A Novel Fabrication Technique of Long Period Fiber Gratings Using a Holographic Optical Element

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We develop a new flexible and precise ultraviolet exposure technique to fabricate a long period fiber grating using a computer-generated holographic optical element (HOE). The HOE can generate a striped beam pattern with about a 300 μm period from a KrF excimer laser. This method offers (1) ease in varying the grating period and (2) grating period precision. We achieve a grating period within an accuracy of ±0.04 μm. This means that the peak wavelength can be controlled within an accuracy of ±0.2 nm with an operating wavelength of 1.55 μm.

Key words: fiber grating, long period fiber grating, computer-generated hologram, holographic optical element, excimer laser, ultraviolet exposure

1. Introduction

A long period fiber grating (LPFG) has become a key device for current optical communication. The gain-flattening filter of an Er-doped amplifier1 is a main application of the LPFG in which it works as an optical loss filter with small backreflection.2

Ultraviolet (UV) beam exposure3 induces a small change of refractive index in the Ge doped core region in a SiO2 glass fiber. The refractive index modulation in its core along the fiber optical axis, or refractive index grating, consists of a series of small refractive index changes in the core. The refractive index characterizes the LPFG, whose grating period of about 50 to 1000 μm and a grating region along the optical axis of several centimeters.

The contact mask method4 and point-by-point writing method5 are two conventional techniques of UV exposure to fabricate the LPFG. The former method adopts a contact mask directly on a fiber, which is a grating form intensity mask. This exposes the fiber with a fixed grating beam pattern, whose period A cannot be changed, and the intensity distribution along the fiber axis is merely a periodic rectangle pattern. The latter method uses a focused UV beam to illuminate a fiber point by point by moving the fiber position. However, the accuracy of its period A is restricted within the one of the fiber movement, and it requires a longer time than the contact mask method. It is difficult to adjust the amount of UV exposure energy while monitoring the growth of the spectrum, because the total number of grating stripes affects the spectrum more than the accumulated UV energy at each independent stripe does.

We develop a flexible and precise UV exposure technique to fabricate a LPFG by applying a computer-generated holographic optical element (HOE) to solve the above problems. The HOE can generate a striped beam pattern whose grating period A is two times larger than the minimum focused spot size of a transmitted UV beam. In our configuration, we can fabricate a LPFG of any grating period from 50 to 1000 μm by setting suitable optics. The grating period A can be varied consecutively by changing the focal length of the focusing zoom lens system. In this experiment, we fabricate a striped beam pattern with a period of around 364 μm and change the grating period A in a range of ±10 μm within an accuracy of ±0.04 μm. This leads to an accuracy in the peak wavelength of its loss spectrum around 1.55 μm within ±0.2 nm. Precise adjustment of the loss peak wavelength and its transmittance can be achieved by monitoring the transmission spectrum during the LPFG writing and its feedback to UV exposure amounts. Diffraction efficiency of HOE limits utilization efficiency of UV light to around 60%, which is more than the opening ratio of contact mask, 50%.

2. Fabrication Optical System

Figure 1 is an illustration of our LPFG fabrication optical system with the HOE. It consists of a KrF excimer laser (λ = 248 nm), the HOE, and a focusing zoom lens system. The HOE diffracts the KrF excimer laser beam into several designed directions, and the zoom lens system makes each beam focus on a focusing plane so that these focused beams form a striped pattern in the plane.

The computer generated HOE has a binary phase pattern and is designed to diffract an incident beam into multiple beams in x and y directions. The diffracted multiple beams have the same interval angles and the same energy in each direction. We design the HOE with the following specifications. The divided angle and number in x direction are Δφx = 1.10 mrad and Nx = 79, and those in y direction are Δφy = 0.24 mrad and Ny = 17, respectively. The HOE pattern is tiled with each unit of 0.224 mm × 1.024 mm. In case of an incident UV beam that is larger than the single unit size, none of the diffracted beams changes its direction or intensity distribution. All divided beams are separately focused and form an over-

