Slit Beam Shaping for Femtosecond Laser Point-by-Point Inscription of Highly Localized Fiber Bragg Grating

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***Abstract*—We propose and experimentally demonstrate a slit beam shaping method for femtosecond laser Point-by-Point (PbP) inscription of highly localized Fiber Bragg Gratings (FBGs). The influence of slit width on the shape and area of Refractive Index Modulation Region (RIMR) induced by a single femtosecond laser pulse was investigated. The shape of RIMR can be changed from a spot to a line with an enlarged RIMR, and hence enhances the coupling strength of core mode and cladding modes. The RIMRs were precisely assembled along the fiber core, producing highly localized FBGs with a spectral comb of pronounced Cladding Mode Resonances (CMRs) intensity of more than 30 dB, a wide wavelength span of 240 nm and a low insertion loss of 0.3 dB. Note that the total processing time for fabricating such a highly localized FBG only requires ∼3.7 s. Subsequently, by including tilted angle on the slit, highly localized tilted FBGs were fabricated and these FBGs show adjustable envelope on the CMRs. Moreover, we investigated the surrounding Refractive Index (RI) response and thermal characteristics of the fabricated highly localized FBGs, which exhibit a sensitivity of 510.87 nm/RIU in a wide RI measurement range and excellent high temperature resistance at 1000°C. Therefore, such highly localized FBGs could potentially be used for multi-parameter sensing in many extreme environments.**

Manuscript received 15 February 2022; revised 8 May 2022 and 23 May 2022; accepted 6 June 2022. Date of publication 13 June 2022; date of current version 16 August 2022. This work was supported in part by the National Natural Science Foundation of China under Grants U1913212, 61875128, and 62005170, in part by the Department of Science and Technology of Guangdong Province under Grants 2019TQ05X113, 2019A1515011393, and 2019B1515120042, and in part by the Shenzhen Science and Technology Program under Grants RCYX20200714114538160, JCYJ20190808162603577, and JCYJ20200109114201731. *(Corresponding author: Xizhen Xu.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2022.3182319.

Digital Object Identifier 10.1109/JLT.2022.3182319

***Index Terms*—Highly localized fiber Bragg gratings, laser materials processing, slit beam shaping.**

I. Introduction

CLADDING Mode Resonances (CMRs) of Fiber Bragg Gratings (FBGs) are sensitive to external changes. They have wide applications in sensing for many parameters, such as strain, bending, acceleration and refractive index (RI) [1]. Due to the RI sensing ability, they can directly perceive humidity fluctuation, and hence can be developed for breath monitoring [2]. Plasmonic fiber sensors based on tilted FBGs with nanoscale gold coating have been used as a biochemical sensor for in-situ detection of gas and electrochemical activity in energy storage devices, and ultrasensitive detection of glucose, protein and cell in biological systems [1], [3]–[5]. Resonant coupling strength and spectral range of cladding modes are two key factors for sensing. Various methods have been proposed to enhance the coupling strength of CMRs in a full octave. Tilted FBGs are the most commonly used CMR elements and could be fabricated by using high energy pulsed excimer UV lasers and phase-mask approach, in which a tilted angle can be introduced by rotating the phase mask relative to the fiber [6]. Moreover, off-axis FBGs are also proposed to excite CMRs. These gratings can be fabricated without any additional rotation in the phase mask [7]. However, these UV-induced type I FBGs cannot withstand a high temperature of up to 320 °C [8], [9].

Femtosecond laser is a powerful tool for fabricating FBGs with enhanced thermal stability. The core mode resonance and CMRs in a femtosecond laser-induced tilted FBG can withstand a high temperature of above 800 °C [10], [11]. However, tilted FBGs and off-axis FBGs, regardless of the fabrication method by using an excimer UV laser or a femtosecond laser, exhibit relatively weak CMRs (<7 dB in transmission) in a narrow spectral range (30-40 nm band below core mode resonance) [7], [10], [11]. Pham *et al.* proposed a concatenating off-axis tilted FBG with an extended CMRs spectral range of 215 nm [12]. A large tilted angle can be used for shifting the CMR envelope to shorter wavelengths, but core mode resonance will disappear as the tilted angle exceeds 6° [12], [13]. It prevents multi-parameter sensing based on CMRs and core mode resonance. Moreover, such device still has a weak resonant coupling strength of <5 dB in CMRs. Bao *et al.* reported an off-axis FBG inscribed with high-intensity femtosecond laser. The CMRs in such off-axis FBGs have a strong resonant coupling strength of >30 dB, whereas the insertion loss is non-negligible (i.e., >2 dB) [14].

