. It is considered that the optical quality of the cleaved fiber end surface was not good enough and/or the coating on the cladding surface, which was unintentionally made during the coating process, deteriorated the cladding mode [9]. Whilst the fringes in the first stop-band have rather good contrast and the corresponding stop-band is deeper than the second stop-band. We note that the DSC type fiber has an inner cladding layer, which might induce the first cladding mode to be distributed quite close to the center of the fiber [9, 13]. Generally, the optical quality of the cleaved end surface of a fiber is good near the center of the fiber compared to the quality out of the center. Furthermore, the cladding mode that is highly confined inside of the fiber has no appreciable interaction with the optical condition of the cladding surface. These might explain the relatively good fringe contrast at the low-order stop-band.

The temperature sensitivity of the SILPG was measured by putting the fiber in an oven. The fringe shift in the first stop-band of the SILPG was measured with an optical spectrum analyzer of a 0.1 nm spectral resolution over temperature range of 60°C–160°C, and the results are plotted in Fig. 3. The oven temperature was measured using a conventional mercury thermometer whose relative reading accuracy was about 0.5°C. As expected from Eq. (6), the fringe shift is well fitted with a linear curve that is shown in Fig. 3 as the dotted line. It has a slope of 55±1 pm/K, and the rms (root mean square) deviation is about 0.1 nm. The high resolution in reading the fringe shift was obtained by using the cross correlation between the fringe spectra measured at different temperatures. The spectrum measured at 75°C was used as the reference spectrum. The spectrum measured at a different temperature is compared with the reference one after intentionally shifting its center wavelength for the best matching. By using a
The temperature-induced wavelength shift of the SILPG plotted as a function of the oven temperature. The rms deviation with a linear fitting curve is 0.1 nm (dotted line) and 0.01 nm with a quadratic fitting curve (solid line).

The reflection spectra of the SILPG measured at two different temperatures, 75°C (dotted line) and 150°C (solid line). The spectrum has been shifted to the longer wavelength direction by 4.1 nm due to the temperature variation.

The reflection spectra of the SILPG measured at two different temperatures, 75°C (dotted line) and 150°C (solid line). The spectrum measured at 75°C is shifted by 4.1 nm and compared with the one of 150°C.

quadratic fitting curve shown as the solid line in Fig. 3, we obtained an improved rms deviation of 0.01 nm over 100°C dynamic range. This corresponds to a reading accuracy of 0.2°C for temperature measurements. The improved rms deviation with the quadratic curve fitting might be explained with the higher order terms that were neglected in driving Eq. (6) and will be discussed in the following discussion section.

Figure 4 shows the reflection spectra of the proposed SILPG device measured at two different temperatures, 75°C and 150°C. It appears that the relative phase of the interference fringe over the envelope curve was not changed appreciably. In order to get a close look, the spectrum measured at 75°C was redrawn after shifting the center wavelength by 4.1 nm in Fig. 5. In the figure, both spectra are well matched each other except for the overall intensity variation, which was due to the source power fluctuation. As was discussed and expected in the previous section, the envelope spectrum of the SILPG, which is determined by the grating itself, is thermally shifted with its embedding interference fringe at a similar rate. Therefore, it can be concluded that the temperature sensing resolution is improved by forming the interference fringe within the conventional broadband resonant spectrum of a single LPG. Our temperature measurement accuracy of 0.2°C rms deviation over 100°C dynamic range is about 7 times better than the result of Patrick (1.5°C) where a conventional LPG was used as the sensing element [4].

4. Discussion

From Eq. (6) and the measured temperature-induced resonant wavelength shifting rate of the SILPG, the thermal variation of the differential effective index and the contribution of the thermal expansion of the fiber to the wavelength shift can be calculated. The differential effective group index of Eq. (6) is calculated to be $\Delta m = (8.1 \pm 0.2) \times 10^{-3}$ from the spectral spacing between adjacent fringe peaks of the SILPG and Eq. (10); the fringe spacing was measured to be 3.9±0.05 nm in the first stop-band of Fig. 1. Using the value of $\Delta m$, the sum of the terms in the parenthesis of Eq. (6) becomes $\frac{\partial \Delta n_{eff}}{\partial T} = (0.3 \pm 0.1) \times 10^{-6} / ^\circ C$. The differential effective index of the fiber is also calculated to be $\Delta n_{eff} = (2.94 \pm 0.005) \times 10^{-3}$ simply from the phase matching condition of the LPG, Eq. (7); the grating periodicity of 500μm was used. By using the thermal expansion coefficient of fused silica, $0.5 \times 10^{-6} / ^\circ C$, the contribution of the thermal expansion of the fiber is calculated to be $1.5 \times 10^{-9} / ^\circ C$; about 200 times smaller than the factor from the temperature-induced differential effective index variation. We conclude from this analysis that most of the fringe shift of the SILPG resulted from the thermal variation of the differential effective index, thus we have $\frac{\partial \Delta n_{eff}}{\partial T} = (0.3 \pm 0.1) \times 10^{-6} / ^\circ C$.

