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Evolution of Optical Fiber Temperature during Fiber Bragg Grating Fabrication Using KrF Excimer Laser

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The temperature distribution in an optical fiber during the fabrication of fiber Bragg gratings (FBGs) using a KrF excimer laser with a phase mask has been analyzed experimentally for typical fabrication conditions. The fluence of UV laser light at the fiber surface has been varied up to 420 mJ/cm^2. These experiments show that (1) scanning electron microscope (SEM) images of the fiber surface facing the excimer laser beam reveal partial physical damage apparently owing to partial melting, so that the surface temperature has increased beyond the softening point of silica glass, which is approximately 1200°C, (2) the optical spectrum transmitted through the FBG during laser irradiation contains spikes coincident in time with the laser pulses that correspond to a near instantaneous shift of the FBG spectrum to a higher temperature spectrum representing fiber core heating of approximately 8°C, and (3) analysis of the energy absorbed by the fiber indicates a bulk temperature rise of approximately 3°C in the fiber. The resulting large variation in the temperature rise over the fiber cross section from a few °C to 1200°C, along with partial physical damage on the surface, will certainly induce large internal stresses in the fiber material and reduce the mechanical strength of the FBG. [DOI: 10.1143/JJAP.43.147]

KEYWORDS: optical fiber, fiber Bragg grating, KrF excimer laser, heat conduction, phase mask

1. Introduction

Because of their simple structure and very sharp spectral response, fiber Bragg gratings (FBGs) are widely used for many optical telecommunication applications. Nowadays they are used in optical strain gauges, resonators of fiber lasers, and numerous types of sensors.

The wide ranging applications of FBGs in many fields may be explained partially because they can be easily fabricated by exposing an optical fiber to a UV excimer laser beam through a phase mask grating. They can also be fabricated using CW UV lasers such as the Ar^+ 240 nm laser with a typical power of approximately 100 mW by a two-beam interference without using a phase mask. However, in this method, accurate tuning is required to intersect the angle between the two beams to obtain the desired central wavelength of the FBG and, hence, it is very sensitive to mechanical vibrations of the optical setup and even to air current. The optical arrangement requires precision alignment. The phase mask method with excimer lasers such as KrF (248 nm) and ArF (193 nm) is more commonly used in industry, primarily because of the ease of the optical setup, but also because of the high power of these lasers.

The excimer laser normally provides 100 mJ to a few 100 mJ energy per pulse at a repetition rate up to approximately 20 Hz. Its pulse width is 20–30 ns. Its output power is several MW to above 10 MW, or 10^7 times higher than that of the CW Ar^+ laser. An FBG is created by inducing defects in the chemical bonding of the germanium dopant in the optical fiber core by exposing it periodically to UV laser light along the axis of the fiber.

Since the cladding is made of pure silica, which is highly transparent and has very low UV absorption, it might seem that the effect of UV irradiation should be very small there. However, when the laser has a high power on the order of MW/cm^2, the effect may become appreciable although the fractional absorption is very low.

If the laser beam is well focused onto the optical fiber, the effect may become serious. Severe physical damage is reported in ref. 1 where an FBG was made by exposing a fiber positioned at the focal point to a single excimer laser pulse using the two-beam interference method. Reference 1 revealed that the surface of the optical fiber was melted by the laser with corrugations corresponding to the FBG grating period. Also, many cracks were observed across the fiber. The condition for FBG fabrication reported in ref. 1, which is intended to generate a type II FBG by a single excimer laser pulse, may be an extreme case. Since an FBG is usually made by exposing a fiber to an excimer laser for about one or few minutes at a 5 to 20 Hz repetition rate, such severe damage as shown in ref. 1 may not occur under such mild condition. We cannot, however, rule out the possibility of partial but similar damage under the standard conditions for FBG fabrication.

If an FBG is damaged in this way during the fabrication process, its mechanical strength will certainly be degraded. The mechanical strengths of optical fibers exposed to two different lasers under the condition of FBG fabrication with the same amount of laser irradiation doses are compared in ref. 2. One was exposed to an Ar^+ 240 nm CW laser and the other, to an excimer laser. Weibull plot analysis of the mechanical strength of the fibers showed that the fiber exposed to the CW laser had almost exactly the same strength as the pristine fiber (~5 GPa), while the strength of the fiber exposed to the excimer laser was reduced by more than half (to 1–2 GPa). This result appears to be very significant because the lifetime of FBGs fabricated using excimer lasers will be shortened significantly in many applications.

