LETTER

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Loss peak adjustment of long period fiber grating fabricated with CO_2 laser by applying tension

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Abstract: This study aims to propose a method for adjusting loss peak in the spectrum of long period fiber grating fabricated with CO_2 laser by applying tension with some weight to make the loss peak suitable for a multi-point temperature sensor under a high temperature environment. This method could achieve an increase of 5.3 dB in the value of loss peak by loading the fiber with a weight of 150 g. Furthermore, it was found that the method had a minimal influence on the temperature sensitivity of the long period fiber grating in the range varying from room temperature to 800°C.

Keywords: LPFG, CO_2 laser, temperature sensing

Classification: Optical systems

References

[1] A. M. Vengsarkar, *et al.*: "Long-period fibre gratings as band-rejection filters," J. Lightwave Technol. **14** (1996) 58 (DOI: 10.1109/50.476137).

[2] T. Enomoto, *et al.*: "Long-period fiber grating in a pure-silica-core fiber written by residual stress relaxation," 1998 OSA Tech. Dig. Series **2** (1998) (DOI: 10.1109/OFC.1998.657398).

[3] G. Humbert and A. Malk: "Characterizations at very high temperature of electric arc-induced long-period fibre gratings," Opt. Commun. **208** (2002) 329 (DOI: 10.1016/S0030-4018(02)01632-2).

[4] K. Morishita, *et al.*: "Refractive index variations and long-period fiber gratings made by the glass structure change," IEICE Trans. Electron. **E86-C** (2003) 1749.

[5] C. D. Poole, *et al.*: "Two-mode fibre spatial-mode converter using periodic core deformation," Electron. Lett. **30** (1994) 1437 (DOI: 10.1049/el:19940948).

[6] D. D. Davis, *et al.*: "Long-period fibre grating fabrication with focused CO_2 laser pulses," Electron. Lett. **34** (1998) 302 (DOI: 10.1049/el:19980239).

[7] D. D. Davis, *et al.*: "Very-high-temperature stable CO_2-laser-induced long-period fibre gratings," Electron. Lett. **35** (1999) 740 (DOI: 10.1049/el:19990483).

[8] O. Koyama, *et al.*: "High temperature detection inside large-scale plants using distributed sensor fabricated by 10 LPG resonant wavelengths multiplexing," IEICE Electron. Express **10** (2013) 20130586 (DOI: 10.1587/elex.10.

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20130586).
[9] Y.-P. Wang, *et al.*: "A novel tunable gain equalizer based on a long-period fibre grating written by high-frequency CO_2 laser pulses," IEEE Photonics Technol. Lett. **15** (2003) 251 (DOI: 10.1109/LPT.2002.806104).
[10] Y. Sato, *et al.*: "Dependence on grating length of transmission spectra of long-period fiber bragg grating," J. Soc. Mater. Sci. Japan **59** (2010) 239 (DOI: 10.2472/jsms.59.239).

1 Introduction

Optical fiber sensors have many advantages in comparison with electrical sensors, such as non-interference with electromagnetic waves, not requiring a power source for the sensing component and remote sensing can be achieved over several kilometers without an amplifier. These sensors can be used in harsh environments where it is difficult for humans to enter; for example, temperature sensors in oil wells. Long period fiber gratings (LPFG) are one of the numerous types of optical fiber sensors. They attenuate the light transmitted through the fiber in a certain wavelength range. The wavelength in which the attenuation at a loss peak is the largest is called as the resonant wavelength (λ_R). One of the characteristics of LPFG is that λ_R shifts depending on the temperature; this feature is useful for temperature sensing applications. Ultraviolet light irradiation [1, 2], arc discharge [3, 4] and light irradiation with a CO_2 laser [5, 6], among others, have been proposed as the fabrication methods of LPFG. Especially, it is known that the LPFGs fabricated by CO_2 laser method are highly stable in environment with high temperature [7].