Furthermore, the femtosecond laser-inscribed highly localized type II FBGs, in which the Refractive Index Modulation Region (RIMR) has a high index contrast and does not cover the entire core cross section, can realize pronounced CMRs with extended wavelength band to a full octave. For example, Adbukerim *et al.* achieved a highly localized type II FBGs by using a femtosecond laser phase mask method. The CMRs in such FBG exceed 30 dB in transmission and spectrally span more than 250 nm [15]. Nevertheless, it is inflexible to tune the Bragg wavelengths by using this approach. In addition, in the case of a femtosecond laser Point-by-Point (PbP) technology, the tightly focused femtosecond laser pulses are very suitable to induce highly localized RIMR, but the RIMR is much smaller than the core mode and limits the coupling strength of core mode and cladding modes [16], [17]. Moreover, in the case of a femtosecond laser line-by-line technology, it is effective to enlarge the RIMR, but the fabrication process is time-consuming [13], [18]. Recently, a novel spatial beam shaping method was proposed for enlarging the RIMR in PbP FBGs [19], [20]. We used this method for efficiently producing high-quality PbP FBGs, exhibiting high reflectivity and low insertion loss [21].

In this letter, we report for the first time, to the best of our knowledge, a slit beam shaping method for femtosecond laser PbP inscription of highly localized type II FBGs, featured by enhanced CMRs comb in a full octave, low insertion loss and excellent high temperature stability. We studied the influence of slit width on the shape and area of RIMs. The RIMR created in the fiber core is line-shaped and exhibits a significantly enlarged area. Hence, the CMRs in the FBGs assembled by such RIMRs could span a full octave in the spectrum and were very pronounced with resonant dips deeper than 30 dB. Tilted localized FBGs were also fabricated by simply rotating the slit, and hence the envelope in CMRs shifts towards shorter wavelengths. Moreover, such FBG exhibits a wide RI measurement range with a sensitivity of 510.87 nm/RIU and could withstand a high temperature of 1000 °C.

II. Setup of Fabricating Highly Localized FBG By Using Slit Beam Shaping

The principle and experimental setup used for the fabrication of highly localized FBGs are shown in Fig. 1, which was modified from our previous setup in [21]. A frequency-doubled fs laser amplifier (Light Conversion, Pharos) with a central wavelength of 513 nm, a pulse duration of 290 fs and a repetition of 200 kHz was used as the laser source. An adjustable mechanical slit (Thorlabs, VA100) was fixed on a rotation stage, which could be used to introduce a tilted angle. A section of coating-removed single mode fiber (SMF, Corning) was mounted on an assembled 3D air bearing translation stage (Aerotech ABL10100-LN, ABL10100-LN, ANT130V 5-CN1-PL2). The laser beam was tightly focused into the fiber core via a 100× oil-immersion objective (NA = 1.25, Leica). The output face of the objective

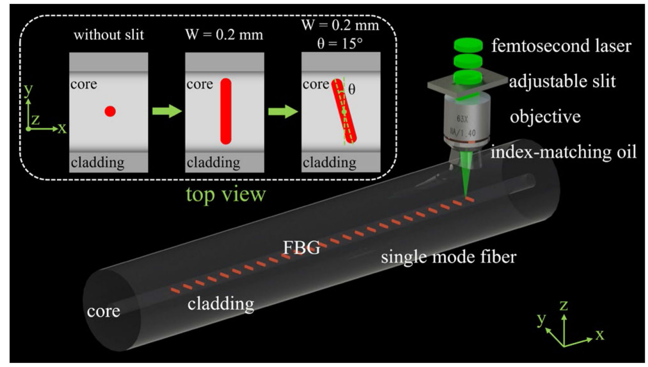

Fig. 1. Schematics of the working principle and experimental setup for fabricating highly localized FBGs by using a femtosecond laser PbP technology and slit beam shaping method. (Insert: the top view of the RIM created by used of various slit widths W and tilted angle θ.).

