A phase mask fiber grating and sensing applications

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Abstract

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This paper presents an investigation of a fabricated fiber grating device characteristics and its applications, using a phase mask writing technique. The use of a most common UV phase laser (KrF eximer laser), with high intensity light source was focussed to the phase mask for writing on a fiber optic sample. The device (i.e. grating) characteristic especially, in sensing application, was investigated. The possibility of using such device for temperature and strain sensors is discussed.

Key words : fiber bragg grating, optical sensor, optical signal processing

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Fiber Bragg grating (FBG) has been of great interest in communications such as tunable filter, in wavelength division multiplexing/demultiplexing (WDM/D), and as fiber sensors such as temperature sensor, vibration sensor, pressure sensor (Kashyap, 1999, Zhang, et al., 2001, Othons and Kalli, 1999, Grattan and Meggitt, 2000) and strain sensitivity (Frazao, 2002). One of the techniques commonly used to inscribe Bragg grating in the core of optical fibers uses a phase mask to spatially modulate and diffract the UV beam to form an interference pattern. The interference pattern induces a refractive index modulation i.e. Bragg grating in the core of the photosensitive fiber which is placed directly behind the phase masks (Hill, et al., 1993). The phase mask technique is a method of writing Bragg gratings because of its simplicity and reduced mechanical sensitivity. The most common UV source used to fabricate Bragg grating with a phase is KrF excimer laser. These UV laser sources typically have low spatial and temporal coherence. The low spatial coherence requires the fiber to be placed in near contact to the grating corrugations on the phase mask in order to induce maximum modulation in the index of refraction. The further the fiber is placed from the phase mask, the lower the induced index modulation, resulting in low reflectivity Bragg gratings. Clearly, the separation of the fiber from the phase mask is a critical parameter in producing quality gratings and relatively easy to fabricate. The advantages offered by optical fiber include low loss transmission, immunity to electromagnetic interference, lightweight, and electrical isolation.

In this paper, we report and demonstrate the importance of the coherence light source in the UV laser used write Bragg grating in a core of fiber optic with the phase mask technique. In addition, the use of such a device for temperature sensors and strain sensors is discussed. In accordance with the strain effect and applied temperature on an optical fiber Bragg grating this corresponds to change in the grating spacing which shift in the Bragg wavelength. In this experiment can be using an application in the telecommunication and fiber optic sensors such as high temperature sensor, fire alarm sensor, vibration sensor, and pressure sensor. Operating Principle

1. Phase mask technique

One of the most effective methods for inscribing Bragg gratings in photosensitive fiber is the phase mask technique. This method employs a diffractive optical element to spatially modulate the UV writing beam. Generally, phase masks may be formed either holographically or by electron
beam lithography. One of the advantages of the electron beam lithography over the holographic technique is that complicated patterns can be written into the mask’s structure such as quadratic chirps and patterns.

Figure 1 shows that the UV radiation at normal incidence, the diffracted radiation is split into $m = 0$ and $\pm 1$ order. The interference pattern at the fiber of two beams of order $\pm 1$ brought together has a period of the grating $\Lambda_g$ related to the diffraction angle $\theta_{m/2}$ by

$$\Lambda_g = \frac{\lambda_{uv}}{2 \sin(\theta_{m/2})} = \frac{\Lambda_{pm}}{2}$$

where $\Lambda_{pm}$ is the period of the phase mask, $\Lambda_g$ is the period of the fringes and $\lambda_{uv}$ is the UV wavelength. The period of the grating etched in the mask is determined by the required Bragg wavelength $\lambda_{Bragg}$ for the grating in the fiber, yielding

$$\Lambda_g = \frac{N \lambda_{Bragg}}{2n_{eff}} = \frac{\Lambda_{pm}}{2}$$

where $N \geq 1$ is an integer indicating the grating period and $n_{eff}$ is effective core index of fiber. The Bragg conditions are $\lambda_{Bragg} = 2n_{eff}\Lambda_g$. The method employs a diffractive optical phase mask to spatially modulate the UV writing beam shown as Figure 2, which may be formed holographically or by electron-beam lithography. The patterns can be written into the electron beams fabricated masks. The phase mask grating has a one-dimension surface-relief structure fabricated in high quality fused silica flat transparent to the UV writing beam.

