Ultrahigh-Temperature Chirped Fiber Bragg Grating Through Thermal Activation

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***Abstract*— The feasibility of thermal regeneration of chirped fiber Bragg gratings inscribed in commercial single-mode fibers using a 248-nm excimer laser has been experimentally demonstrated. Regenerated chirped gratings (RCGs) with a strong and symmetrical reflection profile can be achieved by 80 min of thermal treatment at a temperature of 800 °C. The thermal cycling test results show that the RCGs provide a stable and reproducible spectral response (both in bandwidth and in reflective intensity) over the temperature range from 25 °C to 1000 °C, indicating their good potentials for fiber laser and sensing applications under high-temperature conditions.**

***Index Terms*— Chirped fiber Bragg grating, regenerated chirped fiber grating, high temperature.**

I. Introduction

FIBER bragg gratings (FBGs) have been widely used in the applications of fiber-optic lasers and sensors due to their intrinsic advantages. However, the periodic modulation of refractive index (grating pitch) induced by UV light exposure can be completely erased at the temperature higher than 350 °C [1], which limits the FBG's applications under high temperature condition. To improve the temperature sustainability of FBGs, multiple techniques have been proposed, such as thermal or annealing treatments on the gratings [2], and inscribing type II gratings using femtosecond lasers [3]. Although the aforementioned operations can enhance the FBG's temperature sustainability up to 900 °C, researchers still seek for new methods to simplify the fabrication process and to reduce the cost of manufacture.

Regenerated grating (RG), as a new type of grating, provides the advantage of a simple thermal process and has successfully achieved an operation temperature up to 1400 °C through tailoring the fiber core dopants [4]. Until now, many research works have been done to investigate the behavior of RGs. In 2003, Vasiliev et al. first observed regeneration of grating in germanium-doped fiber without hydrogen loaded [5]. Zhang and Kahrizi reported generation of high temperature resistance FBG using a hydrogen-loaded germanium-doped FBG in [6]. A molecular water model based on decompositions of Si-OH and Ge-OH in annealing process was used to explain the high temperature sustainability of RG [6], [7]. However, Yang et al. has reported that the RG cannot be formed in the boron/germanium-doped fiber without the hydrogenated process [8]. Meanwhile, etching the fiber cladding has also been studied to change the temperature sensitivity [9], thermal regeneration ratio and strain effect in the RGs [10], [11]. Among above researches, there are very limited reports on the regeneration of chirped fiber Bragg grating (as an important component of grating family). Compare to FBGs, the strength of Chirped gratings (CGs) decays much quicker when it is under high temperature condition, due to the original low average grating strength over a broadband and the necessary of phase matching condition between gratings with different pitches.

In this letter, we experimentally demonstrate the feasibility of thermal regeneration of CGs inscribed in commercial single-mode fibers (Corning SMF-28) using a 248 nm excimer laser. The Seed Grating (SG) is erased completely at the temperature of 800 °C and then the RCG is achieved through a normal thermal annealing process. The RCG presents the same spectrum bandwidth compared with the SG, and maintains a stable spectral profile when the temperature reaches 1000 °C. The thermal cycling test shows that the RCG provides a stable and reproducible spectral response over the temperature range from 25 °C to 1000 °C, making it a good fiber-optic component for high temperature environment. As such, the RCG can be used for the normal applications of CG, but also can be used for the applications at high temperature environment. For instance, it is suitable for applications DFB fiber lasers, fiber sensor operating in high temperature environment. In addition, it offers the possibility of future high-temperature communication components, such as dispersion compensators, optical fiber band-pass

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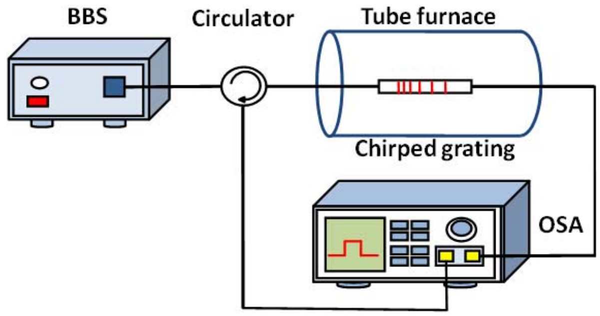

Fig. 1. Schematic diagram of the experimental setup.

filter and etc., which is more durable in the heat-escalating industrial and extreme environments [12].