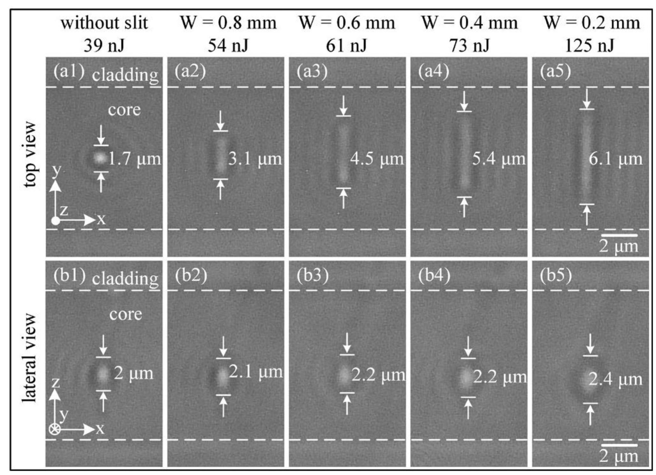

Fig. 2. (a) Top-view-, and (b) lateral-view- microscope images of the RIMs created in fiber core by a single femtosecond laser pulse with slit beam shaping. A sample inscribed without slit beam shaping and four samples inscribed with decreasing slit widths of W = 0.8 mm, 0.6 mm, 0.4 mm and 0.2 mm were demonstrated.

and SMF were immersed in the index matching oil to reduce the aberration at silica/air interfaces. The boundary between core and cladding can be observed via the objective. The fiber was moved precisely by controlling translation stage, so that focal spot of the beam can be located in the middle of the fiber core. The shutter was opened and the fiber was translated along the fiber axis (i.e., the x-axis in Fig. 1). Then a highly localized FBG consisting of a series of periodic RIMRs was realized. In this process, the area, shape and tilted angle of RIMRs could be flexibly controlled by adjusting the width and tilted angle of slit. The focused beam waist (i.e., ω_x and ω_y) on each axis (i.e., x- and y-axis) was expressed as [19]

$$\omega_x = \frac{f\lambda}{\pi W_x}, \omega_y = \frac{f\lambda}{\pi W_y}, \tag{1}$$

where Wx and Wy are the beam waists of the unfocused Gaussian beam on the x- and y-axis, respectively, f is the focal length of the objective, λ is the laser wavelength. Note that the ω_y will be extended by reducing W_y of the incident beam and the shape