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Optical Fiber
Length $L_x$
Interval $\Delta y$

period $\Lambda_x$
width $h_y$

width $h_x$

Fig. 2. Construction of the striped beam pattern. Each of the 79 beams divided in the $x$ direction forms a peak independently, and 17 beams in the $y$ direction are superposed on each other and form a flat beam pattern.

all striped beam pattern. Figure 2 shows the concept of this pattern construction. In the $x$ direction along the fiber axis, 79 divided beams form 79 independent stripes on the focal plane. The period $\Lambda_x$ is determined by the effective focal length of the zoom lens system, $f_{zoom}$, and the divided angle, $\Delta \phi_x$, as shown by the following equation:

$$\Lambda_x = f_{zoom} \cdot \Delta \phi_x. \quad (1)$$

The distance between the HOE and the forward principal plane of the zoom lens system is equal to the effective focal length of the lens system, which means that the system is a telecentric configuration for any divided beam. This assures normal incidence of each divided beam on the focusing plane, so that the grating period $\Lambda_x$ is constant even if a fiber on the plane is slightly out of focus.

A beam width defined by full width at half maximum (FWHM) is expressed in the following equation:

$$h_x = f_{zoom} \cdot \Delta \theta_x, \quad (2)$$

where $\Delta \theta_x$ means the divergence angle of the incident KrF laser beam defined by FWHM. The ratio, $r$, of one stripe width $h_x$ to the grating period $\Lambda_x$ is expressed by $\Delta \theta_x$ and $\Delta \phi_x$, independent of $f_{zoom}$ as follows:

$$r = \frac{h_x}{\Lambda_x} = \frac{\Delta \theta_x}{\Delta \phi_x}. \quad (3)$$

$\Delta \phi_x$ was set to 1.10 mrad so $r$ would be 0.5. Fluctuation of peak intensity in each stripe comes from variation of each diffracted beam by the HOE, which we estimated to be less than ±5%.

In the $y$ direction perpendicular to the fiber axis, equations similar to (1) and (2) can apply. However, each beam is set to superpose on each other so as to form homogeneous intensity distribution in the $y$ direction. Beam width $h_y$ is set larger than the interval of each divided beam, $\Lambda_y$, so that beam intensity in the $y$ direction has a top flat length of 1.2 mm on the plane for enough space of tolerance to place fiber.

The zoom lens system consists of two spherical lenses in this experiment. Focal length of each lens is 540 mm and the variable distance $l$ between the two lenses is 195 mm ± 25 mm. The effective focal length of the zoom lens system is expressed as follows:

$$f_{zoom} = \frac{f^2}{2f - l}. \quad (4)$$

$f_{zoom}$ shows approximately linear dependence on $l$ in a short range of $l$. Accuracy of ±100 μm in the interval $l$ around 195 mm leads to the accuracy of $\Lambda_y$ within ±0.04 μm, according to the Eqs. (1) and (4). We can control the grating period $\Lambda_y$ to nanometer order precision.

3. Results and Discussion

Figure 3 shows a portion of beam intensity distribution measured by an UV photosensitive film on a focusing plane. The grating period $\Lambda_x$ in the $x$ direction is 358.4 μm and the top flat intensity region is 1.2 mm long in the $y$ direction.

Figure 4 shows the relationship between $l$ and $\Lambda_x$. Black circles are experimental data for $l = 170$–220 mm which coincide with a solid line calculated from Eqs. (1) and (4). The variable range of $\Lambda_x$ is ±10 μm for $l = 195$ mm ± 25 mm.

We fabricate LPFGs using this system to confirm its effectiveness. Sample fibers are dispersion shifted fibers (DSF) made by Fujikura Corporation and are exposed to hydrogen pressure of $2.9 \times 10^6$ Pa at room temperature for 2 weeks.

Figure 5 shows transmission spectra of four different LPFGs which are written with four different grating periods. Loss peak wavelengths satisfy a mode coupling condition:

$$\lambda_p = (\Delta n + \delta n_{DC}) \cdot \Lambda_x, \quad (5)$$

where $\delta n_{DC}$ is a DC component of induced effective index change by UV illumination and $\Delta n$ is the difference between the effective index of the core mode and cladding mode. $\Delta n$