We previously reported a multi-point temperature sensor that works at high temperatures by cascading a number of CO_2-laser-induced LPFGs with different λ_R values [8]. In this sensor, the temperature is simultaneously detected at multi-locations by evaluating the amount of the shift at each λ_R in the loss spectrum. The loss spectrum of the sensor consists of the loss spectrum of each of the cascaded LPFGs. Therefore, each λ_R is affected by the other loss spectra and it is thus necessary to adjust the loss value (L_R) of the loss peak at the λ_R in each spectrum. For the L_R adjustment, the transverse-load method [9] was used. However, the effect of the adjustment method on the temperature sensitivity under a high temperature environment is yet to be evaluated.

This study aims to propose a method for adjusting L_R by applying tension to a CO_2-laser-induced LPFG. We present the effectiveness and validity of the proposed method through experimental results and theoretical study. Furthermore, the effect on the temperature sensitivity of LPFG was evaluated at a wide range, from room temperature to 800°C.

2 Experimental set-up

Fig. 1 shows the experimental set-up for LPFGs fabrication with weight added to an optical fiber. In this experiment, commercially available single-mode optical fibers were used. Constant tension was applied by fixing an end of the optical fiber on the 1-dimension moving stage, and the other end was connected to a weight and

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thus the fiber was maintained in a horizontal position. The refractive index of the fiber core can be lowered depending on the CO_2 laser irradiation power, P_L. The fiber jacket in the irradiated part of the fiber was removed before irradiation. The stage can be moved with the controller to only a grating period, Λ, along the fiber axis. After irradiating and moving several times, LPFG with length L can be fabricated. In this work, λ_R and L_R of loss peak was measured for each weight, x, after a LPFG was fabricated. For this measurement, a broadband light source (BLS) and optical spectrum analyzer (OSA) were used. A computer was connected to the OSA to analyze the loss spectrum of the CO_2-laser-LPFG and obtain λ_R and L_R in it.

Fig. 2*a* shows the temperature evaluation set-up for the CO_2-laser-induced LPFG, which was placed in the heating furnace with weights ranging from 2 to 150 g. Fig. 2*b* shows the temperature increase rate of the furnace, which can reach ~1100°C. The average increase rate was ~20°C/min until 80% of the pre-set temperature was reached, then the temperature gradually stabilized at the pre-set value. The LPFG in the furnace was also loaded with a tension of weight x.

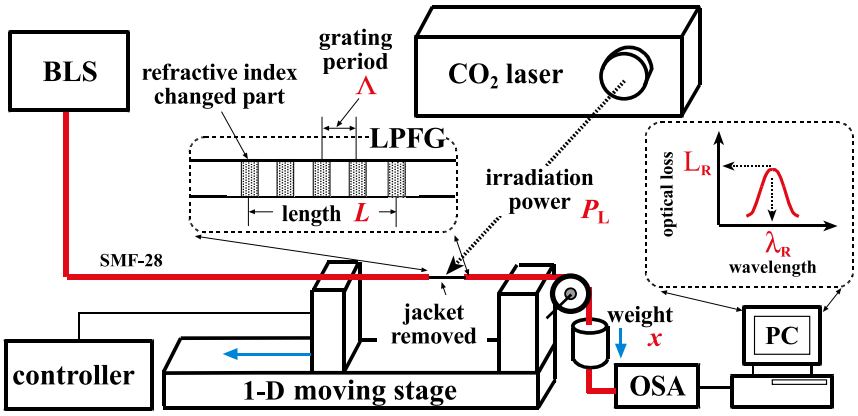

Fig. 1. Experimental set-up for LPFG fabrication.