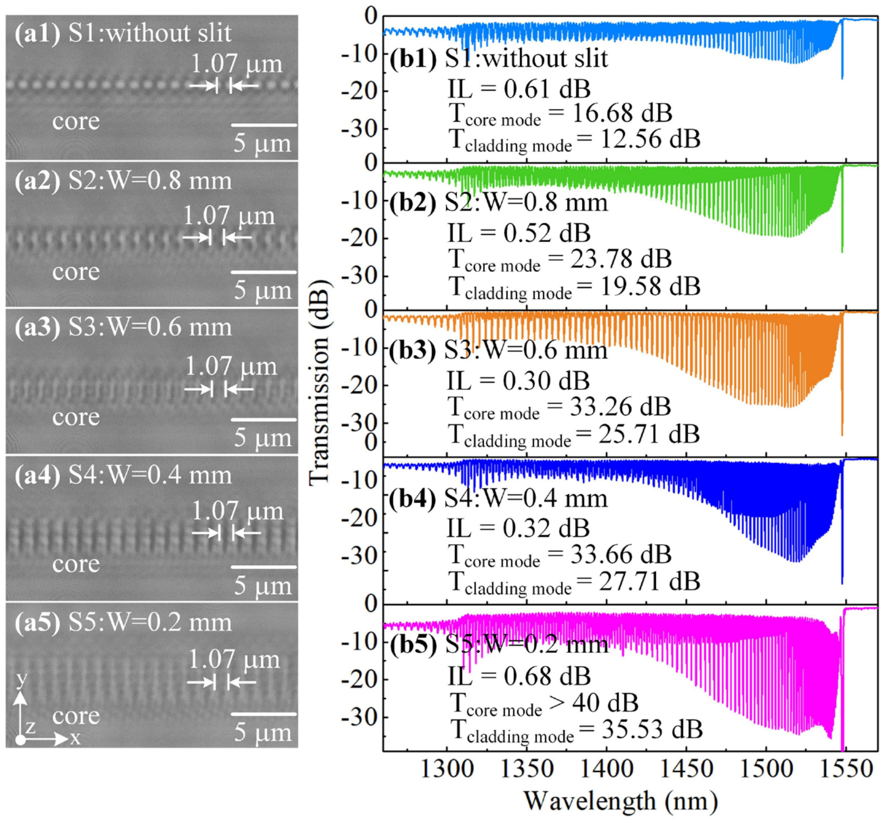

Fig. 3. A PbP FBG S1 inscribed without slit beam shaping and four PbP FBGs S2-S5 inscribed by using slit beam shaping with a decreasing slit width of W = 0.8 mm, 0.6 mm, 0.4 mm, and 0.2 mm. (a) Top-view microscope images and (b) transmission spectra of S1-S5.

of focal volume can be transformed to an elongated line, which means each RIMR induced by a single femtosecond laser pulse will significantly increase.

III. Fabrication of Highly Localized FBG

We experimentally studied the effect of slit width on the shape and the area of RIMRs. A single femtosecond laser pulse with pulse energy of 39 nJ was focused directly in the fiber core without a slit. As shown in Fig. 2(a1) and (b1), the RIMR top view shows a near circular spot with a width ω_y of 1.7 μm on the y-axis and the RIMR lateral view shows a depth ω_z of 2 μm on the z-axis. Then, a slit was inserted in front of the objective. The femtosecond laser beam propagated through the slit and was focused into the fiber core. The slit width W varies from 0.8 mm to 0.2 mm with a step of 0.2 mm and the corresponding on-target single pulse energies range from 54 nJ to 125 nJ. In case the slit width W decreases, as displayed in Fig. 2(a2)–(a6) and (b2)–(b6), the width ωy of RIMR on the y-axis increases drastically, whereas the width ωx of RIMR on the x-axis and the depth ωz of RIMR on the z-axis remain almost unchanged. A largest width ω_y of 6.1 μm can be achieved at the slit width W of 0.2 mm. It means the shape of RIMR has been transformed from a spot to a line with enlarged area, which is beneficial for enhancing the coupling strength in FBGs. Moreover, the geometry in such RIMRs is also in favor of producing tilted FBGs.

Subsequently, we employed such a slit beam shaping method to fabricate highly localized FBGs. A PbP FBG sample S1 was inscribed without slit beam shaping and four PbP FBGs (S2, S3, S4, and S5) were inscribed with decreasing slit width W of 0.8 mm, 0.6 mm, 0.4 mm and 0.2 mm, respectively. The corresponding single laser pulse energies used for fabricating S1-S5 were 39 nJ, 54 nJ, 61 nJ, 73 nJ and 125 nJ, respectively. Moreover, the moving speed of the translation stage and the laser frequency were set to 1.07 mm/s and 1 kHz, respectively. All of these FBGs have the same grating pitch of 1.07 μm and the same grating length of 4 mm. The transmission spectra of the FBGs were measured by a broadband light source (Fiber Lake) and an Optical Spectrum Analyzer (OSA, Yokogawa AQ6370C). The scanning span ranged from 1265 nm to 1600 nm. The resolution, sampling interval and sampling were set to 0.02 nm, 0.007 nm and 50001, respectively. The sensibility was set to High 1. As shown in Fig. 3(a1), the PbP FBG S1 fabricated without slit beam shaping exhibits a point-shaped RIMR. Moreover, the slit beam shaping was used for inscribing PbP FBGs S2-S4. As shown in Fig. 3(a2)–(a5), an elongated RIM could be created. Note that the RIMs in S1-S5 are highly localized since the RIMR is still smaller than the core mode field. This effect is beneficial for generating strong CMRs. Fig. 3(b1)–(b5) show that all of the five FBGs exhibit a low insertion loss of <0.68 dB and a Bragg wavelength of 1550 nm. The CMRs can span a full octave of ~240 nm in the transmission spectra and have a cutoff wavelength situated at ~1310 nm. The wavelength range