II. Regeneration Mechanism

Grating regeneration is a dramatic process, in which the conventional type I gratings are employed as "seeds", and annealed at high temperature to form reborn and stable gratings. These reborn gratings have the ultra-high temperature sustainability up to 1400 °C. Generally the hydrogenation of fibers is a vital preprocess for some types of fibers for example, boron/germanium co-doped photosensitive fiber to achieve the grating regeneration. However, the regeneration behavior has also been observed in other types of fibers without the pre-treatment of hydrogen, such as high germanium doped fiber. These experimental observations have depicted the grating thermal regeneration a complicated mechanism, in which two principles based on chemical reactions are commonly used: grating periodical crystallization [13] and the change of dopants diffusion [7]. However, some of the experimental observations cannot be explicitly explained solely based on these two formation mechanisms, for instance, the difference between the center wavelengths and bandwidths of SG and RG. Yang et al. have employed a well-known principle from the aspect of physical phenomena: the grating stress relaxation during high temperature annealing to describe the above mentioned observations [8]. In their work, the increase in effective index of the fiber and reduction in RG period are used to explain the overlapping of the center wavelengths between the SG and RG. Normally, when the SG is treated at high temperature, the center wavelength and bandwidth vary with the temperature and elapsing of treatment time. However, the bandwidth of produced RG is smaller than SG is observed in almost all of the RGs. In this work, a thermally RCG is experimentally investigated and the results indicate that the bandwidth of the CG remains almost constant during and after thermal annealing. The detailed discussions on experimental preparation and results are described in the following section.

III. Experiment and Discussion

Figure 1 demonstrates the schematic diagram of the temperature processing system. The light generated by a broadband source (BBS) is guided into the CG via a circulator. The reflection and transmission spectra are recorded by an optical spectrum analyzer (OSA) at a wavelength resolution of 0.02 nm. The 20 mm-long seed linear CGs are written into a SMF-28 fiber by using a chirped phase mask and a 248nm KrF excimer laser. We use two cylindrical lenses to expand the laser beam size up to 40 mm. Then, a 20 mm long uniform intensity laser beam is taken from the center of the 40 mm expanded beam for the grating inscription process. Before the inscription, the fibers are hydrogen loaded to improve the photosensitivity under a pressure of 11.3 MPa for 10 days at room temperature. The fabricated seed CGs are annealed in an oven to out-diffuse the hydrogen at 50 °C for two days. The grating transmission strengths then decay to and stabilized at −16 dB. The initial reflection spectrum of SG at 20 °C is shown in Fig. 2(a). The center wavelength λ_B and reflectivity R of the SG are ~1546.6 nm and ~97.5%, respectively, 3dB bandwidth of the seed CG is ~26.3 nm.

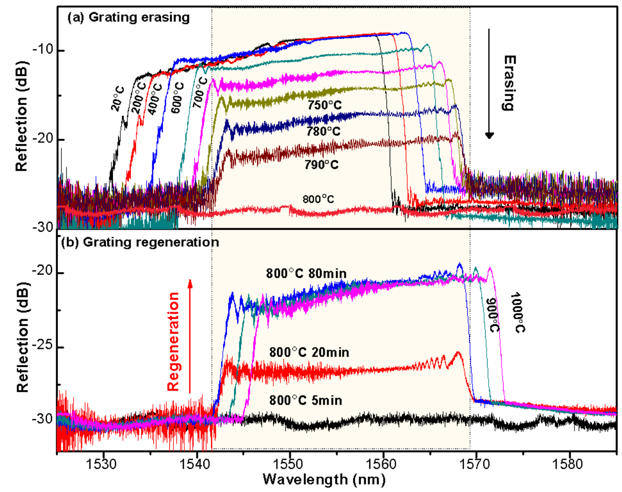

Fig. 2. (a) Reflection spectra of seed CG change with a thermal treatment process, and (b) variation of grating intensity during the regeneration process.