The differential effective group index was found to be about 3 times larger than the differential effective index of the fiber ($\Delta m/\Delta n_{eff} \approx 2.8$). The difference
between two indices is not negligible in LPG devices, which appreciably depends on the type of fiber and the order of the involved cladding mode [12]. It has been also reported that the resonant wavelength of a LPG coupled to a different cladding mode was shifted at a different rate during the grating writing process [14]. The ratio between the UV-induced wavelength-shifting rate of two different cladding modes was observed to be larger than 2 times in some modes. Thus it is expected that the temperature-induced resonant wavelength-shifting rate will appreciably depend on the order of the cladding mode.

The measured fringe shift was well fitted to a quadratic curve, about 10 times better than to a linear curve. As was mentioned before with Eq. (6), the temperature-induced wavelength shift is an explicit and implicit function of wavelength through the differential effective group index of the fiber. Moreover, the derivative of the differential effective index with respect to temperature might be a function of wavelength as well. Therefore, the curvature of the plotted data in Fig. 2 might be explained as these second-order effects. However, further analysis was limited due to the experimental errors in measuring the oven temperature (~0.05°C) by a mercury thermometer and the power fluctuation of the LED (light emitting diode) light source (~0.5 dB). The oven was initially heated up to 170°C, and then turned off during the measurements. The cooling rate of the oven gradually slowed down from about 1.7°C/min at 160°C to 0.4°C/min at 60°C. Future improved apparatus is expected to allow better sensor performance.

It was also observed that a simple cleaved end without reflection coating gave interference fringes in the reflection spectrum, but the background intensity level was very low (~15 dB lower than the coated one). The Fresnel reflection at the cleaved fiber end explains the formation of the faint interference fringes of the SILPG without a coated reflector. Although, in our experiment, gold coating was used to make the reflector, we also got a similar fringe contrast with silver coating [15]. It is to be noted that the fringe contrast is primarily determined by the optical quality of the cleaved fiber end surface and/or the cladding surface.

5. Conclusion

We have presented a novel sensor device based on a LPG but having an improved sensing resolution over the devices based on conventional LPGs. The improved resolution was obtained by measuring, in the reflection mode, the shift of the fine interference fringe pattern formed within the broad resonant spectrum of a conventional LPG. The fringe formation in the SILPG has been explained by the mechanism used for a conventional LPG pair. A reflector was made at one cleaved end of the fiber embedding the LPG, which reflects simultaneously the core and cladding modes coupled by the LPG and guided along the fiber. The reflected modes interfere with each other at the same grating and produce the fringe pattern. The fringe spacing is inversely proportional to the distance between the grating center and the fiber end. It also depends on the differential effective group index of the fiber. The interference fringes are enveloped by the broadband resonant spectrum of the LPG, and the fine internal structure makes possible the improved temperature resolution.

For temperature sensing, we observed that the fringes moved toward the longer wavelength with increasing temperature at the rate of 55±1 pm/°C. Most of the thermally induced fringe shift was attributed to the variation of the differential effective index of the fiber. The contribution of the thermal expansion of the fiber was calculated to be less than 1%. The temperature measurement accuracy of 0.2°C rms deviation was obtained over 100°C dynamic range. The interference fringe was observed to be shifted together with its enveloping curve, which implies that grating formation does not appreciably change the differential effective group index of the fiber. From the measured fringe spacing and the wavelength shifting rate, the thermal variation of the differential effective index was calculated to be $\frac{\partial \Delta n_{ef}}{\partial T} = (0.3 \pm 0.1) \times 10^{-6} /{°C}$. We expect that the proposed SILPG device will be useful not only as a sensor for fine temperature measurements but also as a multi-channel filter for DWDM telecommunications.

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References


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