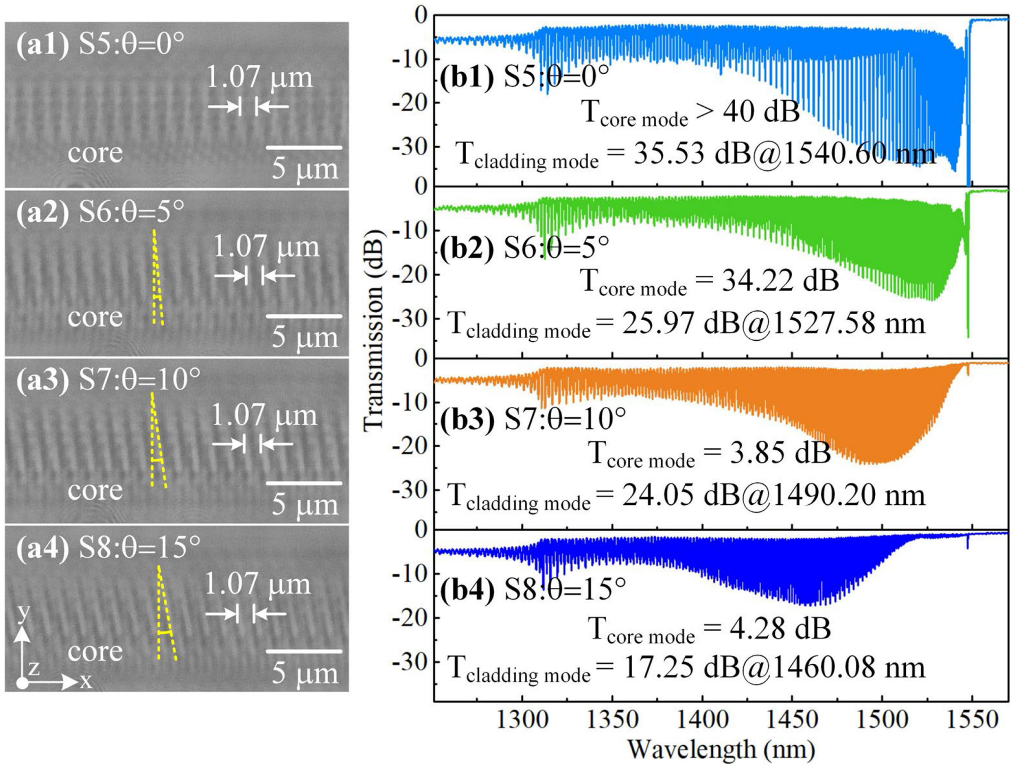

Fig. 4. Four PbP FBGs S5-S8 inscribed by using a constant slit width of W = 0.2 mm with an increasing tilted angle θ of 0°, 5°, 10°, and 15°. (a) Top-view microscope images and (b) transmission spectra of S5-S8.

of the CMRs in such FBGs is much wider than conventional tilted FBGs or off-axis FBGs induced by femtosecond laser [12], [17]. Moreover, in the case of S1, as shown in Fig. 3(b1), the CMR exhibits a relatively weak intensity of 12.56 dB, resulting from the small RIMR in S1. As shown in Fig. 3(b2), S2 has an increasing cladding mode intensity of 19.58 dB. In the case of S3 and S4, the CMR intensity can exceed 20 dB. A CMR intensity of 35.53 dB has been achieved in S5, as displayed in Fig. 3(b3)-(b5). Meanwhile, a strong core mode intensity of more than 40 dB was also achieved in S5. These results illustrated that the slit beam shaping can significantly increase cladding modes and core mode intensity since the overlap between the RIMR area and mode field is enlarged. Therefore, compared with the line-by-line technique, the highly localized FBGs created by our method exhibit a more pronounced CMR intensity, a wider CMR range and a lower insertion loss. Given the moving speed of 1.07 mm/s and the grating length of 4 mm, the total time for creating such FBGs only requires ~3.7 s, which is more efficient [13], [18].

