Japanese Journal of Applied Physics
Vol. 45, No. 12, 2006, pp. 9100–9102

Apodization Method Owing to the Finite Length of UV Laser Coherence in Fabricating Fiber Bragg Gratings

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(Received May 24, 2006; accepted August 21, 2006; published online December 7, 2006)

A very effective apodization, in which side lobes are suppressed to below a particular noise level, is found to operate automatically in a two-beam interference device for fabricating fiber Bragg gratings when a pair of mirrors deflecting two beams are off parallel to each other. This is considered to be a consequence of the short temporal coherence length of the KrF excimer laser used. [DOI: 10.1143/JJAP.45.9100]

KEYWORDS: fiber Bragg grating, optical fiber, two-beam interference, excimer laser

1. Introduction

Because fiber Bragg gratings (FBGs) have very sharp narrowband reflection spectra, they are well suited to applications involving narrowband optical signals, such as optical filters in optical telecommunication systems, fiber laser cavities, and various types of fiber sensor.

An FBG has a periodic refractive index structure inside an optical fiber in its longitudinal direction. It is commonly fabricated by exposing the optical fiber to UV laser light to create a photoinduced refractive index variation. Since the grating period is very short, on the order of 0.5 µm, irradiation is normally performed by exposing the fiber to the interference patterns of UV laser light so that the patterns are transprinted into the fiber. There are two standard methods for generating these interference patterns: the phase mask and the two-beam interference methods.[1] In the phase mask method, the interference pitch is defined by the grating period of the mask; hence, the resulting FBG wavelength is fixed. On the other hand, in the two-beam interference method, the crossing angle of the beams is controlled by adjusting mirror reflection angle. This has the substantial advantage of permitting FBG production with different FBG wavelengths. To let the two beams interfere each other in the two-beam interference method, the path lengths of the two beams must be the same within the coherence length of the laser. For this reason, lasers with a high coherence quality, such as an argon ion laser, are generally preferred for FBG fabrication.

In addition to selecting a suitable laser source in terms of coherence, spectral shaping is important in fabricating high-quality FBGs for generating a clean spectral peak in an FBG reflection signal. Apodization is a well-known technique for suppressing side lobes in a reflection spectrum by forming a spatial profile of refractive index modulation that varies smoothly in the longitudinal direction, rather than abruptly as in the case of a rectangular profile. Apodization is commonly performed by shaping the profile of the incident UV laser beam intensity on the fiber so that the profile of the deposited energy varies smoothly along the FBGs during fabrication. Some examples explored are a double-exposure technique,[2] the dithering control of a phase mask[3] and the use of a self-apodized phase mask.[4] Our method yielded a near-perfect apodization without the geometric and optical constraints of the previous techniques.

We performed a two-beam interference experiment using a high-power excimer laser with a rather short coherence length, as opposed to the general preference for high-coherence laser sources. We found that we could obtain FBGs with a high reflectivity and without side lobes in their reflection spectrum or below a particular noise level. That is, a near-perfect apodization was easily attained. The origin of this new type of apodization appears to be related to the coherence length of the excimer laser employed in the experiments.

2. Experimental Methods and Results

The two-beam interference method for FBG fabrication was originally developed by Meltz *et al.*[5] who used a half mirror and two mirrors. Since one of the two beams underwent mirror reflection once whereas the other underwent two mirror reflections in their experiment, the beams did not cross each other with the same handedness; thus, the interference was incomplete. Askins *et al.*[6] corrected this by adding another mirror reflection to the first beam to ensure an equal number of mirror reflections for both beams. However, adding another mirror made the optical setup rather complex to control. Instead of a half mirror, Kashyap[7] used a phase mask as a beam splitter. This ensured a symmetrical arrangement of optical components, such as mirrors and their controls, which vastly eased the fine adjustment and control of parameters, such as mirror angle.