To perform the regeneration, the SG is inserted into a heating tube which is capable of heating temperature up to 1100 °C. We also maintain uniform temperature along the entire length of the gratings by placing the CG in the center of the oven. The thermal annealing scheme is presented in Fig. 3(a), in which the temperature is gradually increased to 800 °C with a heating ramp of 10 °C/min and kept at 800 °C for 80 minutes, and then passively cooled down. From Fig. 2, we can observe that with the increasing of the temperature, the intensity of SG gradually decreases, and the reflection spectrum completely disappears at the temperature of 800 °C. Holding this temperature for 80 minutes, the reflection spectrum is generated and the reflection intensity increases again. During the cooling process, the intensity of reflection spectrum remains unchanged. The evolutions of reflection spectra during regeneration are shown in Fig. 2(b) and Fig. 3(b). The strength of RCG is weakened to −20 dB at room temperature after the regeneration treatment.

It is noted that the reflection bandwidth is slightly reduced in the temperature range of 200-500 °C which is the region when thermal decay begins. This may due to the dopants diffusion occurs firstly at the smaller grating pitch, the grating

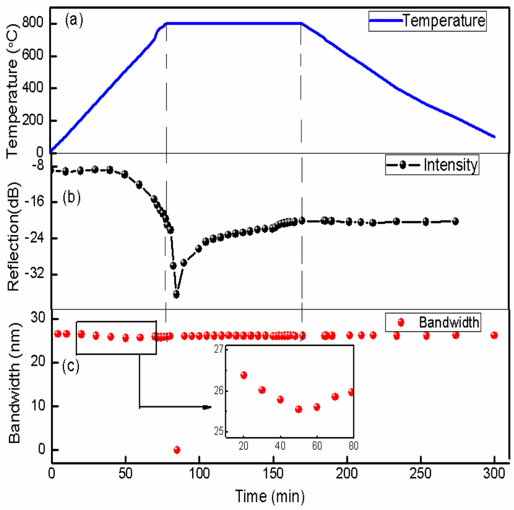

Fig. 3. Regeneration process: seed CG is heated from $t = 0$. The (a) temperature, (b) reflection spectrum and (c) 3dB bandwidth of RCG in this process are shown. Inset: the variation of bandwidth from 200 °C to 780 °C.

has longer pitch withstands the higher thermal stability [7]. The bandwidth then slightly increases in the temperature range of 500 °C to 800 °C as shown in Fig. 3(c). It may be able to explain that the increase of temperature induces the relaxation of internal stress in CG, leads to a small increase in the dc index change, but decrease of ac index modulation due to dopants diffusion [7], and decrease of the grating pitch [8]. In general, the bandwidth of the RG significantly narrows compared with the original SG. In comparison, the regeneration process of CG hardly narrows the spectral bandwidth, and the bandwidth of RCG stabilizes at ~26.1 nm, which is very important to preserve the characteristics of CG.

Temperature response of RCG is measured at the temperature ranging from 25 °C to 1000 °C. The temperature of the tube furnace increases at the rate of 10 °C/min until 1000 °C. To avoid the influence of temperature fluctuation and inhomogeneity along the grating, the temperature of the tube furnace is kept constant for 20 minutes to ensure well distribution of temperature before each record. The RCG is subjected to a further thermal cycling test to determine its thermal repeatability. The shift of center wavelength of the reflection spectrum as the function of temperature is shown in Fig. 4. The temperature sensitivity of 15.1 pm/°C with a maximum error of 0.35% is obtained as shown by the error bars. These results indicate that the RCG sensor presents a good thermal repeatability. Besides, the spectral bandwidth versus temperature response of RCG is also shown in Fig. 4. We observe that the bandwidth of RCG remains almost unchanged and has maximum error of 0.5% during the thermal cycling test.