Moreover, it could be seen from Fig. 3(b1)–(b5) that the FBGs S1-S5 exhibit strong lower-order CMRs near core mode resonance, but the higher-order CMRs at shorter wavelength range, which are more sensitive to environments, are still weak. A line-shaped RIMR can be achieved with a narrow slit, for example, the RIMR exhibits the largest width ω_y of 6.1 μm at the slit width W of 0.2 mm, as shown in Fig. 2(a5). Hence, we can further produce titled FBGs with enhanced higher-order CMRs by simply rotating the slit relative to the fiber axis, i.e., introducing a tilted angle θ in the fabrication process. As shown in Fig. 4(a1)–(a4), the PbP FBG S5 without tilted angle and another three PbP FBGs S6-S8 with tilted angle θ of 5°, 10°, and 15°, respectively, were fabricated by using the same slit width W of 0.2 mm, laser pulse energy of 125 nJ, grating pitch of 1.07 μm and grating length of 4 mm. As displayed in Fig. 4(b1)–(b4), the core mode resonance vanishes vastly with tilted angle increasing. The spectral range (i.e., 240 nm) of CMRs remains almost unchanged, but the envelope in continuous comb shifts towards shorter wavelength. This phenomenon is similar to that observed in conventional excimer UV-induced type I tilted FBGs. Moreover, the CMR intensity maximum decreases with tilted angle increasing, shifting from 35.53 dB at 1540.60 nm to 17.25 dB at 1460.08 nm. The spectral evolution indicates the localized RIMRs with a larger tilted angle can enhance the coupling from forward propagating core mode to higher-order backward propagating cladding modes [1].

IV. Sensing Characteristics

The highly localized FBG is very suitable for biochemical sensing, since it exhibits strong CMR in a wide span of 240 nm. The surrounding RI response of the FBG S5 was studied by using the standard RI matching liquids with RI ranging from 1.33 to 1.45. As shown in Fig. 5, the higher-order CMRs at shorter wavelengths gradually disappear as the surrounding RI increases. Moreover, the response vanishes at a surrounding RI of 1.45, which results from the conversion

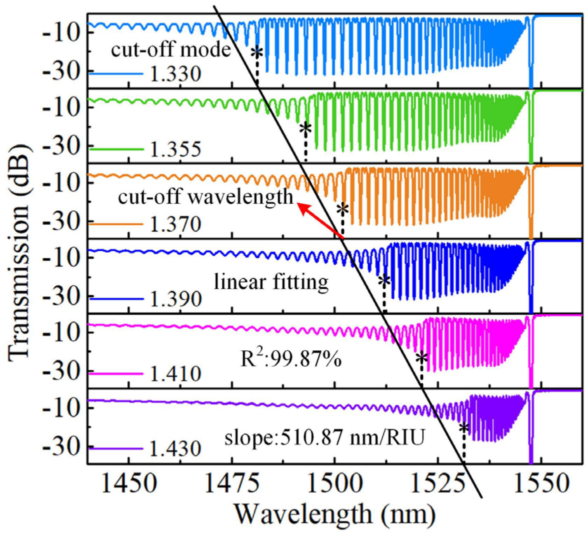

Fig. 5. Evolutions of transmission spectra of the fabricated highly localized FBG S5 in various RI liquids with a linear fit of the cut-off wavelength with RI.

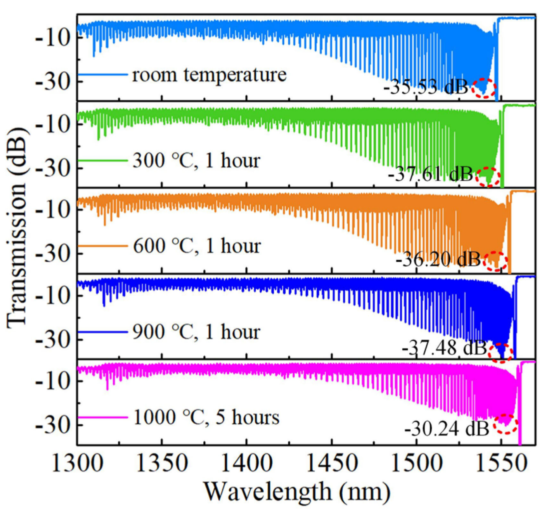

Fig. 6. Transmission spectra of the FBG S5 at elevated temperatures from room temperature to 1000°C.