To clarify the damage process in optical fibers, the very first consideration is how much the temperature rises and

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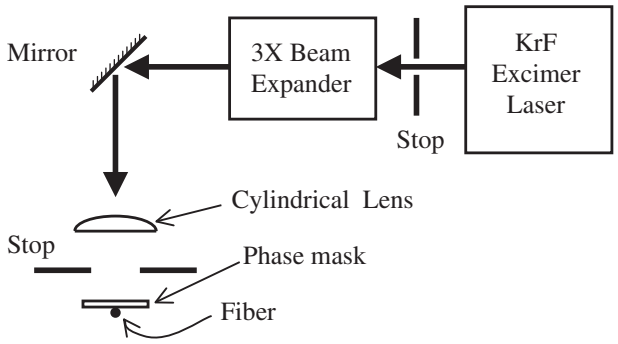

Fig. 1. Schematic of FBG fabrication.

how it evolves dynamically across the fiber during exposure to an excimer laser pulse. This paper provides experimental information on the temperature behavior of FBGs during fabrication.

2. Experiments

The schematic of our experimental apparatus[3] is shown in Fig. 1. The excimer laser (Lambda Physik COMPex-102) delivers up to 200 mJ of energy at 248 nm with a pulse width of 25 ns at a repetition rate of 1–20 Hz. The $8 \times 24\,\mathrm{mm}^2$ rectangular laser output beam is shaped by a $5 \times 5\,\mathrm{mm}^2$ stop to select a higher quality uniform portion of the beam. This limits the power to one-quarter of the laser output. After passing through a 3X beam expander, the beam is deflected downward by a mirror and focused by a cylindrical lens with a focal length of 100 mm. A bare optical fiber is positioned 80 mm away from the cylindrical lens, i.e., 20 mm in front of the focal point. A phase mask grating is placed above the fiber at a distance of less than 1 mm from the fiber. A second stop is placed above the mask. The beam size in the plane of the fiber is 12 mm along the fiber and 0.65 mm in the transverse direction. This yields an FBG length of 12 mm. The fluence of the excimer laser light at the fiber has been varied up to $420\,\mathrm{mJ/cm}^2$.

The optical fiber used is a standard single mode fiber (Corning SMF-28), whose core and cladding diameters are 8.3 and 125 μm, respectively. The effective refractive index n_{eff} is about 1.4456. Prior to the experiment, the fiber was kept under 10 MPa hydrogen gas for ten days for hydrogen loading to increase the sensitivity of the fiber to UV light. The resin coating of the fiber is removed and the fiber is ultrasonically cleaned just before it is placed underneath the phase mask. Grating period p of the phase mask is 1070.3 nm giving a grating pitch $\Lambda =: p/2$ in the fiber core; hence, the FBG central wavelength is expected to be $\lambda_0 = 2n_{\mathrm{eff}}\Lambda = 2n_{\mathrm{eff}}p/2 \sim 1547\,\mathrm{nm}$.

We normally monitor FBG formation by injecting a broadband light signal from an amplified spontaneous emission (ASE) source (Thorlabs ASE-7701-AP) and analyzing the signal transmitted through the FBG with an optical spectrum analyzer (Advantest Q8384).[3] In the experiment described here, we have monitored the FBG formation using a wavelength-scannable LD light source (Ando AQ4321A, wavelength resolution 1 pm) and a high-speed photodetector (Thorlabs SIR5-FC, 5 GHz bandwidth and 70 ps minimum rise time) to achieve high resolution in the dynamic evolution of the spectrum.