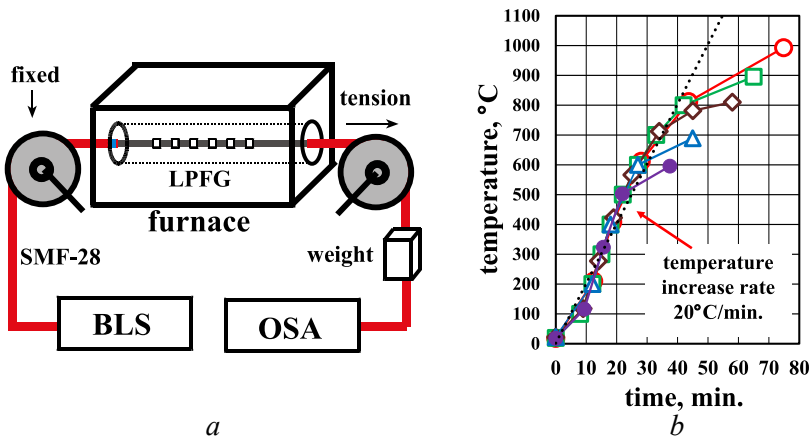

Fig. 2. *a*. Experimental set-up for temperature evaluation.
b. Temperature increase rate of heating furnace.

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3 Tension dependence of the loss value at λ_R

All of the evaluated LPFGs were fabricated using the same parameters: P_L = 4.8 W, Λ = 500 µm, L = 0.025 m and x = 12.8 g. Fig. 3 shows the changes in the loss spectrum when x varied in the range 12.8–150 g after the LPFG fabrication. The temperature of the environment was maintained to 27°C. As x increased, L_R also increased. The L_R of the LPFG samples were: 7.88 dB with 12.8 g, 9.19 dB with 50 g, 10.9 dB with 100 g and 13.0 dB with 150 g. Fig. 4 shows the amounts of the L_R changes using 12.8 g as a reference. Each point in Fig. 4 indicates the average value of seven LPFG samples for each weight. The slope obtained by a linear approximation was 0.035 dB/g. Since the L_R change increased almost linearly until 5.3 dB (150 g), L_R can be adjusted by changing the tension. Furthermore, theoretical L_R values were calculated, and then compared with the experimental results. The L_R change can be expressed as (1) and (2), based on reference [1, 10]:

$$\Delta L_R = -10\log_{10}\frac{1-\sin^2\{\kappa(L+\Delta L)\}}{1-\sin^2(\kappa L)}, \tag{1}$$

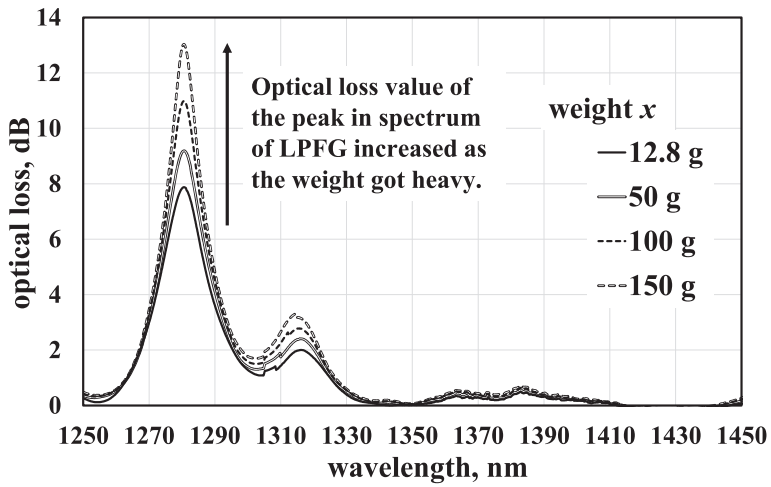

Fig. 3. Loss spectrum change by applying tension.

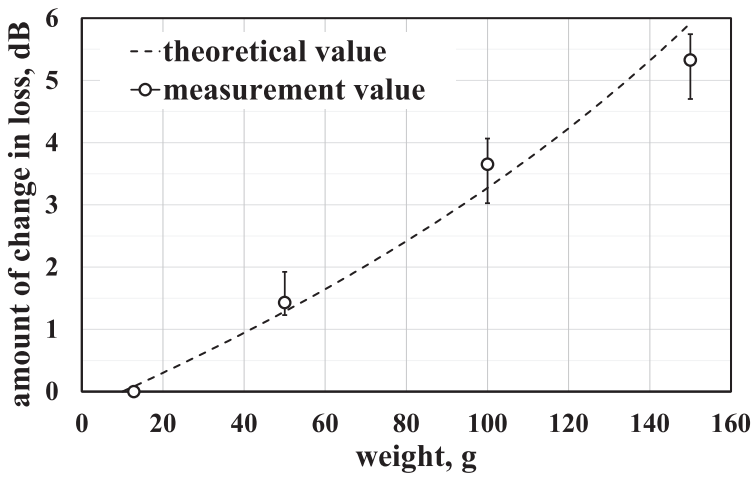

Fig. 4. Loss peak change by applying tension.

