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Post-exposure processing and refractive index change in hydrogen-loaded/annealed fiber grating

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ABSTRACT

Refractive index change induced by post-exposing in annealed and unannealed fiber Bragg grating are investigated in theory and experiment. The relationship between grating index change, initial refractive index distribution and post-exposure are analyzed based on the two-step process photosensitive theory to build up the mathematical models of the refractive mean index and the refractive index modulation change. With 193 nm UV laser post-exposure processing, the evolutions of resonant wavelength and reflectivity are demonstrated and the kinetics of refractive mean index and refractive index modulation are discussed.

1. Introduction

Optical fiber Bragg gratings (FBGs) are generally based on the photoinscription of a refractive index modulation along the core of the fiber, which are widely used in various fields, such as in temperature/strain sensing, dispersion compensation, fiber laser, wavelength division multiplexing/demultiplexing [1–4]. It is found that the reflectivity of FBGs could be significantly amplified [5], the grating wavelength could redshift, and the thermal stability would be enhanced [6] with the UV exposing when the FBGs are fabricated from hydrogen-loaded fiber and even in annealed optic fiber [7–9].

However, the most of investigates are focused on describing the experimental phenomenon on the photosensitive characteristic under post-exposure. In this paper, we demonstrate mathematical models to describe refractive index changes of FBG during post-exposing based on the two-step process theory, and analyze the wavelength shift and the reflectivity growth of grating with exposure increasing. Experiments are conducted to discuss the role of post-exposure by using 193 nm UV laser.

2. Theoretical modeling

The photosensitivity reaction is essentially a two-step process described symbolically as [10]

$$A \xrightarrow[k_1]{h\nu} B \xrightarrow[k_2]{h\nu} C \tag{1}$$

where $h\nu$ represents photonic energy, k_1 and k_2 are the rate coefficients of the reactions ($k_1 \gg k_2$), A, B and C are chemical species, which have been shown likely to be GeODC(II) defects, GeH radicals and GeE′ centers, respectively.

When the UV laser irradiates through phase mask into the fiber core, the distribution of the refractive index changes in the fiber core induced by exposure can be represented by Fourier series

$$\Delta n(z) = \Delta n_0 + \Delta n_1 \cos\left(\frac{2\pi z}{\Lambda}\right) + \cdots \tag{2}$$

where defining z axis is the longitudinal direction of fiber, the pitch of phase mask is 2Λ. Δn_0 and Δn_1 are Fourier coefficients. For weak perturbations, we approximate $\Delta n_0 = \Delta n_{\mathrm{mean}} \approx \Delta n_{\mathrm{eff}}$, $\Delta n_1 \approx \Delta n_{\mathrm{mod}}$, where Δn_{mean} is refractive mean index change, Δn_{eff} is effective refractive index change, and Δn_{mod} is refractive index modulation change, which can be obtained by coupled-mode theory [11,12]

$$\Delta n_{\mathrm{mod}} = \frac{\lambda \tan h^{-1}\left(\sqrt{R}\right)}{\pi L} \tag{3}$$

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$$\Delta n_{\text{mean}} \approx \Delta n_{\text{eff}} = \frac{\Delta\lambda}{2\Lambda} \quad (4)$$

where λ, R and L are wavelength, reflectivity and length of grating, respectively. According to the two-step photosensitive theory, residual species B in the fiber after grating inscribing could be transform into species C and cause further refractive index changes with post-exposing.

Defining the grating inscribing is 0th exposure and is written as $\Delta n_0(z)$, the 1st, 2nd…ith exposure(post-exposure) are written as $\Delta n_1(z), \Delta n_2(z) \ldots \Delta n_i(z)$ and assuming them do not induce new refractive index modulation in FBG. N_i is the UV pulses number, the variation of refractive index change $\Delta n_i^{\text{vary}}(z)$ is given by $\Delta n_i^{\text{vary}}(z) = \Delta n_i(z) - \Delta n_0(z)$, similarly the variation of Δn_{mod} and Δn_{mean} is given by $\Delta n_{\text{mod}-i}^{\text{vary}}(z) = \Delta n_{\text{mod}-i}(z) - \Delta n_{\text{mod}-0}(z)$ and $\Delta n_i^{\text{vary}}(z) = \Delta n_{\text{mean}-i}(z) - \Delta n_{\text{mean}-0}(z)$. By calculating the Fourier coefficient of $\Delta n_i^{\text{vary}}(z)$, the variation of refractive mean index change and refractive index modulation change can be written as

$$\Delta n_{\text{mod}-i}^{\text{vary}}(N_i) = \frac{2}{\Lambda}\int_0^{\Lambda} \Delta n_i^{\text{vary}}(N_i, z)\cos\left(\frac{2\pi z}{\Lambda}\right)\mathrm{d}z \quad (5)$$

$$\Delta n_{\text{mean}-i}^{\text{vary}}(N_i) = \frac{1}{\Lambda}\int_0^{\Lambda} \Delta n_i^{\text{vary}}(N_i, z)\,\mathrm{d}z \quad (6)$$

Refractive index change is proportional to the concentration of species C, and the variation of refractive index change can be expressed as

$$\Delta n_i^{\text{vary}}(N_i, z) = \phi \cdot \Delta\left[C_i^{\text{vary}}(N_i, z)\right] \quad (7)$$

where $\Delta\left[C_i^{\text{vary}}\right]$ is the variation of species C concentration during post-expsuring, ϕ is the coefficient between species C concentration and refractive index change. $\Delta n_{\text{mod}-i}^{\text{vary}}(N_i)$ can be further described by

$$\Delta n_{\text{mod}-i}^{\text{vary}}(N_i) = \frac{2}{\Lambda}\int_0^{\Lambda} \phi \cdot \Delta\left[C_i^{\text{vary}}(N_i, z)\right]\cos\left(\frac{2\pi z}{\Lambda}\right)\mathrm{d}z \quad (8)$$