The geometry of our two-beam interference experiment is shown in Fig. 1. The excimer laser light incident on the phase mask is diffracted into ±1st-order beams. The two beams are reflected by the mirrors and cross at the position of the optical fiber. The grating period of the phase mask is 1072.34 nm in the experiments reported here. This gives a diffraction angle of 13.37° for KrF excimer laser light ($\lambda =$ 248 nm). The distance $2s$ between the two mirrors at their axes of rotation is 70.3 mm. We made FBGs in three different wavelength bands, 1.55, 1.3, and 1.0 µm, by adjusting mirror angle. The fiber was positioned at the point where the two beams crossed when the mirrors were rotated,

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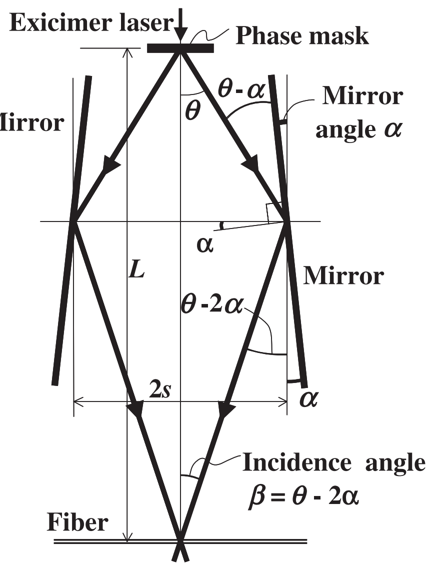

Fig. 1. Two-beam interference geometry.

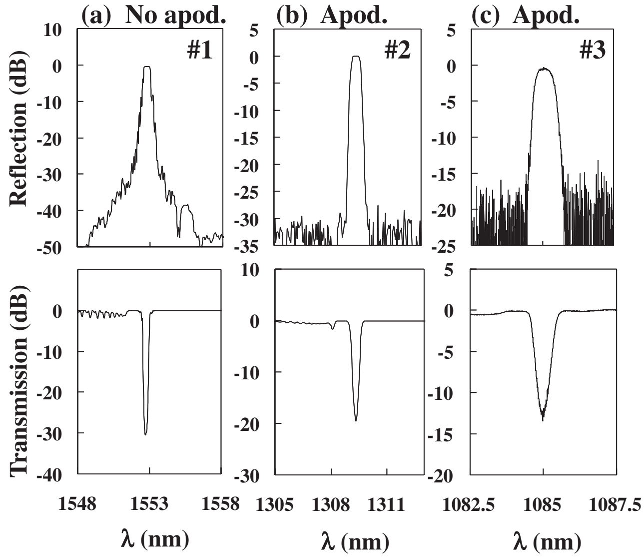

Fig. 2. Spectra of three different FBGs.

Table I. Parameters used in experiments.

FBG	#1	#2	#3
Mirror angle α (deg)	0.00	-1.27	-2.97
Fiber to mask distance L (mm)	295.8	271.2	248.2
Incidence angle $\beta = \theta - 2\alpha$ (deg)	13.36	15.91	19.31
Optical path difference Δ (mm)	0.00	0.332	0.781
λ_{FBG} (nm)	1552.7	1309.4	1085.0

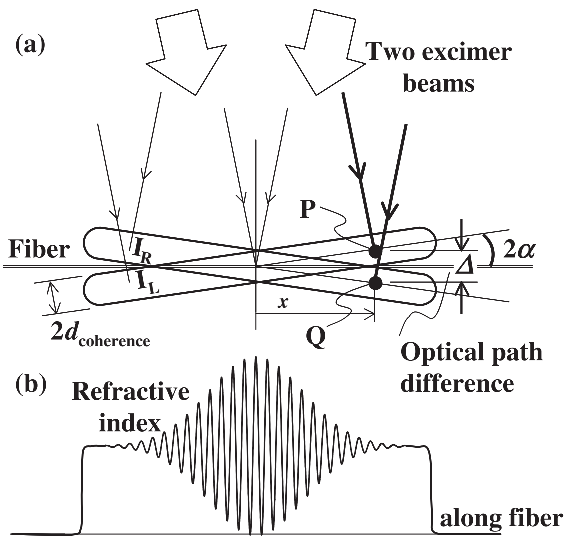

Fig. 3. Schematic of apodization physics model.

and its distance from the phase mask is listed in Table I, together with the other parameters used in the experiments.

We used a KrF excimer laser (Lambda Physik, COMPex-102MJ with an unstable resonator). The beam was shaped using an optical stop to a size of $7.5 \times 7.5\,mm^2$, and the energy delivered to the phase mask is 30 mJ per pulse at a repetition rate of 20 Hz. The energy density at the fiber was increased by a factor of 12 using a cylindrical lens. The length of the FBGs is the same as the beam width of 7.5 mm. The zeroth order and higher-order beams generated using the phase mask were blocked using optical stops. SMF-28 optical fibers were used for FBGs #1 and #2, and an HI-1060 fiber was used for FBG #3. The fibers were loaded with hydrogen at a pressure of 100 atm for 10 days prior to the experiments to increase their UV sensitivity. The duration of excimer laser irradiation was set to be 3 min. The transmission and reflection spectra of the three FBGs are shown in Fig. 2. Many side lobes were observed in for FBG #1 [Fig. 2(a)], which was fabricated with the two mirrors in parallel. As the mirrors were rotated from $\alpha = 0$ to the angles corresponding to the FBG reflection wavelengths of 1.3 and 1 μm, the side lobes disappeared completely in the reflection spectra, falling below the noise level.

