Growth of Long-Period Gratings in H_2-Loaded Fiber After 193-nm UV Inscription

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***Abstract*—This letter reports and provides an explanation for the growth behavior of long-period gratings in H_2-loaded fiber immediately after 193-nm UV inscription. Growth of grating resonance peak by as much as 14 dB was measured. Impact of temperature and grating strength, immediately after UV inscription, on the growth behavior are also discussed.**

***Index Terms*—Fabrication, long-period gratings, photosensitivity, thermal stability.**

I. Introduction

LONG-PERIOD gratings (LPG's), which couple the fundamental guided mode to forward propagating cladding modes [1], have attracted considerable interest because of their extensive applications in both telecommunications and fiber-sensing systems. LPG's are commonly fabricated in fibers loaded with H_2 under high pressure so as to enhance its photosensitivity. After the UV writing process, the unreacted H_2 slowly diffuse out of the fiber and changed the effective index of propagation of guided optical modes. This causes a large change in both the central wavelength [2], [3] and the peak loss of the resonance peaks [4]. Even though Jang *et al.* [4] reported the growth of LPG's in H_2-loaded fiber after 248-nm UV inscription, they offered no explanation to their observation. In this letter, we report the growth characteristics of LPG's inscribed with 193-nm UV light in H_2-loaded fibers and offer an extension of the explanation given by Bakhti *et al.* [2] to account for the growth dynamics of the LPG's immediately after 193-nm UV inscription. The effects of temperature and initial strength of LPG's on the growth behavior are also discussed.

II. Experiment and Discussion

In the experiments, 2.5-cm-long LPG's with a period of 400 μm were written in Corning SMF-28 fiber that had been previously H_2-loaded at 140 atm at 70 °C for seven days. The fiber was exposed to a 193-nm ArF excimer laser with an energy density of 140 mJ/cm^2/pulse and a repetition rate of 4 Hz through an amplitude mask. A broad-band light source and an optical spectrum analyzer were used to monitor the transmission spectra of LPG's during and after UV inscription. After the UV inscription process, the LPG's continue to grow with time. Fig. 1 shows the transmission spectra of an LPG at different times immediately after UV inscription has stopped. Five resonance peaks ($LP_{02}\sim LP_{06}$ cladding modes) were observed in the wavelength range of 1180$\sim$1680 nm. The maximal resonance peak (LP_{06} cladding mode), with a loss of 3.92 dB (corresponds to a calculated index modulation of 1.1×10^{-4}) just after inscription [Fig. 1(a)], reached 17.91 dB after 20 h [Fig. 1(d)]. The growth of the resonance peaks of the LPG with time is plotted in Fig. 2. It can be seen that the resonance peaks grew rapidly during the first few hours and reached the maximum value after 20 h. They then decreased slowly to about 15.5 dB (index modulation $\approx 1.8 \times 10^{-4}$) after 440 h [Fig. 1(e)].

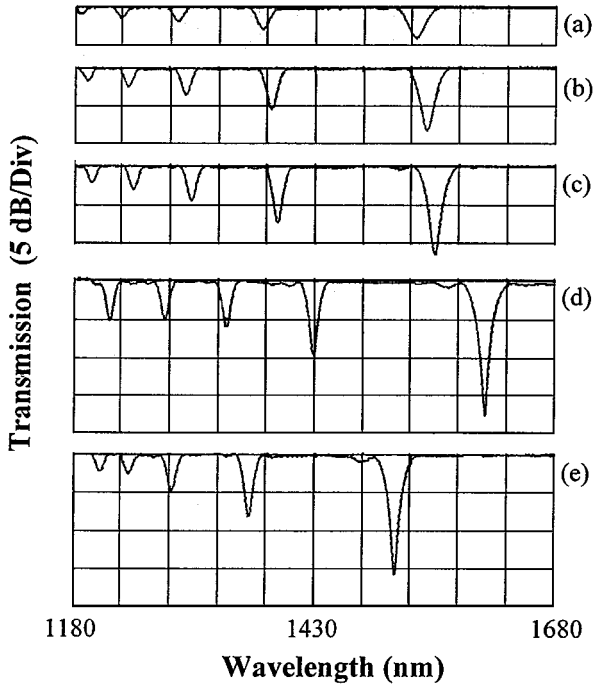

Fig. 1. Transmission spectra of the LPG at different time after UV inscription: (a) just after inscription, (b) after 0.5 h, (c) after 1.0 h, (d) after 20 h, and (e) after 264 h.