In order to demonstrate the stability of RCG, the device is kept at high temperature of 900 °C for 8 hours. As presented by the blue markers in Fig. 5, the reflected intensity exhibits small fluctuation of 0.15 dB. The black markers that represent the reflection bandwidth of the RCG which exhibit a small fluctuation in a range of 0.0128 nm at the temperature of 900 °C for 8 hours. The experimental results in Fig. 5 have

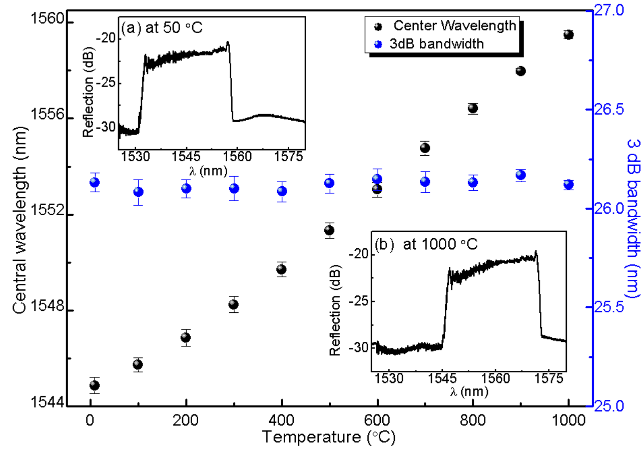

Fig. 4. The experimental results of central wavelength (the center between two band edges at 3dB below the maximum reflected power) shift (black dot) and 3dB bandwidth variation (blue dot) as functions of temperature change. Inset: Reflection spectra of RCG at (a) 50 °C and (b) 1000 °C.

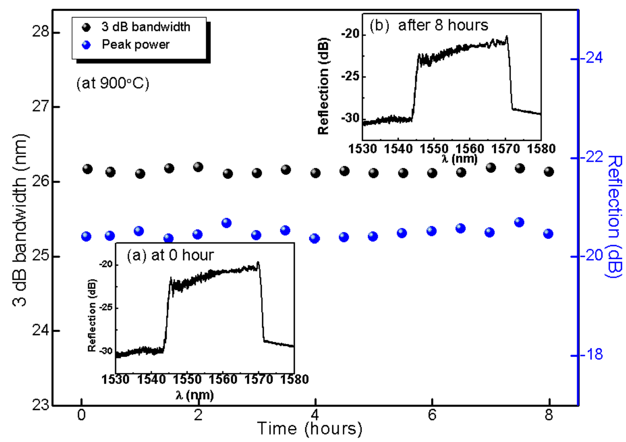

Fig. 5. Thermal stability at temperature of 900 °C for eight hours. Inset: Reflection spectra of RCG at (a) 0 hour and (b) 8 hours.

proven the high temperature stability of the proposed RCGs. This demonstration has opened up the new possibilities for the usage of fiber components at extreme environments.

IV. Conclusion

In summary, a RCG with high-temperature sustainability produced from a seed CG, has been proposed and demonstrated. A RCG with 3dB bandwidth of 26.1 nm has been manufactured through the thermal activation of a seed CG with bandwidth of 26.3 nm. The experiment results indicate that the bandwidth of RCG remains constant throughout and after the regeneration process. The RCG has a temperature sensitivity of 15.1 pm/°C and has shown a good repeatability and high temperature stability. The RCG can be employed in numerous applications such as communication, sensing applications in extreme environment such as oil & gas, chemical processing and radioactive plant.

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