The profile of the periodic gratings is chosen such that when the UV beam is incident on the phase mask, the zero-order-diffracted beam is suppressed to less than a few percent of the transmitted power. In addition, the diffracted plus and minus first orders are maximized, each containing, typically, more than 35% of the transmitted power. A near-field fringe pattern is produced by the interference of the plus and minus first-order diffracted beams. The period of the fringes is one-half that of the mask. The interference pattern photoimprints a refractive-index modulation in the core of a photosensitive optical fiber placed in contact with or in close proximity immediately behind the phase mask. A cylindrical lens is used to focus the fringe pattern along the fiber core. The phase mask greatly reduces the complexity of the fiber grating fabrication system. The simplicity of

Figure 1. Schematic of the UV radiation at normal incidence of a phase masks.
using only one optical element provides a robust 
and an inherently stable method for reproducing 
fiber Bragg grating. Since the fiber is usually placed 
directly behind the phase mask in the near field of 
the diffracting UV beams, sensitivity to mechanical 
vibrations and, therefore, stability problems are 
minimized. Low temporal coherence does not 
affect the writing capability due to the geometry of 
the problem.

2. Temperature and strain sensitivity of 
Bragg grating

The Bragg grating resonance, which is 
the center wavelength of light back reflected from 
a Bragg grating depends on the effective index of 
refraction of the core and the periodicity of the 
grating. The effective index of refraction, as well 
as the periodic spacing between the grating planes, 
will be affected by changes in strain and tempera-
ture. The shift in the Bragg grating center wave-
length due to strain and temperature changes is 
given by

$$\Delta \lambda_{\text{Bragg}} = 2 \left( \frac{\partial \Lambda}{\partial l} + n \frac{\partial n}{\partial l} \right) \Delta l + 2 \left( \frac{\partial \Lambda}{\partial T} + n \frac{\partial n}{\partial T} \right) \Delta T$$

(3)

where \( T \) is temperature and \( l \) is length of strain 
effect. The first term in (3) represents the strain 
effect on an optical fiber. This corresponds to a 
change in the grating spacing and the strain optic 
induced change in the refractive index. The above 
strain effect term may be expressed as

$$\Delta \lambda_{\text{Bragg}} = \lambda_{\text{Bragg}} \left( 1 - p_e \right) \epsilon_z$$

(4)

where \( p_e \) is an effective strain-optic constant de-
defined as

$$p_e = \frac{n^2}{2} \left[ p_{12} - \nu(p_{11} + p_{12}) \right]$$

(5)

where \( p_{11} \) and \( p_{12} \) are components of the strain optic 
tensor, \( n \) is the index of the core, and \( \nu \) is the 
Poisson’s ratio. For a typical optical fiber \( p_{11} = 0.113, p_{12} = 0.252, \nu = 0.16 \) and \( n = 1.482 \).

The second term in (3) represents the tem-
perature effect on an optical fiber. A shift in the 
Bragg wavelength due to thermal expansion 
changes the grating spacing and changes the index 
of refraction. This fractional wavelength shift for 
temperature change \( \Delta T \) can be written as

$$\Delta \lambda_{\text{Bragg}} = \lambda_{\text{Bragg}} \left( \alpha - \zeta \right) \Delta T$$

(6)

where \( \alpha = (1/\Lambda)(d\Lambda/dT) \) is the thermal expansion 
coefficient for the fiber (=0.55×10⁻⁶ for silica). The
quantity $\zeta = (1/n)(\partial n/\partial T)$ represents the thermo-optic coefficient and it is approximately equal to $8.6 \times 10^{-6}/^\circ\text{C}$ for the germanium-doped silica core fiber.