This result indicates that a very effective apodization effect is created only by rotating the mirrors. Our interpretation of the apodization effect is shown schematically in Fig. 3. When the two mirrors are rotated symmetrically at the same angle α in Fig. 1, the image of the phase mask at the fiber position after reflection by a mirror is tilted at the angle 2α. Since the two images are tilted in opposite directions, they intersect as shown in Fig. 3, where the images are depicted as I_R and I_L with depths equal to the temporal coherence length $d_{coherence}$ in the direction of beam propagation. The optical path difference Δ is generated away from the FBG center. Interference occurs in the region where the two images I_R and I_L overlap, but not outside the region, where the difference Δ becomes larger than the coherence length $d_{coherence}$. Since the path difference Δ is zero at the center ($x = 0$), the interference is maximal and falls off toward the edge of the FBG, resulting in a refractive index pattern that creates the apodization effect. It should be noted that, in this case, the index averaged over the interference period is uniform along the fiber, because the fiber is exposed to the beam even with a partial or no interference; that is, the apodized ac component of refractive index modulation is superimposed on its dc component. This yields a perfect apodization, which is symmetric in both positive and negative directions of the index modulation pattern.

The coherence length of the excimer laser is estimated from our data using the apodization condition, $d_{\text{coherence}} < \Delta$ for FBGs #2 and #3. The Δ values listed in Table I imply that $d_{\text{coherence}}$ is less than 0.33 mm, which appears to be in good agreement with the length derived from the spectral width of the KrF excimer laser emission reported in ref. 8, that is, $\lambda^2/\Delta\lambda = (248\,\text{nm})^2/(0.5\,\text{nm}) = 0.12\,\text{mm}$. Our first estimate for the coherence length may be longer than 0.12 mm because our excimer laser is equipped with an unstable resonator.

The transmission minimum becomes shallower as the mirror angle increases from #1 to #2 and from #2 to #3, because the effective FBG length becomes shorter with an apodized refractive index profile.

Here, we have demonstrated apodization for 1.3 and 1 µm FBGs using a phase mask that produces a 1.55 µm FBG in the phase mask method. We also have confirmed that apodization is realized in the opposite case, i.e., apodization in a 1.55 µm FBG is realized using a phase mask that produces a 1.3 µm FBG in the phase mask method.

3. Discussion

It is commonly assumed that UV lasers with better coherence should be used to facilitate the formation of an interference pattern for FBG fabrication. Thus, high-quality UV lasers such as argon ion lasers and injection-locked excimer lasers, have been used. However, our analysis shows that the present geometric apodization technique may not work as well for these lasers with a long coherence length. That is, if the coherence length is longer than the path difference at the edge of an FBG, the interference pattern will be uniform. Thus, lasers with a relatively short coherence length, such as excimer lasers, are better suited for FBG fabrication by this method.

Frohlich and Kashyap[9] suggested the possibility of FBG apodization based on the finite coherence length of a UV laser. That is, if the laser beam is split into two and brought together with a predetermined path length difference, the interference fringe contrast will be affected by the degree of incoherence. To achieve this, they proposed, as an example, a scanning technique applied to a mirror interferometer like ours, but no experimental proof was provided. Here, we have utilized the finite coherence length of a UV laser for FBG apodization, but our approach completely avoids the complex mechanical control implied in ref. 9. Our method is much simpler, in that it involves tilting the two mirrors off parallel, as demonstrated above. The method is novel and provides a very powerful means of near-perfect apodization of FBGs.

4. Conclusions

A two-beam interference device was constructed, and very efficient narrowband FBGs were fabricated with a high reproducibility. When two mirrors are symmetrically rotated from their parallel position, the two images of a phase mask at the position of an optical fiber cross each other obliquely. This generates an optical path difference along the length of an FBG such that, when the coherence length of the laser used is shorter than this path difference, apodization is automatically induced. This apodization technique is considered very effective in suppressing side lobes to below a particular noise level.

Acknowledgement

We acknowledge Dr. D. H. McNeill for carefully proof reading our manuscript.

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