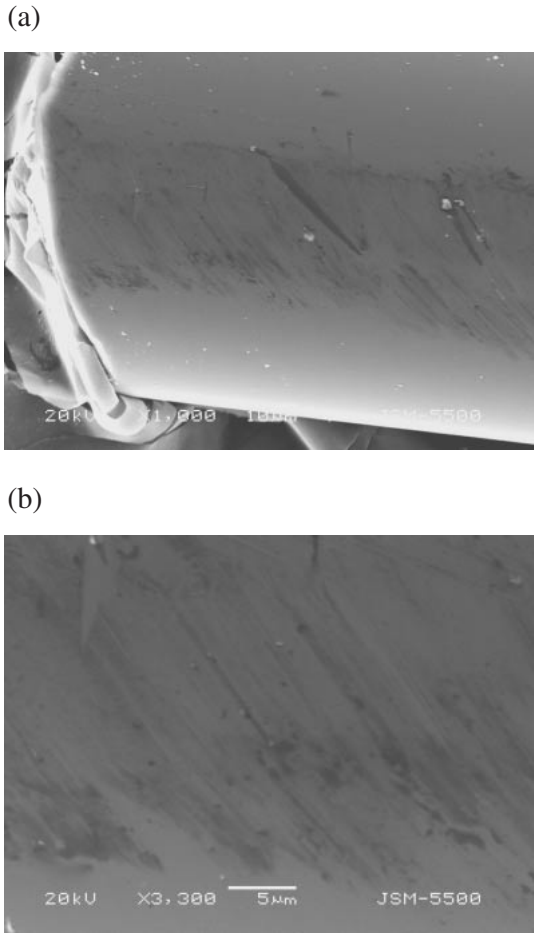

Fig. 2. SEM images of FBG surface exposed to the excimer laser. Magnification is 1000X in (a) and 3300X in (b).

When the fiber is exposed to the excimer laser beam at 180 mJ/pulse at a 20 Hz repetition rate, a transmission spectrum with −30 dB at the FBG wavelength and 0.2 nm width can be easily obtained within about two minutes. A scanning electron microscope (SEM) image of the surface of an FBG fabricated in this manner is shown in Fig. 2. The magnification is 1000X in (a) and 3300X in (b). Scratchlike damage is clearly visible with many stripes in the circumferential direction over approximately 30 μm, or 1/8 of the fiber circumference, i.e., over a 30° angle. The damaged portion is magnified in Fig. 2(b). Although weak and faint, many stripes corresponding to the pitch of the FBG, which is approximately 0.5 μm, i.e., one-half of the grating pitch p of the phase mask, are visible. Since the softening temperature of pure silica glass is 1100–1200°C, the surface of the damaged portion has exceeded that temperature. Since the fluence is typical of the level commonly used in FBG fabrication, we consider that FBGs fabricated by excimer laser irradiation will have physical damage relatively similar to that shown in Fig. 2.

We usually monitor the transmission spectrum as the FBG grows during exposure of the fiber to the excimer laser, and we always observe spikes in the spectrum corresponding to the excimer laser pulse. The spikes are positive at wavelengths below the FBG central wavelength and negative at wavelengths above the FBG central wavelength. A typical spectrum obtained with the wavelength scannable LD light

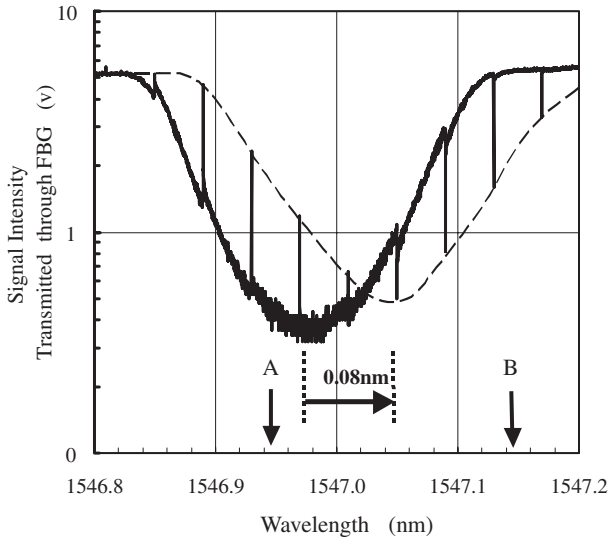

Fig. 3. Spectrum of optical signal transmitted through the FBG. Spikes correspond to excimer laser pulse. Dashed line is generated by smoothly connecting peak points of the spikes. Temporal evolutions of the signal with wavelengths fixed at A and B are shown in Fig. 5.