It is mentioned above that post-exposure do not induce new refractive index modulation in FBG, $\Delta n_{\text{mod}-i}^{\text{vary}}(N_i)$ becomes

$$\Delta n_{\text{mod}-i}^{\text{vary}}(N_i) = \frac{2}{\Lambda}\int_0^{\Lambda}\int_{N_1}^{N_i} -\phi \cdot k_2(z) \cdot [B(N, z)]\cos\left(\frac{2\pi z}{\Lambda}\right)\mathrm{d}N\mathrm{d}z \quad (9)$$

Refractive index modulation achieves maximum value when species B is completely converted to C, we obtain

$$\Delta n_{\text{mod}}^{\text{max}} = \frac{2}{\Lambda}\int_0^{\Lambda} \phi \cdot [B_0(N_0, z)]\cos\left(\frac{2\pi z}{\Lambda}\right)\mathrm{d}z \quad (10)$$

According to two-step process theory, $[B_0(N_0, z)]$ can be described by

$$[B_0(N_0, z)] = [A_{\text{int}}] \cdot k_1(z)\frac{e^{-k_1(z)N_0} - e^{-k_2(z)N_0}}{k_2(z) - k_1(z)} \quad (11)$$

where $[A_{\text{int}}]$ is the initial concentration of species A, k_1 and k_2 is influenced by the interference light field of UV exposure and photosensitive fiber (including germanium concentration, hydrogen concentration), which can be described by $k_1 = \sigma_1 I(z)$ and $k_2 = \sigma_2 I^2(z)$ [13], where $I(z)$ is the distribution of interference light field, σ_1 and σ_2 are photosensitivity reaction coefficients of fiber. Using Eqs. (9) and (10), we obtain

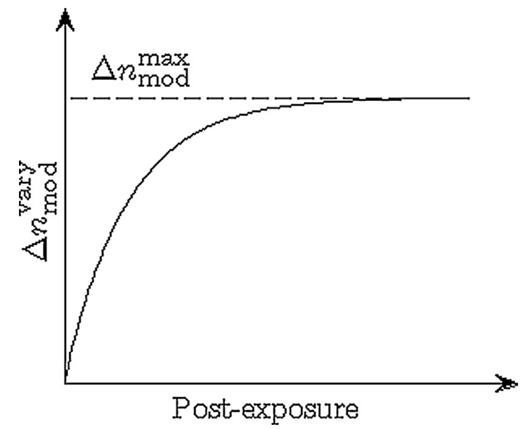

Fig. 1. Growths of grating refractive index modulation.

$$\Delta n_{\text{mod}-i}^{\text{vary}}(N_i) = \Delta n_{\text{mod}}^{\text{max}}\left[1 - e^{-k_2(N_i - N_0)}\right] \quad (12)$$

The kinetics of $\Delta n_{\text{mod}}^{\text{vary}}$ with post-exposing of calculated by Eq. (12) is shown in Fig. 1. As shown in Fig. 1, $\Delta n_{\text{mod}}^{vary}$ increase rapidly at the beginning of the exposure and exhibits saturation for longer exposure time, the maximum achievable index change is determined by the initial concentration distribution of species B, which is related to the interference light field when grating is inscribed. The growth rate is related to k_2, it should be noted that the hydrogen is not a necessary condition for $\Delta n_{\text{mod}}^{\text{max}'}$s growth under post-exposing, but the presence of hydrogen will speed up this reaction (new B species will generate with post-exposure).

Similarly, $\Delta n_{\text{mean}-i}^{\text{vary}}(N_i)$ can be further described by

$$\Delta n_{\text{mean}-i}^{\text{vary}}(N_i) = \frac{1}{\Lambda}\int_0^{\Lambda} \phi \cdot \Delta\left[C_i^{vary}(N_i, z)\right]\mathrm{d}z \quad (13)$$

In the optical fiber with a high hydrogen concentration ($k_1 \gg k_2$), for $[B(N_0, z)]/[A_{\text{int}}] \ll 1$, the growth of species C can be approximately given by

$$\Delta\left[C_i^{\text{vary}}(N_i, z)\right] = [C(z, N_i) - C(z, N_0)] \approx [A_{\text{int}}]\frac{k_2(z)\left[1 - e^{-k_1(z)(N_i+N_0)}\right] - k_1(z)\left[1 - e^{-k_2(z)(N_i+N_0)}\right]}{k_2(z) - k_1(z)} \quad (14)$$

Using Eq. (14), we obtain

$$\Delta n_{\text{mean-i}}^{\text{vary}}(N_i) \approx \frac{1}{\Lambda}\int_0^{\Lambda} \phi \cdot [A_{\text{int}}]\frac{k_2(z)\left[1 - e^{-k_1(z)(N_i+N_0)}\right] - k_1(z)\left[1 - e^{-k_2(z)(N_i+N_0)}\right]}{k_2(z) - k_1(z)}\mathrm{d}z \quad (15)$$

Eq. (15) is the model of $\Delta n_{\text{mean}}^{\text{vary}}$ that we use to describe kinetic of refractive mean index change under post-exposing when the optical fiber has a high hydrogen concentration ($k_1 \gg k_2$). The kinetic is shown in Fig. 2(a). The growth rate of $\Delta n_{\text{mean}}^{\text{vary}}$ is affected by the interference light field of UV exposure and photosensitive fiber (including germanium concentration, hydrogen concentration).