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$$\kappa = k\frac{\delta n}{2}, \tag{2}$$

where κ, ΔL and δn represent the coupling coefficient, LPFG length change and refractive index change of the fiber core, respectively. δn is defined as (3):

$$\delta n = n - n'\frac{L}{L + \Delta L}, \tag{3}$$

where n and n' respectively represent the refractive index of the core before and after CO_2 laser irradiation. It was assumed that δn depended only on ΔL produced by applying tension. Moreover, ΔL was expressed as (4):

$$\Delta L = \frac{g}{K}x \cdot 10^{-3}, \tag{4}$$

where g and K represent the gravitational acceleration and elastic coefficient, respectively. It was assumed that ΔL depended only on x. The calculation parameters were set as follows: $\kappa = 3.1501 \times 10^5$, $K = 1.5060\,\mathrm{N/m}$, $g = 9.8065\,\mathrm{m/s^2}$, $n = 1.4557$ and $n' = 1.4554$ (the values of n and n' were experimentally measured). The dashed line in Fig. 4 shows the calculated results, which were consistent with the experimental values. This confirms that the adjustment method for L_R was appropriate.

Next, the dependence of λ_R on the tension applied was evaluated. Seven samples of the CO_2-laser-induced LPFG were additionally fabricated with the same parameters. Fig. 5 shows the average shift of λ_R depending on the weight. The temperature was also kept at 27°C. The values were compared using 12.8 g as a reference. The λ_R slightly red-shifted as the weight increased. The largest shift was 0.5 nm for 150 g, this was evaluated as a temperature change of 4.2°C employing a temperature coefficient of 0.119 nm/°C. Therefore, when the proposed method is used, it is necessary to consider temperature error into the λ_R shift at the room temperature.

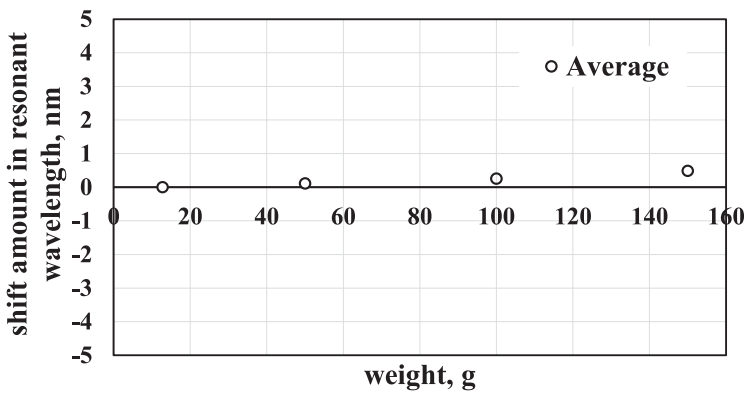

Fig. 5. Resonant wavelength change according to tension.

4 Adjustment limitation of L_R

Fig. 6 shows the rupture rate of the optical fiber with each weight. The loading time of the weight was set to 3 min., and the number of trials was 22. The rupture rate

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was 0% in the range 12.8–100 g. Then, it increased to ~5% with 150 g. Therefore, the upper limit for stable adjustment was set to 3.7 dB with 100 g.

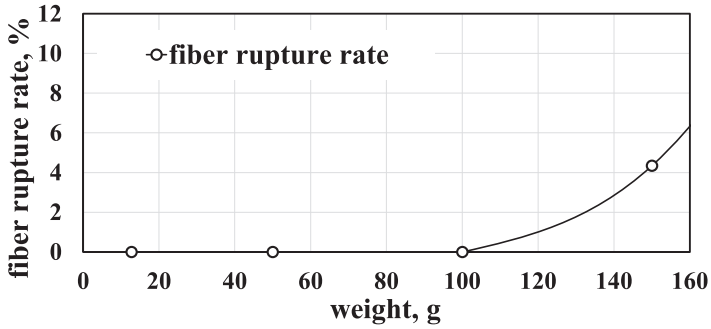

Fig. 6. Fiber rupture rate depending on weight.