source and the fast photodetector is shown in Fig. 3. The excimer laser pulse energy is 180 mJ/pulse, and the FBG has been fabricated by running the excimer laser at a 20 Hz repetition rate for 2 min. Subsequently, the spectrum shown in Fig. 3 has been obtained with the excimer laser operating at a 1 Hz repetition rate. The sweep time is about 10 s in this figure and spikes appear every second when the excimer laser is turned on. These spikes can be interpreted as a momentary shift of the spectrum to longer wavelengths by the laser pulse, as indicated by a dashed line in the figure which is generated by smoothly connecting the peak points of the spikes. The wavelength shift is approximately 0.08 nm. After a series of experiments, the temperature dependence of the FBG wavelength was determined separately. The result is shown in Fig. 4 and 10 pm/°C is obtained. Thus, an instantaneous shift of 0.08 nm corresponds to a temperature increase of 0.08 nm/(10 pm/°C) ~8°C. Since this information is derived from the spectrum of light transmitted through the FBG formed in the fiber core, the temperature increase of approximately 8°C occurs at the fiber core.

To examine the dynamic evolution of the temperature, the

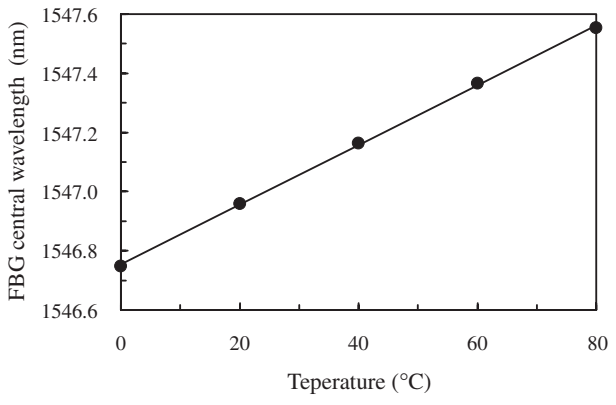

Fig. 4. Temperature dependence of FBG central wavelength.

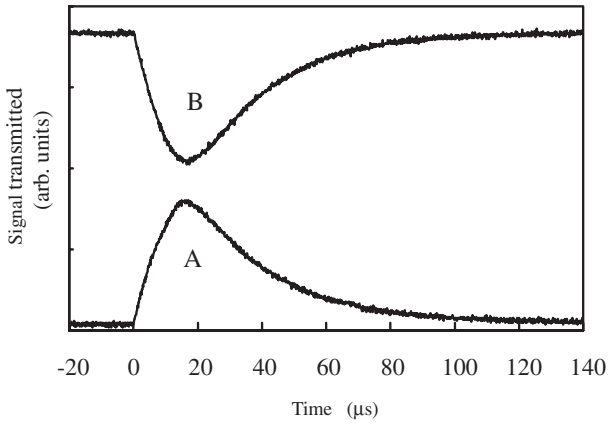

Fig. 5. Temporal evolution of the light signal transmitted through the FBG. Wavelength of the signals (A) and (B) are those marked in Fig. 3.

temporal response of the transmission signal is measured by fixing the wavelength of the LD light source. This is shown in Fig. 5 for two wavelengths, 0.02 nm shorter (labeled A) and 0.16 nm longer (B) than the FBG central wavelength shown in Fig. 3. The temperature of the FBG fiber core rises within 15–20 μs to its maximum, which is approximately 8°C as shown above, and cools down within about 100 μsec.

The temperature increase of the FBG as a whole can be deduced from the thermal energy balance and the physical properties of silica glass, which are described by

$$\Delta E = \rho \cdot V \cdot c \cdot \Delta T, \tag{1}$$

by measuring the energy ΔE absorbed by the FBG, where ρ is the density, V is the FBG volume, and c is specific heat. The excimer laser pulse energy is measured at the laser output, above the cylindrical lens, and underneath the fiber using a UV power meter. The result of these measurements is shown in Fig. 6(a). The size of the laser beam is $0.65 \times 12\,\mathrm{mm}^2$ at the plane of the fiber, for an energy density of $32.5\,\mathrm{mJ}/(0.65 \times 12\,\mathrm{mm}^2) \sim 420\,\mathrm{mJ/cm}^2$ for the highest energy data point. The difference between energies with and without the fiber inserted, which gives the energy absorbed by the fiber, is small but clearly detectable. The absorbed energy is plotted in Fig. 6(b), which is about 3% for all the applied energies, as can be seen in Fig. 6(c). Using physical properties of pure silica glass, i.e., its density $\rho = 2.2 \times 10^3\,\mathrm{kg/m}^3$ and specific heat $c = 0.74 \times 10^3\,\mathrm{J/(kgK)}$, together with the fiber volume $V = \pi(125\,\mu\mathrm{m}/2)^2 \times 15\,\mathrm{mm}$, we find $\Delta T = 3.38$°C for $\Delta E = 1\,\mathrm{mJ}$. This value of 3.38°C is, of course, the temperature increase averaged over the FBG volume.

