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Cooling-Rate Induced Fiber Birefringence Variation in Regenerated High Birefringent Fiber

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Abstract**—**In this paper, we have reported birefringence manipulation in regenerated high birefringent fiber Bragg grating (RPMG) by using CO_2 laser annealing method. The results indicate that the birefringence of RPMG remains unchanged after CO_2 laser annealing followed by slow cooling process, but reduced after fast cooling process (~5.6×10^{-5}). After a series of annealing procedures with different cooling rates, the obtained results show that slower the cooling rate, higher the birefringence of RPMG. The volume, thermal expansion coefficient (TEC) and glass transition temperature (T_g) change of stress applying part in RPMG during cooling process are responsible for the birefringence change. Therefore, these findings are important to the RPMG sensor in high and dynamic temperature environment. The measuring accuracy, range and sensitivity of RPMG sensor is greatly affected by its birefringence value. This work also opens up a new application of CO_2 laser for fiber annealing and birefringence modification.

Keywords**—**Birefringence, CO_2 laser annealing, regenerated gratings, thermal stress.

I.INTRODUCTION

HIGH birefringence fiber, also called polarization maintaining fiber (PMF), is commonly used in various types of fiber optics devices. In sensing application, high birefringent fiber was proved to be useful in simultaneous sensing of temperature and strain by its two orthogonal polarization modes [1], [2]. Other than that, multi-axis strain sensing using high birefringent fiber has been demonstrated [3]-[5]. Birefringence in PMF is caused by two different properties in the fiber, specifically geometrical and stress. Stress-induced birefringence is due to the composition variation between each section of the optical fiber [6]. High mechanical stress is introduced into the optical fiber during manufacturing process of high birefringent fiber, which causes a weaker stress-induced birefringence in the optical fiber [7]. Therefore, the thermal relaxation of mechanical stress by annealing process can be increasing the birefringence of the fiber [8]. Birefringence enhancement by slow cooling process was reported in [9], [10]. Slow cooling process leads to volume compaction of stress applying part in high birefringent fiber. The T_g and TEC of the silica glass also changes after different cooling process [11]-[13]. This can be explained by the free volume model of amorphous material [14]. Slow cooling after high temperature annealing provides sufficient time for the silica molecules arrangement, which leads to lower free volume in the glass matrix [15]. This process is reversible and repeatable by reannealing at different cooling rates.

The birefringence of the high birefringent fiber is dependent to its thermal history [9]. This behavior affects the accuracy and functioning of high birefringent fiber sensor [16], [17] and interferometric sensor using high birefringent fiber [10]. Therefore, post-treatment of high birefringent fiber to modify its birefringence is important for regulating and bettering the functioning of high birefringent fiber sensor.

CO_2 laser is a much suitable option for the birefringence manipulation study in high birefringent fiber. This is because the CO_2 laser annealing has the advantages of effective control, small and focused targeting area, as well as fast response time. The thermal response of the fiber Bragg grating has been studied in [18]. The time constant of heating and cooling response of fiber Bragg grating is investigated by using a periodic CO_2 laser irradiation to create a rapid temperature change environment. Besides that, the heating direction test is also carried out to study the effect due to axial asymmetric to the fiber. The results show that the temporal thermal response of the fiber Bragg grating is independent to the annealing temperature and direction. CO_2 laser annealing is commonly used in the fabrication process of long period grating on optical fiber. CO_2 laser annealing is perturbing the refractive index of the optical fiber by mechanical stress relaxation. Besides that, the thermal stress in the optical fiber can also be pertubated with CO_2 laser annealing technique by manipulating the cooling rate [15].

In this paper, we have reported birefringence manipulation in regenerated high birefringent fiber Bragg grating (RPMG) by using CO_2 laser annealing method. The results indicate that the birefringence of RPMG remains unchanged after CO_2 laser annealing followed by slow cooling process, but reduced after fast cooling process. After a series of annealing procedures with different cooling rates, the obtained results show that slower the cooling rate, higher the birefringence of RPMG. The volume, thermal expansion coefficient (TEC) and glass transition temperature (T_g) change of stress applying part in RPMG during cooling process are responsible for the birefringence change.

II.METHODOLOGY

The thermal response of optical fiber to CO2 laser annealing is characterized using a regenerated fiber Bragg grating. The grating is annealed with focused CO_2 laser beam at two different laser power: 3.6W and 7.2W while the reflection spectrum of the grating is observed continuously

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using an Optical Spectrum Analyzer (OSA), until the Bragg wavelength stabilized. After that, the CO_2 laser is switched off immediately and the Bragg wavelength of the grating is recorded continuously. The time constant of the cooling process is calculated based on the Bragg wavelength change against time.