**Experiment**

The experiment setup for inscribing Bragg grating with a phase mask is shown in Figure 3. A KrF excimer laser was using as the UV source for inscribing Bragg grating with a phase mask. The photosensitive fiber was attached on to a mount that allowed its separation from the phase mask to be adjusted. The excimer laser (248 nm) was operating at 10 mJ with a repetition rate of 200 Hz. The beam was directed into the phase mask and focused with a plane-cylindrical lens ($f = 200$ mm) onto the fiber. The dimension of the phase mask used in this experiment is 25 mm x 3 mm, the period of the grating corrugation is 1060 nm. The zero-order-diffracted beam was suppressed below 3% and each of the plus and minus first-order diffracted beams contained 35% of the transmitted light. Using this phase mask, Bragg gratings inscribed in fibers (single mode fiber type I having a diameter 125 µm effective core index ($n_{eff}$) = 1.4474 and fiber core is silica germanium boron) and duration of UV exposure 60 s were kept constant throughout the experiment. In this experiment, using a broadband light source launch into the fiber core traveled to the optical spectrum analyzer for a detected the Bragg wavelength.

The experimental set up for temperature sensitivity of fiber Bragg grating system is shown in Figure 4 (a), using the broadband light source launched into the fiber Bragg grating pass of the oven traveled on to be detected the Bragg wavelength ($\lambda_{Bragg}$) by the optical spectrum analyzer (OSA), at the oven controlled temperature and varied temperature from 25, 35, 45 to 205°C, which fiber Bragg grating.

The experimental setup for the strain sensitivity of fiber Bragg grating system is shown in Figure 4 (b). We used the broadband light source launched into fiber Bragg grating traveled to the detector and the detected by optical spectrum analyzer with Bragg wavelength. When the fiber Bragg grating have fixed distance 40 cm between point A and point B. At point B was a fixed with a micrometer for strain the fiber Bragg grating by varied a distance at the micrometer for micro strain ($\mu$ε) from 0, 200 $\mu$ε, 400 $\mu$ε to 1800 $\mu$ε.

**Results**

The result for inscribing Bragg grating with a phase mask technique is show in Figure 5. The transmission spectrum of Bragg grating and the percent reflectivity of Bragg grating from writing using the phase mask technique.
Figure 4. The experiment setup used: (a) temperature sensitivity and (b) strain sensitivity

![Experiment Setup Diagram]

Figure 5. Graph of Bragg grating characteristics: (a) Transmission (b) Reflectivity (%)
Figure 6 (a), shows the effect of temperature while the applied is used temperature from 25°C to 205°C, Bragg grating wavelength as a function of temperature change for a 1535.44 nm grating. The grating spacing and changes of the index of refraction change the wavelength. Figure 6 (b), shows the result under variable strain from 0 µε to 1800 µε at constant temperature 25°C, have a shift in the Bragg grating wavelength as a function of applied strain for a 1535.44 nm grating. From these results it can be observed that the wavelength of Bragg grating increases with both temperature and strain.

The good linear relationship between temperature and Bragg wavelength has shown the potential of using for a device sensing applications, railway track, bridge, building and earthquake monitoring, the strain or temperature measurement can used for the required monitor.

Discussion and Conclusions

The use of UV laser source for fiber Bragg grating by phase mask writing has been demonstrated. One of the techniques commonly used to inscribe Bragg grating in the core of optical fibers uses a phase mask to spatially modulate and diffract the UV beam to form an interference pattern. The interference pattern induces a refractive index modulation in the core of the photosensitive fiber, which is a placed directly behind the phase mask. The phase mask technique is relatively easy of fabricate, and makes the core grating an ideal candidate for use in telecommunication and sensing applications such as temperature sensing and strain sensing. Result of transmission spectrum and reflectivity of light in fiber Bragg grating have been relationship with Bragg wavelength. When resulted, of the strain effect and apply temperature
A phase mask fiber grating and sensing applications

on an optical fiber Bragg grating. This corresponds to change in the grating spacing and the refractive index of fiber. Therefore, it shifted in the Bragg wavelength. In this resulted, can be using an application, in the telecommunication and fiber optic sensors as high temperature sensor, fire alarm sensor, vibration sensor, and pressure sensor. The fiber grating for communication may be implement in the system for signal filtering, gain flatness, optical memory etc., The other increase of the communication capacity and performance.

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