of the cladding mode into leaky mode when the surrounding RI is equal or larger than the effective RI of cladding mode. The cut-off wavelength marked by asterisks could be regarded as a linear function of the surrounding RI with a slope of 510.87 nm/RIU. These results are consistent with a tilted FBG inscribed by using line-by-line technology [13] or a highly localized FBG created by using a phase mask technology [15].

Furthermore, the high-temperature response of the fabricated highly localized FBG was studied by using a tube furnace (Carbolite, Gero HTRH). The FBG sample S5 was placed into the center of tube furnace. A B-type thermocouple was placed in proximity to the FBG to in-situ record the temperature. The heating procedure was set as 1 hour at 300°C, 1 hour at 600°C, 1 hour at 900°C and 5 hours at 1000°C. Fig. 6 shows

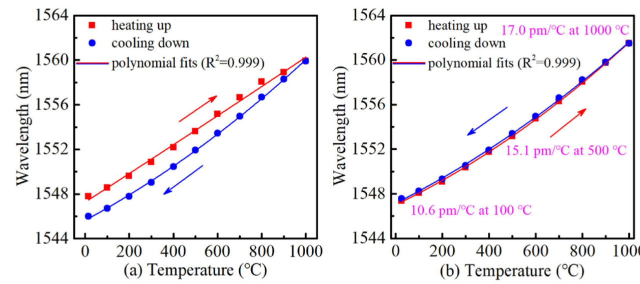

Fig. 7. Bragg wavelength shift as functions of temperature increasing and decreasing between 25°C and 1000°C (a) before annealing and (b) after annealing process.

that the CMR intensity could exceed ∼36 dB at 300°C, 600°C and 900°C, which is larger than that at room temperature (i.e., ∼35 dB). After annealing at 1000°C for 5 hours, the CMR intensity decreases slightly to 30.24 dB. This indicates the type I modulation region formed by the relaxation of internal stress has been erased, leading to a decrease in the cladding mode coupling. Moreover, we used the Gaussian fit algorithm to extract the Bragg wavelength from the spectra. The results are plotted in Fig. 7(a) and (b) [22] and well fitted by a third order polynomial function. After this annealing process, the hysteresis could be eliminated, and the curves show excellent thermal stability and repeatability, benefiting from the relaxation of residual stress [23], [24]. The temperature sensitivities are 10.6 pm/°C at 25°C – 300°C, 15.1 pm/°C at 300°C – 600°C, and 17.0 pm/°C at 600°C – 1000°C, which is in accord with conventional silica-based FBGs sensors [8]–[10], [25]. Therefore, such highly localized FBGs can survive at 1000°C, which is similar with FBGs created by using phase mask [15], and hence are promising for multi-parameter sensing in harsh environments.

V. Conclusion

In summary, we demonstrated an efficient method for creating highly localized FBGs by using a femtosecond laser PbP technique with a slit beam shaping method. The effect of slit width on the shape and area of the created RIMR was studied, and a line-shaped RIMR with an enlarged area was obtained by using a slit width of 0.2 mm. A high-quality highly localized FBG, featured by a pronounced CMR intensity of more than 30 dB, a wide CMR range of 240 nm and a low insertion loss of 0.3 dB, was successfully fabricated by using these RIMRs. The total time for producing such FBG only requires ∼3.7s. We also demonstrated the fabrication of tilted highly localized FBGs by introducing a tilted angle through rotation of the slit. The envelope of the CMRs in such titled FBGs can be shifted towards shorter wavelengths. Moreover, the highly localized FBG exhibits a wide RI measurement range with a sensitivity of 510.87 nm/RIU and it can withstand a high temperature of 1000°C. As a result, such highly localized FBGs are promising for multi-parameter sensing in harsh environments, such as hypersonic vehicles, aero-engines, and nuclear reactors.

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