By summarizing the above results, our study of the temperature rise in an FBG under typical fabrication conditions shows that

(1) SEM observation of the FBG surface yields $T =$ 1100–1200°C or more at the surface where the excimer laser beam is incident;
(2) The spikes in the transmission spectrum indicate $\Delta T \sim 8$°C at the fiber core of the FBG; and,
(3) Measurements of the absorbed energy yield ΔT equal to a few degrees averaged over the FBG volume.

The temperature increment has very large range over the fiber cross section.

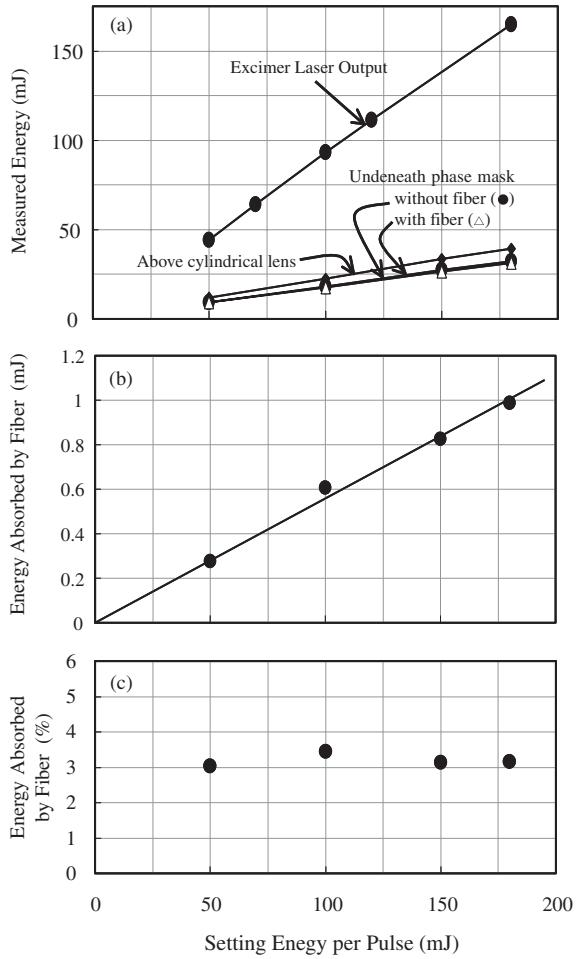

Fig. 6. Energy of excimer UV laser measured at various locations. (a) is at the laser exit, at above the cylindrical lens and at the position beneath the fiber with and without its presence. (b) is the energy absorbed by the fiber and (c) shows its fraction in percentage.

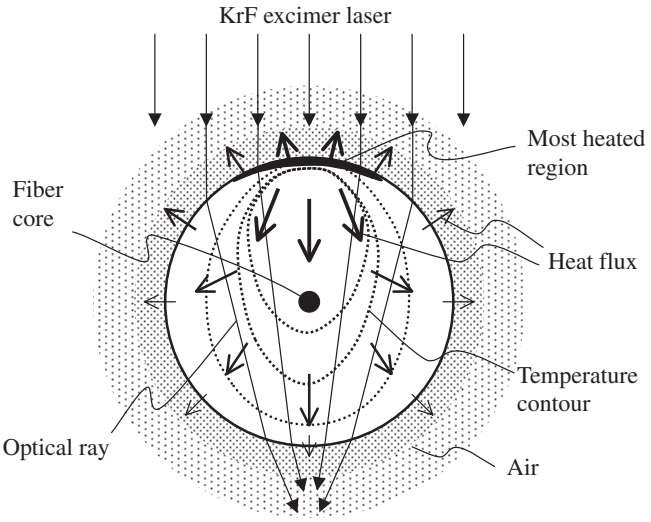

Fig. 7. Schematic of temperature and heat flow evolutions on the fiber cross section of the FBG.

