Simultaneous strain and temperature sensor using superimposed tilted Bragg gratings

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We report the use of superimposed tilted Bragg gratings for the simultaneous measurement of longitudinal strain and temperature. The gratings are inscribed using only one phase mask tilted in the plane perpendicular to the laser beam. They are overlaid so to behave as a punctual sensor. The sensor allows real time measurements and a great ease of use. Its accuracy falls within 3°C and 12 με in the ranges 25-90°C and 0-1500 με.

Introduction

Fiber Bragg grating sensing is based on the principle that the measured information is wavelength-encoded in the reflection spectrum of the grating. This behavior leads to a sensor immune to fluctuating light levels, source power and connector losses. However the cross-sensitivity between temperature and strain effects cannot be easily resolved. Various schemes have thus been developed to discriminate between these effects [1, 2, 3]. More recently, a strain and temperature sensor using a fiber Bragg grating written on the splice joint between two different fibers has been reported [4]. It ensured weak errors of ± 8.5 με and ± 1.6°C. However, the sensor was rather fragile and the maximum measurable strain was limited to 500 με. A sensor composed of two superimposed fiber Bragg gratings (SFBG) exhibiting two different Bragg wavelengths constitutes a good alternative to these previous schemes [5]. SFBG are commonly obtained using two phase masks [6] or by the interferometric technique [7]. This last method requires the rotation of the mirrors and the relative displacement of the fiber to tune the Bragg wavelength of the inscribed gratings. A great care must thus be taken to ensure that the intersecting beams form the fringe pattern at exactly the same location of the fiber each time a new grating is written. The phase mask method is easier to use but the tuning of the Bragg wavelength is only possible using different masks, which is rather expensive. An alternative method is to strain the fiber during the inscription of the grating [8]. The tuning range is however limited by the mechanical strength of the fiber and is only a few nanometers. To overcome these disadvantages, we have written superimposed Bragg gratings using only one phase mask. The possible tuning range allowed by our method can extend to about 150 nanometers. Using the theory of tilted gratings [9], we can predict the Bragg wavelength of the grating. We use here a dual grating for simultaneous strain and temperature measurement.

Experiment

The SFBG were inscribed into hydrogen-loaded single mode fiber through a 1060 nm period phase mask. We used a frequency doubled Argon laser with 6 mm beam width and about 150 mW power. The phase mask was mounted on a rotator so that it was possible to apply a tilt in the plane perpendicular to the laser beam. To modify the inscribed wavelength, the only parameter to change is the angle θ (see Figure 1).

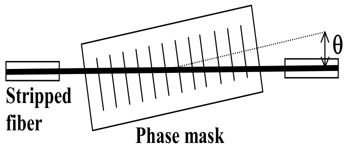

Figure 1: Rotation of the phase mask to superimpose tilted fiber Bragg gratings

This single modification confers to the method a great ease of use. When θ is null, the inscribed grating is uniform and its central wavelength is called λ_{Bragg}. It depends both on the period of the mask and on the refractive index of the fiber. When θ is not null, the central wavelength of the tilted grating is simply given by :

$$\lambda'_{\text{Bragg}} = \frac{\lambda_{\text{Bragg}}}{\cos\theta} \quad (1)$$

Because of the cosine function, the central wavelength of a tilted grating is always greater than the one of the uniform grating. Unfortunately the angle θ cannot take any value. Erdogan and Sipe have already used the coupled mode equations to study the evolution of the maximum grating reflectivity versus tilt angles [9]. They have reported that the reflectivity decreases steadily to zero for tilt angles varying from 0 to 45 degrees. They have also shown the appearance of several punctual sharp drops during this evolution. In our experiments, we have obtained a similar behavior leading to the impossibility to measure the reflected spectrum at some tilt angles. Physically, this behavior comes from the total coupling between the LP_{01} mode launched into the tilted grating and the continuum of radiated modes. This limitation was however not problematic for us since our interest was to manufacture SFBG with reflected peaks far from each other. The more the tilt angle is high, the more the grating is short and the more the exposure time must be high to get a reflected peak.
We have used a dual superimposed grating for the simultaneous measurement of strain and temperature. A previous work presented a sensor using two uniform gratings of 850 nm and 1300 nm of central wavelengths [4]. The sensor required the use of two LEDs, two couplers and two optical spectrum analyzers. Our goal was to use a simpler setup so that the interrogation scheme can offer real-time measurement and a decrease of the cost.