5 Impact of loss peak adjustment method on temperature sensitivity

Fig. 7 shows the spectrum when the temperature was changed from room temperature to 800°C with the 78.8 g weight. The λ_R red-shifted linearly with an increase in the temperature. The shift was 91 nm, and the temperature coefficient was 0.119 nm/°C. Similarly, the evaluation was conducted several times with each weight from 2 to 150 g when the temperature in the heating furnace changed from room temperature to 800°C. Each point in Fig. 8 represents the average temperature coefficient for each weight. The total average of the evaluated temperature coefficients was 0.106 nm/°C. The temperature coefficient change using the proposed method with weights from 2 to 150 g was minor; it fluctuated within ±0.013 nm/°C. It was considered that this fluctuation resulted from the degree of accuracy in the experimental set-ups for LPFG fabrication and temperature evaluation. Consequently, the proposed method was found to have only a slight effect on λ_R shift.

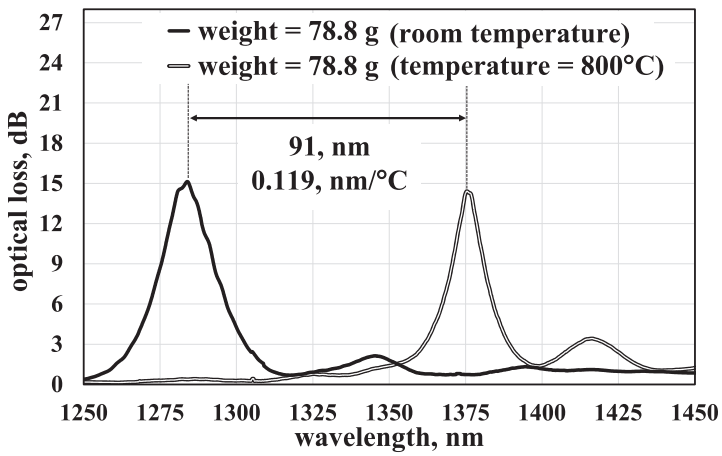

Fig. 7. Loss spectra of LPFG applied tension in room temperature and in high temperature.

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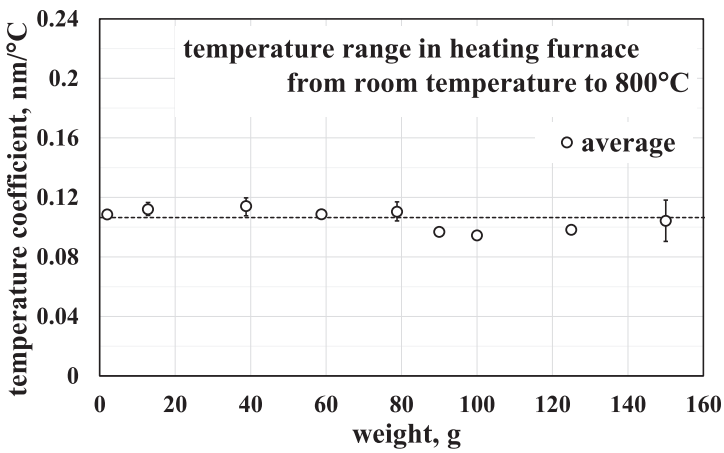

Fig. 8. Temperature sensitivity of LPFG depending on tension.

6 Conclusion

A tension applying method was proposed for the loss value adjustment on LPFGs to evaluate their suitability for a multi-point temperature sensor used in a harsh environment. We investigated the adjustment performance of the proposed method for CO_2-laser-induced LPFGs. We found that this method is useful for adjusting the loss value until 5.3 dB. Furthermore, we demonstrated that the proposed method has a minimal influence on the temperature sensitivity of the LPFG in the range from room temperature to 800°C.

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