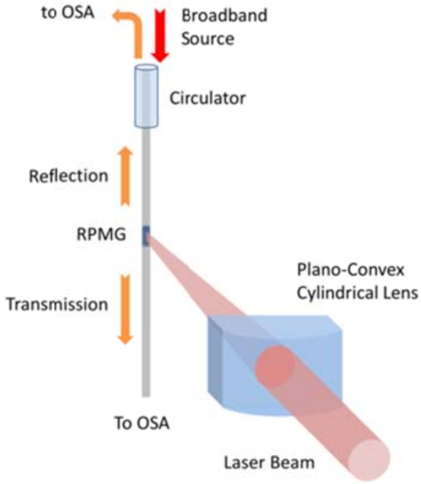

Fig. 1 The schematic diagram of the CO_2 laser annealing setup

During grating preparation, a 5mm long fiber Bragg grating is inscribed on panda type high birefringent fiber using KrF excimer laser and phasemask lithography technique. Prior to grating inscription, the fiber is photosensitized by hydrogen loading under 1500psi for one week. After grating inscription, the grating is annealed using an oven at 80°C for ~12 hours for the out diffusion of residual hydrogen molecules from the fiber. Subsequently, thermal regeneration of the seed grating is performed using a high temperature tube furnace. During the regeneration process, the annealing temperature is increased in steps from room temperature to ~850°C, at which point the birefringence completely disappears. The heating rate is ~10°C per minute. The grating strength gradually degenerated until it is fully erased. Soon after that, a gradually regeneration in grating strength is happened and stabilized. After the grating is stabilized, the produced RPMG is left to cool down until room temperature inside the furnace by simply turning off the power of the furnace. The reflection spectra of the RPMG are recorded continuously using an OSA. After that, the RPMG produced is annealed with programmed and focused CO_2 laser beam [15], [19] as shown in Fig. 1. The intensity of the CO_2 laser is increased with a step of ~1.8W per second, up to ~14.4 W. The laser beam intensity is kept constant at this level for ~5 minutes before it is reduced to 0 at a different rate. The RPMG is first slowly cooled down with a rate of ~0.09W per second, followed by reannealing and fast cooling by turning off the laser immediately. The reflection spectrum is recorded before and after annealing treatment to measure the change in birefringence of the fiber. To further study the relationship between the cooling rate and the birefringence of the RPMG, a series of annealing procedures with decreasing cooling rate are performed on the RPMG. The RPMG was annealed and cooled down to room temperature under 4 different cooling rates, in the sequence of 0.09W/s, 0.03W/s, 0.009W/s, and 0.003W/s. In between each annealing treatment, the birefringence of the RPMG is restored to a lower state by re-annealing followed by fast cooling process.

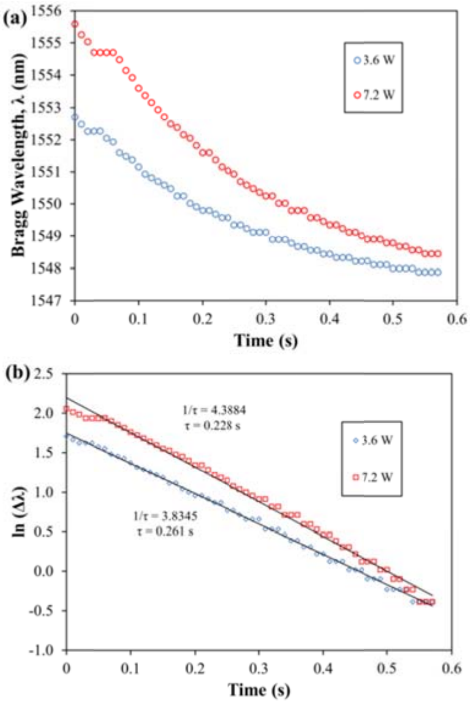

Fig. 2 (a), (b) The thermal response of RPMG during cooling process. Δλ represents the Bragg wavelength change with respect to the Bragg wavelength at room temperature. τ represents the time constant of thermal response

III.Results and Discussions

The cooling curve of the RPMG after different intensity of CO_2 laser annealing is plotted as shown in Fig. 2. In Fig. 2 (a), the Bragg wavelengths shift with respect to Bragg wavelength at room temperature is plotted against time. Fig. 2 (b) is plotted by calculating the natural logarithm of the Bragg wavelength change during cooling process with respect to Bragg wavelength at room temperature. The time constant of the cooling process is calculated based on the gradient of the curve in Fig. 2 (b). The time constant of the RPMG after annealing with 3.6 W and 7.2 W of CO_2 laser beam are 0.261 s and 0.228s respectively.