3. Discussion

The temperature increase during excimer laser irradiation of FBGs during fabrication show that it ranges from a few °C to above 1000°C over the fiber cross section. The temperature distribution and heat flow on and around the fiber cross section are illustrated schematically in Fig. 7. A surface area corresponding to approximately 30° of the circumference is heated rapidly to a temperature close to or exceeding the softening point for silica glass. The fiber core is heated directly by the excimer laser beam and/or by the heat conducted from the surface, which has reached about 8°C. The temperature increase for the FBG as a whole is only a few °C.

A surface temperature above 1000°C is unusually high. The thickness of the surface layer can be estimated from eq. (1) assuming that most of the absorbed energy is deposited in this layer. Taking the volume of the surface layer as equal to the FBG length of 15 mm, multiplied by the 30 μm circumferential length of the scratch in the SEM images, multiplied by the thickness d, and taking $\Delta T = 1200$°C as the softening point of silica glass, yields a thickness d of 0.57 μm if half of the laser energy is absorbed there, i.e., $\Delta E = 1/2$ mJ. If 10% of the energy is absorbed, the thickness is $d \sim 0.11$ μm. This estimate, although crude, indicates that the layer is extremely thin.

If the temperature increase at the fiber core is solely due to the energy absorbed there, the transmission signal should not have the time delay shown in Fig. 5. The delay time of 15–20 μs appears to be the time for conduction of heat deposited at the surface to the fiber core. Heat transport and removal by the surrounding air will, of course, require a more detailed analysis.

One might suspect that the large surface temperature rise originates from foreign material on the surface which may have a high absorption efficiency for excimer laser light. Since the fiber surface is cleaned by cleaning tissue with alcohol after removing the coated resin and is further cleaned ultrasonically in alcohol before being mounted in the optical system, we consider that this is unlikely. On the other hand, the phase mask placed above the fiber is used for many months in our experiments without any cleaning, and there is no particular deterioration in the FBG characteristics or any evident damage on its surface. The mask is also made of silica glass but is fluorine-doped to ensure higher UV transmission and lower absorption. If the fiber is made of material with fluorine doping, we expect that strong surface absorption of the laser light may not occur.

Our result that a very thin surface layer, perhaps less than 1 μm thick, has exceeded 1000°C and the FBG as a bulk has increased by a few °C indicates that large internal stresses are induced in the fiber. The stress can be removed by annealing and is discussed in many articles.[4)] in which the discussions are focused on the defects induced by UV laser light on Ge chemical bonding in the fiber core. However, there is little or no discussion, to our knowledge, on fiber cladding which occupies the bulk of the fiber volumewise and is made of pure silica. Our results suggest that an investigation of stress removal by annealing for the bulk FBG is required. The scratchlike stripes may also certainly reduce the mechanical strength of the fiber. Reference 2 shows by Weibull plot analysis a large deterioration in the strength of the fiber exposed to the excimer laser, whereas that exposed to a CW laser of Ar^+ 240 nm has very little or no deterioration at all. Further study is required to determine

whether the damage to the fiber in the form of scratchlike stripes is the cause of this kind of degradation in mechanical strength.

4. Conclusions

We have conducted an experimental study of the temperature rise in an FBG during exposure to KrF excimer laser light using phase mask under typical FBG fabrication conditions. The irradiation energy is $420\,mJ/cm^2$ at the position of the fiber. The following results have been obtained:

(1) SEM observation of the FBG surface has revealed weak but clear physical damage with scratchlike marks stretching over $30\,\mu m$ in the direction of the fiber circumference on the side where the laser light is incident. This indicates that a very thin surface layer of the fiber has reached or exceeded the glass softening temperature, i.e., $\sim 1200^\circ C$.

(2) The spectrum of light transmitted through the FBG contains spikes corresponding to the time of the laser pulses, implying a nearly instantaneous shift of the spectrum to one at a higher temperature. The temperature increase at the fiber core implied in this interpretation is approximately $8^\circ C$.

(3) Measurement of the UV laser light absorbed by the fiber together with an energy balance analysis has yielded a temperature increase of a few $^\circ C$ averaged over the entire FBG.

The temperature distribution over the fiber cross section, with a very large range from a few $^\circ C$ to over $1000^\circ C$, may induce large internal stresses in the fiber. Whether the stress can all be removed by annealing requires further study. Also, whether the physical damage appearing as scratchlike marks is responsible for the degradation of mechanical strength reported in ref. 2 awaits further study.

Acknowledgement

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