The growth of the LPG after UV inscription can be explained by the diffusion of H_2 in the core and the cladding of the fiber. In the LPG's, there are clearly defined sections that have and have not been exposed to UV light during inscription (refer to inset in Fig. 2). The H_2 concentration in the exposed core section is much less than that in the unexposed core section because most of H_2 was used up in the reaction that causes the

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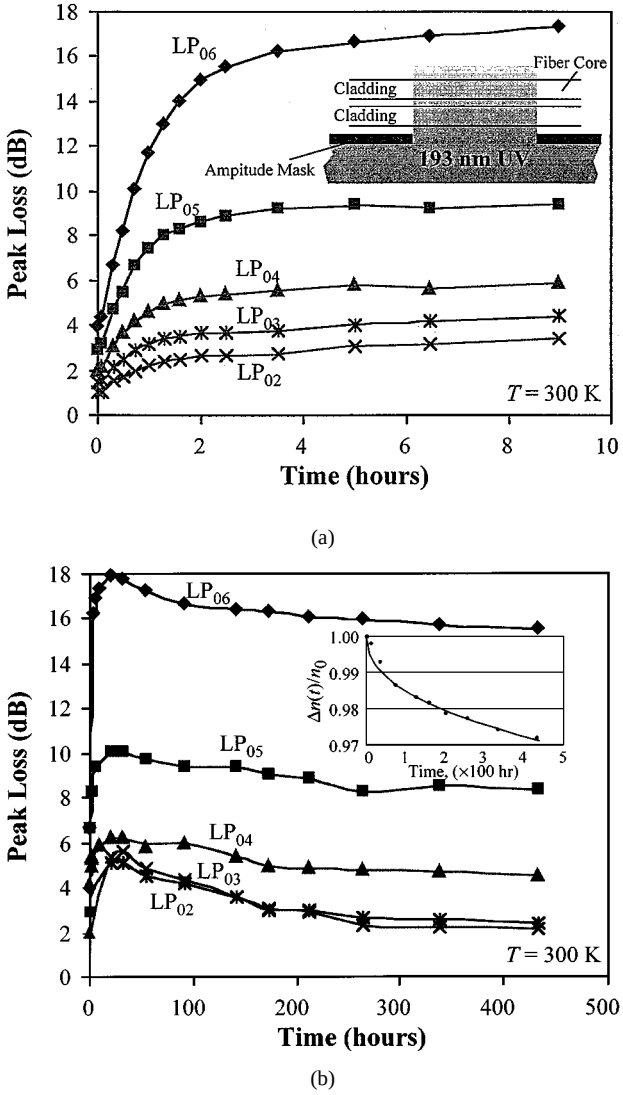

Fig. 2. Growth of resonance peaks of the LPG with time after UV inscription. (a) Short-term growth. Inset shows section of the fiber irradiated with UV light. (b) Long-term growth. Inset shows the experimental result (dots) and prediction (solid line) of the decay of the LPG's LP_{06} resonance after it reaches its maximum loss.

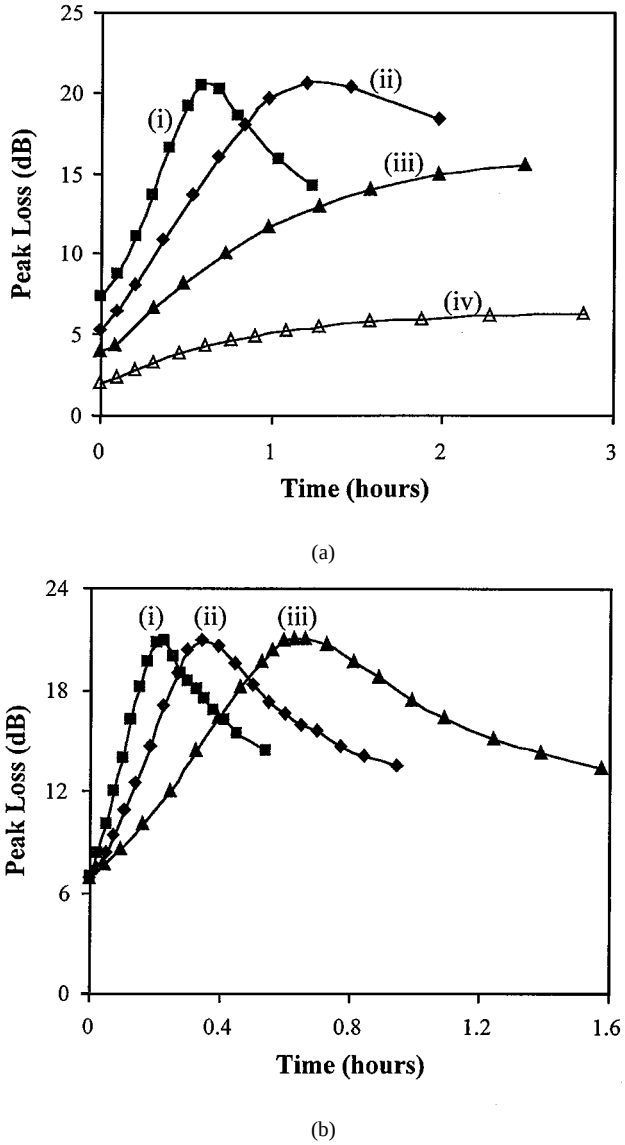

Fig. 3. Growth of the maximal resonance peak of the LPG's immediately after UV inscription. (a) With different initial grating strengths: i) 7.36 dB; ii) 5.29 dB; iii) 3.92 dB; iv) 2.02 dB. (b) At different temperatures: i) 43°C; ii) 32°C; iii) 23°C.