During thermal regeneration process, the birefringence of the grating is reduced gradually until zero at regeneration temperature. At this point, the grating strength reduced rapidly indicating the initiation of the grating regeneration process. When the grating is completely diminished and regrown, the birefringence of the grating does not recover immediately. Instead, the birefringence is recovered during the cooling process. Based on our observation, the birefringence of RPMG is higher than that of the seed grating after cooling down to room temperature. The Bragg wavelength of the grating is shifted towards the longer wavelength after regeneration process.

The birefringence change is calculated based on the spacing between the reflection peaks of two orthogonal modes. The results in Fig. 3 shows that the birefringence of RPMG remains unchanged after CO_2 laser annealing followed by slow cooling process, but reduced after fast cooling process (~5.6×10^{-5}). The volume, TEC and T_g change of stress applying part in RPMG during cooling process are responsible for the birefringence change. Slower cooling process causes the volume of the stress applying parts of the fiber to be reduced [9]. Besides that, the T_g and TEC are reduced and increased respectively after slow cooling process. Slow cooling process promotes structural rearrangement of glass matrix which causes the stress applying part to have higher density and TEC, but lower T_g after being cooled down to room temperature. The resulting effect of the slow cooling process is the increased birefriengence of the RPMG. The effect is opposite after fast cooling process.

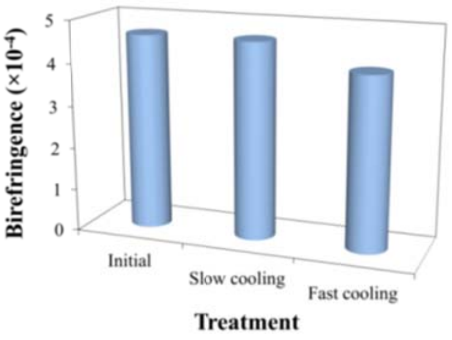

Fig. 3 The birefringence variation after slow and fast cooling process

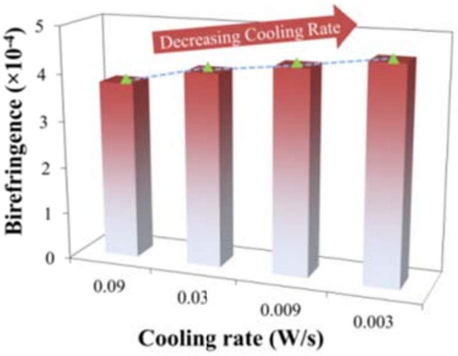

Fig. 4 The Birefringence change after a series of annealing treatment with decreasing cooling rate

After a series of annealing procedures with different cooling rates, the obtained results in Fig. 4 show that slower the cooling rate, higher the birefringence of RPMG. These findings are important to the RPMG sensor in high and dynamic temperature environment. The measuring accuracy, range and sensitivity of RPMG sensor is greatly affected by its birefringence value. This work also opens up a new application of CO_2 laser for fiber annealing and birefringence modification.

IV. CONCLUSION

In conclusion, the cooling-rate induced birefringence variation in RPMG has been manifested using the CO_2 laser annealing method. The birefringence of RPMG is increased after slow cooling process, and vice-versa. The slower the cooling rate used, the higher the birefringence of RPMG. These findings are important to the RPMG sensor in high and dynamic temperature environment. The measuring accuracy, range, and sensitivity of RPMG sensor is greatly affected by its birefringence value. This work also opens up a new application of CO_2 laser for fiber annealing and birefringence modification.

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REFERENCES

[1] L. A. Ferreira, F. M. Araujo, J. L. Santos, and F. Farahi, “Simultaneous measurement of strain and temperature using interferometrically interrogated fiber Bragg grating sensors,” Opt. Eng., vol. 39, no. 8, pp. 2226–2234, Aug. 2000.

[2] G. H. Chen, L. Y. Liu, H. Z. Jia, J. M. Yu, L. Xu, and W. C. Wang, “Simultaneous strain and temperature measurements with fiber Bragg grating written in novel Hi-Bi optical fiber,” IEEE Photon. Technol. Lett., vol. 16, no. 1, pp. 221–223, Jan. 2004.

