International Conference on Optics in Precision Engineering and Nanotechnology 2011

High fluence KrF excimer laser fabricated Bragg grating in a microfiber

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Abstract

We fabricated a type II fiber Bragg grating in a ~7.6 μm diameter microfiber, using a KrF excimer laser at a high fluence level of ~1.1 J/cm\textsuperscript{2} through a phase mask. The proposed microfiber Bragg grating (MFBG) is used to sense the refractive index (RI) of the surrounding medium.

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Selection and/or peer-review under responsibility of the Organising Committee of the ICOPEN 2011 conference

Keywords: Fiber Bragg grating; microfiber; KrF excimer laser; refractive index sensing

1. Introduction

Fiber Bragg grating (FBG) and long period grating (LPG) have been widely utilized in fiber optics sensing systems in recent years. LPG can determine ambient refractive index (RI) \cite{1}, since it couples light from the fiber core to the cladding, making the transmitted light sensitive to the RI of the surrounding medium. However, LPG possesses a broad bandwidth transmission dip that makes it unsuitable for multiplexing of the sensors. In addition, LPG is sensitive to the bending of the optical fiber, which brings with it a cross-sensitivity issue. An etched or polished FBG can also measure ambient RI \cite{2-5}, but the mechanical strength is greatly reduced due to the post-processing procedure. To overcome the above-mentioned disadvantages of the LPG and the etched/polished FBG, we fabricated a Bragg grating in a ~7.6 μm diameter microfiber using a high-power KrF excimer laser through a phase mask. The proposed microfiber Bragg grating (MFBG) can sense the RI of the surrounding medium.

2. Principle

A 7.6 μm diameter microfiber can support the propagation of multi modes at wavelengths around 1550 nm \cite{6}, which can be coupled back by the grating in the microfiber. Based on the coupled-mode theory at phase matching
condition [7], the $m^{th}$ order resonance wavelength for reflection of a mode of effective refractive index $n_i$ into a mode of index $n_j$ can be described by:

$$\lambda_{m,i,j} = \left( n_i + n_j \right) \Lambda_{FBG} / m$$

(1)

where $\Lambda_{FBG}$ is the grating period.

It is known that an ideal phase mask (consisting only of ±1 diffraction orders) produces an FBG with a period equal to half of the phase mask pitch $\Lambda_{PM}$, i.e., $\Lambda_{FBG} = \Lambda_{PM} / 2$, and the first order reflected wavelength is defined as the Bragg wavelength. However, in practice, the zeroth and higher diffraction orders of the phase mask cannot be completely suppressed, leading to that an FBG possesses two separate periods (i.e., $\Lambda_{FBG}$ and $\Lambda_{PM}$), which was proven in a type I FBG using differential interference contrast imaging technique [8]. The type I FBG is normally fabricated under a low-fluence (<1 J/cm²) multi-pulse exposure from a KrF excimer laser, creating a refractive index modulation in the core of the photosensitive fiber. In 1993, Malo et al. [9] reported that a high-fluence single-pulse excimer laser exposure (~1 J/cm²) can result in a type II grating along the core-cladding boundary with a period that is the same as the phase mask pitch, i.e., $\Lambda_{FBG} = \Lambda_{PM}$. The authors also suggested that a weak grating with a period of $\Lambda_{PM} / 2$ may exist but could not detect due to the low spatial resolution of the microscope. We irradiated high-fluence KrF excimer laser pulses onto a microfiber, and thus to produce a type II grating.

For the grating with a period of $\Lambda_{PM}$, the second order reflected wavelength caused by mode coupling of the counter propagating fundamental modes with effective refractive index $n_i$ can be derived from (1) as:

$$\lambda_{2,1,1} = n_i \Lambda_{PM}$$

(2)

The second order reflected wavelength caused by mode coupling of the counter propagating fundamental and higher $j^{th}$ order modes is given by:

$$\lambda_{2,1,j} = (n_i + n_j) \Lambda_{PM} / 2$$

(3)

Effective mode coupling depends on the overlaps among the forward-propagating mode field distribution, the backward-propagating mode field distribution, and the cross-sectional position of the grating. Although multi modes can be supported to propagate along the 7.6-μm-diameter microfiber, only those having effective mode couplings can form obvious reflection peaks [10].

3. Experiment

The microfiber was fabricated using the same technique as described in [10], but no hydrogen loading is employed for the microfiber in this work. In the fabrication of the MFBG, we used a 248 nm KrF excimer laser with a pulse repetition rate of 10 Hz and a fluence of around 1.1 J/cm², through a 1 cm long uniform phase mask with a pitch of 1082.3 nm. The type II MFBG was formed after around 500 pulses of irradiation. Fig. 1 shows the optical microscope image of the MFBG. After coupling a red-colour HeNe laser beam into the microfiber, several bright fringes were observed along the microfiber, indicating the existence of the grating. We noted that the intensity of the scattered light from the grating is not that evenly distributed, suggesting that the damage grating formed is not perfectly uniform. By observing the section without any grating in the microfiber, no such fringes were observed, confirming that the observed fringes are not due to scattering of light from dust particles on the surface of the microfiber.

The measured reflection spectrum of the MFBG is shown in Fig. 2. During the grating fabrication process, we found that there was no obvious monotonic increase in the reflectivity of the reflected spectrum usually observed during the fabrication of a type I grating. Two reflected peaks were observed in Fig. 2. The peak at 1554.64 nm is due to mode coupling of the counter propagating fundamental HE11 modes, while the other peak at 1548.29 nm is a result of the coupling of the counter propagating fundamental HE11 and the higher order TE01/HE21/TM01 modes. These two peaks agree well with our theoretical results whereby we obtained $\lambda_{2,1,1} = 1554.62$ nm peak with (2), and $\lambda_{2,1,3} = 1548.18$ nm peak with (3), using HE21 mode as an example in calculation. No other reflected peak is observed in the wavelength range of 1520-1620 nm (limited by the light source), suggesting that no grating is written into the core of the microfiber, since from theory, a peak at 1536.6 nm using (3) should have been expected due to the coupling between the HE11 and HE12 modes.

We used sugar solutions with RI values ranging from 1.3332 to 1.4481 to determine the RI sensitivity of the
MFBG. Fig. 3 shows the relationship between the peak wavelength $\lambda_{2,1,1}$ and the ambient RI. It can be seen that, the resonance shifts to a longer wavelength as the ambient RI increases. Also, a relatively high RI sensitivity is achieved when the ambient RI is close to the RI value of the fiber cladding, since the mode field propagated within the fiber is less confined in the microfiber and hence more easily affected by the RI of the surrounding medium. The RI sensitivity is determined from the gradient of the exponentially fitted curve shown in Fig. 3. The resonance wavelength caused by the fundamental mode coupling is determined to have a maximum sensitivity of about 79.9 nm/RIU (refractive index unit) at the RI value of 1.4481.

4. Conclusion

We have successfully fabricated a type II Bragg grating in a microfiber using a high power KrF excimer laser. The MFBG inscribed in a 7.6-μm-diameter microfiber has a maximum RI sensitivity of 79.9 nm/RIU when the RI of the surrounding medium is 1.4481.

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Fig. 2. Reflection spectrum of an MFBG immersed in air.

Fig. 3. Fundamental mode wavelength versus the RI of the surrounding medium.