refractive-index change. Furthermore, strong absorption of the 193-nm UV light by the core could raise its temperature by more than 200 °C [5] and cause rapid diffusion of H_2 into the exposed core section from the cladding and the adjacent unexposed core section. We can ignore the effect of the UV light on the exposed cladding section because the transmission of 193-nm light across the fiber's fused silica cladding is typically greater than 99.99%. Therefore, the H_2 concentration in the unexposed core section and the cladding remain approximately constant after the grating writing process. Consequently, there is a large difference of H_2 concentration between the exposed core section and the unexposed core section and between the exposed core section and the exposed cladding region immediately after UV inscription. In order to restore equilibrium, H_2 will diffuse from both the unexposed core section and the cladding region to the exposed core section as well as into the surroundings. Since the refractive index of the fiber is related to the H_2 concentration [6], the refilling of H_2 will further raise the refractive index of the exposed core section. As a result, the index modulation will be increased, and hence the strength of the LPG will grow. The growth process continues until the H_2 concentration in both the exposed core section and the unexposed core section is approximately equal (~20 h after grating inscription). The in-diffusion of H_2 into the exposed core section is relatively fast in comparison with the out-diffusion of H_2 from both the exposed and unexposed core sections into the cladding because of the much smaller volume of the fiber core. For the next 420 h, H_2 in the exposed core section, unexposed core section, and cladding region will slowly diffuse out of the fiber. During this period, the rate of H_2 out-diffusion from both the exposed core section and the unexposed core section is equal and thus will not cause further change in the refractive index modulation nor the grating strength, but it will shift the resonance peaks to a short wavelength [Fig. 1(e)]. The reason for the decrease of the loss peak in Fig. 2 is mainly due to the decay of the grating [7]. The inset in Fig. 2(b) shows the decay of the LP_{06} resonance peak after

reaching the maximum value. It agrees well with the prediction made by Erdogan's power law model

$$\Delta n(t)/\Delta n_0 = 1/(1 + At^{\alpha})$$

with $A = 0.00191$ and $\alpha = 0.452$.

The growth behavior of the LPG's after UV inscription depends strongly on its initial strength. Fig. 3(a) shows the growth of the maximal resonance peak of the LPG's with different initial strength. It can be seen that LPG's with larger initial strength grow more rapidly. In the LPG with larger initial strengths, more H_2 in the exposed core section were used up during UV inscription, resulting in larger H_2 concentration differences between the exposed core section and the unexposed core section. Hence the diffusion of H_2 into the exposed core section is faster, resulting in a more rapid growth of the grating strength.

The H_2 diffuse faster with increase in temperature, thus heating can hasten the growth of the LPG's. Fig. 3(b) shows the growth of the maximal resonance peak of the LPG's with the same initial strength at different temperatures. It only took 13 min for the peak loss to grow from 6.9 dB to about 21 dB at 43 °C. Similar process required 20 and 38 min at 32 °C and 23 °C, respectively. After reaching about 21 dB the peak loss decreases with time. In the measurement, a low OSA resolution was used (resolution set to 5 nm) because of the low power density of the broadband light source, thus the actual value of the peak loss could be much larger than 21 dB. The mechanism that causes this decrease behavior is different from that in Fig. 2 and is happening at much faster rate. The decrease of the peak loss in Fig. 3(b) is due to the fact that the peak loss S of LPG's follows a sinusoidal function of the refractive index modulation and is given by $S = \sin^2(\eta L)$. Where L is the grating length and η is the coupling coefficient that is directly proportional to the index modulation [8]. As the index modulation increases, the peak loss increases until $\eta L = \pi/2$. When $\eta L > \pi/2$, the peak loss decreases with the index modulation. Since the initial strength of the LPG's in Fig. 3(b) is relatively large, the refilling of H_2 raise the refractive index modulation and eventually $\eta L > \pi/2$, so the peak loss increases initially and then decreases subsequently. The decrease of the peak loss in Fig. 3(a) is also due to the same reason.

In summary, we presented our observation of the evolution of the growth of LPG's in H_2-loaded fiber, after inscription with 193-nm light. Our results shows that LPG's peak loss at the end of UV writing is significantly underestimated due to the differential between unreacted and reacted Hydrogen in the core and cladding. An explanation to account for the large change in the resonance peak and the impact of temperature and grating initial strength on the growth behavior were also presented.

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