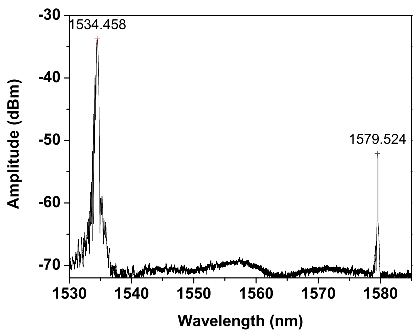

Figure 2: Reflected spectrum of the dual superimposed grating used for sensing purposes

To discriminate between strain and temperature, the sensitivities of the two gratings in response to these two effects must be different. It is the case if their Bragg wavelengths are sufficiently far from each other. We have thus determined the tilt angle allowing to design a SFBG presenting two reflected peaks as distant as possible within the bandwidth of the optical source. Since we planed to use an ASE source covering the C+L bands, we have superimposed a uniform grating and a 14° tilted grating. The reflected spectrum is presented in Figure 2. Bragg wavelength shifts due to a combination of temperature and strain are given by the following set of equations :

$$\begin{pmatrix} \Delta\lambda_{\text{Bragg1}} \\ \Delta\lambda_{\text{Bragg2}} \end{pmatrix} = \begin{pmatrix} K_{T1} & K_{\varepsilon 1} \\ K_{T2} & K_{\varepsilon 2} \end{pmatrix} \begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} \quad (2)$$

where ΔT and Δε represent the shifts in temperature and in strain, respectively. K_T is determined by the thermo-optic coefficient and by the thermal expansion coefficient. K_ε is linked to both the Poisson ratio of the fiber and the photoelastic coefficient. As the thermo-optic and photoelastic coefficients are wavelength dependent, fractional wavelength shifts of every grating are different even if the gratings undergo the same levels of temperature and strain. The coefficients of the K matrix have been experimentally determined by separately measuring the Bragg wavelength shifts in response to temperature and strain. Once K is known and provided that the matrix inversion is well conditioned, changes of strain and temperature can be obtained taking the inverse of Eq. (2). Strain was applied by different loads placed at the end of the fiber containing the SFBG. Temperature was set using an oven regulated by a thermoelectric temperature controller. The calibrations were realized using a tunable laser source, a wavemeter and an optical powermeter. Figure 3 shows the calculated linear regressions. The measured values of the K elements were respectively K_{T1} = 9.41 ± 0.03 pm/°C, K_{T2} = 9.82 ± 0.04 pm/°C, $K_{\varepsilon 1}$ = 1.22 ± 0.01 pm/με, $K_{\varepsilon 2}$ = 1.29 ± 0.01 pm/με. The determinant of K is not null and thus the matrix is well conditioned. The dual sensor was finally tested for the simultaneous measurement of temperature and strain. The peak wavelengths were measured using a broadband light source and an optical spectrum analyzer ANDO AQ 6317C. This last one provides a wavelength sampling of 1 pm during the recording of the reflection spectrum. Its wavelength reproducibility is guaranteed to be equal to ± 5 pm. This value yields to a random error of the sensor of ± 0.5°C or ± 5 με. The optical spectrum analyzer was controlled by a computer in which an autocorrelation algorithm was implemented [10]. Using a gaussian extrapolation around the Bragg wavelength of every grating, the algorithm allows a subpicometric wavelength sampling, ensuring a very weak extrapolation error and a greater resolution for the determination of the wavelength shifts.

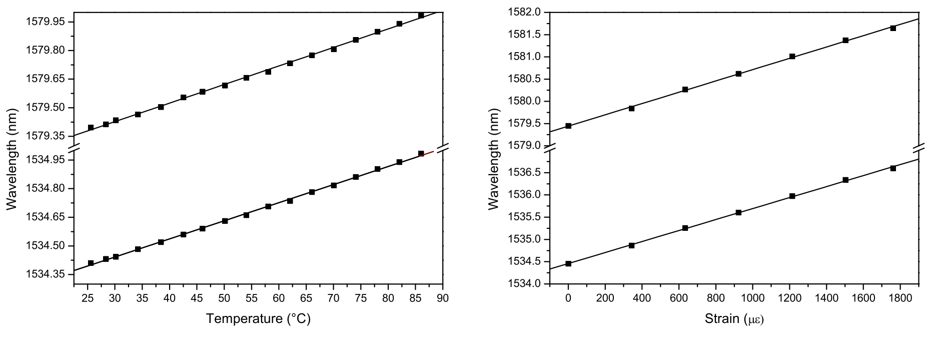

Figure 3: Wavelength shifts of the two gratings with respect to temperature and strain

The table below shows some experimental results. The errors on the determination of temperature and strain were respectively within ± 3°C and ± 12 $\mu\varepsilon$. Owing to the autocorrelation demodulation technique, the accuracy of our sensor is very good.

		The set points of temperature			
		29.3°C	**46.3°C**	**67.8°C**	**86.9°C**
The set points of strain	**344 με**	27.6°C 353 με	48.7°C 355 με	70.1°C 332 με	84.2°C 354 με
	634 με	31.9°C 646 με	49.2°C 626 με	64.9°C 623 με	85.8°C 629 με
	923 με	28.7°C 913 με	45.2°C 918 με	68.7°C 911 με	87.4°C 934 με
	1215 με	31.5°C 1204 με	43.1°C 1220 με	64.9°C 1222 με	89.2°C 1209 με

Conclusion

We have presented a simple, accurate and ponctual sensor for the simultaneous measurements of temperature and strain. It uses two superimposed tilted gratings inscribed through only one phase mask. The wavelength shift between the two reflected peaks is about 45 nm allowing the use of a simple interrogation scheme with only one source and one spectrum analyzer. This ensures real-time measurements and a decrease of the overall costs compared to already existing setups.

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