[3] C. C. Ye, S. E. Staines, S. W. James, and R. P. Tatam, “A polarization-maintaining fiber Bragg grating interrogation system for multi-axis strain sensing,” Meas. Sci. Technol., vol. 13, no. 9, pp. 1446–1449, Aug. 2002.

[4] T. Mawatari and D. Nelson, “A multi-parameter Bragg grating fiber optic sensor and triaxial strain measurement,” Smart Mater. Struct., vol. 17, no. 3, May 2008, Art. ID. 035033.

[5] C. M. Lawrence, D. V. Nelson, E. Udd, and T. Bennett, “A fiber optic sensor for transverse strain measurement,” Exp. Mech., vol. 39, no. 3, pp. 202–209, Sep. 1999.

[6] P. L. Chu and R. A. Sammut, “Analytical method for calculation of stresses and material birefringence in polarization maintaining optical fiber,” J. Lightw. Technol., vol. 2, no. 5, pp. 650–662, Oct. 1984.

[7] M. Taccaa, M. Ferrario, P. Boffi, and M. Martinelli, “Drawing parameters optimization for birefringence reduction in optical fibers,” Opt. Commun., vol. 283, no. 9, pp. 1773–1776, May 2010.

[8] F. Just, R. Spittel, J. Bierlich, S. Grimm, M. Jäger, H. Bartelt, “The influence of the fiber drawing process on intrinsic stress and the resulting birefringence optimization of PM fibers,” Opt. Mater., vol. 42, pp. 345–350, Apr. 2015.

[9] A. Ourmazd, M. P. Varnham, R. D. Birch, and D. N. Payne, “Thermal properties of highly birefringent optical fibers & preforms,” Appl. Opt., vol. 22, no. 15, pp. 2374–2379, Aug. 1983.

[10] A. Ourmazd, R. D. Birch, M. P. Varnham, D. N. Payne, and E. J. Tarbox, “Enhancement of birefringence in polarization maintaining fiber by thermal annealing,” Electron. Lett., vol. 19, no. 4, pp. 143–144, Feb. 1983.

[11] C. T. Moynihan, A. J. Easteal, J. Wilder, and J. Tucker, “Dependence of the glass transition temperature on heating and cooling rate,” J. Phys. Chem., vol. 78, no. 26, pp. 2673–2677, Dec. 1974.

[12] M. I. Ojovan, “Viscosity and glass transition in amorphous oxides,” Adv. Condens. Matter Phys., vol. 2008, 2008, Art. ID. 817829.

[13] Y. Wang, X. Bian, and R. Jia, “Effects of cooling rate on thermal expansion of Cu49Hf42Al9 metallic glass,” Trans. Nonferrous Metals Soc. China, vol. 21, no. 9, pp. 2031–2036, 2011.

[14] D. Turnbull and M. H. Cohen, “Free-volume model of the amorphous phase: Glass transition,” J. Chem. Phys., vol. 34, no. 1, pp. 120–125, Jan. 1961.

[15] M. H. Lai, K. S. Lim, D. S. Gunawardena, H. Z. Yang, W. Y. Chong, H. Ahmad, “Thermal stress modification in regenerated fiber Bragg grating via manipulation of glass transition temperature based on CO_2-laser annealing,” Opt. Lett., vol. 40, no. 5, pp. 748–751, Mar. 2015.
[16] G. A. Pavlath and H. J. Shaw, “Birefringence and polarization effects in fiber gyroscopes,” Appl. Opt., vol. 21, no. 10, pp. 1752–1757, May 1982.
[17] C. C. Ye, S. E. Staines, S. W. James, and R. P. Tatam, “A polarization-maintaining fiber Bragg grating interrogation system for multi-axis strain sensing,” Meas. Sci. Technol., vol. 13, no. 9, pp. 1446–1449, Aug. 2002.
[18] Changrui Liao, Dong-ning Wang, Yuhua Li, Tong Sun, and Kenneth T. V. Grattan, “Temporal thermal response of Type II–IR fiber Bragg gratings,” Appl. Opt., vol. 48, no. 16, pp. 3001-3007, Jun 2009.
[19] M. H. Lai, D. S. Gunawardena, K. S. Lim, H. Z. Yang, and H. Ahmad, “Observation of grating regeneration by direct CO2 laser annealing,” Opt. Exp., vol. 23, no. 1, pp. 452–463, Jan. 2015.