Novel and Improved Methods of Writing Bragg Gratings with Phase Masks

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Abstract-The authors demonstrate the importance of spatial coherence of the writing beam for inscribing Bragg gratings with a phase mask. Bragg gratings were written using a normal excimer laser with the fiber placed at various distances away from the phase mask. This was repeated with an excimer laser that was modified to improve the beam spatial coherence showing dramatic improvement in the ability to inscribe gratings. Tunability of the inscribed Bragg grating wavelength, utilizing a single phase mask in conjunction with the improved spatial coherence of the excitation source, is demonstrated.

I. INTRODUCTION

OVER the past few years, there has been a great deal of interest in fiber Bragg gratings due to their importance in the field of telecommunications and fiber sensors [1] [2]. One of the techniques commonly used to inscribe Bragg gratings in the core of optical fibers utilizes 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 mask [3], [4]. The phase mask technique is gaining recognition over the interferometric [5] and point-by-point [6] methods of writing Bragg gratings due to its simplicity and reduced mechanical sensitivity. The most common UV source used to fabricate Bragg gratings with a phase mask are KrF excimer lasers. 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 [7], [8]. The further the fiber is placed form 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. However, placing the fiber in contact with the fine grating corrugations is not desirable due to possible damage to the phase mask. In this letter, we report and demonstrate the importance of spatial coherence in the UV source used in writing Bragg gratings using the phase mask technique. We demonstrate that by improving the spatial coherence of the *W* writing beam, not only do we improve the strength and quality of the gratings inscribed by the phase mask technique, we also relax the requirement of the fiber to be in contact with the phase mask. We also demonstrate the ability to fine tune the Bragg grating center wavelength.

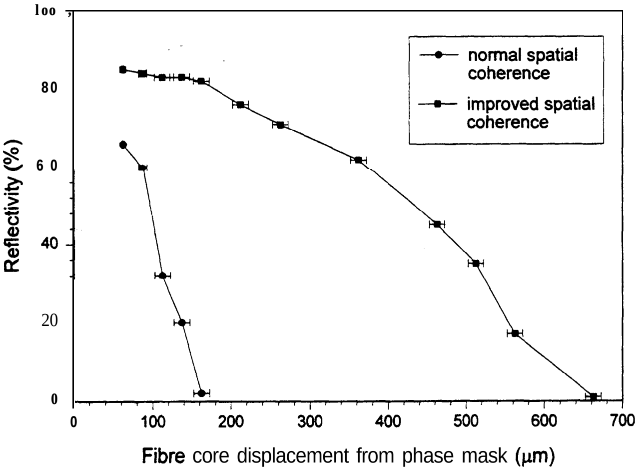

Fig. 1. A comparison of Bragg grating reflectivities as a function of the fiber core distance from the phase mask for both normal and improved spatial coherent beams.

II. EXPERIMENT

A KrF excimer laser (Lumonics 600) was used as the UV source for inscribing Bragg gratings 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 was operating at 55 mJ with a repetition rate of 10 Hz and a 12 ns pulse duration. The beam was directed into the phase mask and focused with a cylindrical lens onto the fiber. The beam dimensions at the fiber were 1 cm x 0.4 cm with the focused spot being approximately 1.5 cm behind the fiber. The dimensions of the phase mask (developed by QPS Technology Inc.) used in this experiment is 10 mm x 5 mm and the period of the grating corrugation is 1062 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 were inscribed in several fibers (AT&T Accutether single mode fiber at 1550 nm having a mode field diameter of 6.4 μm), each time varying the separation between the fiber and the phase mask (see Fig. 2). The *fluence* (100 $\mathrm{mJ/cm^2}$) and duration of *W* exposure (60 s) were kept constant throughout the experiment.

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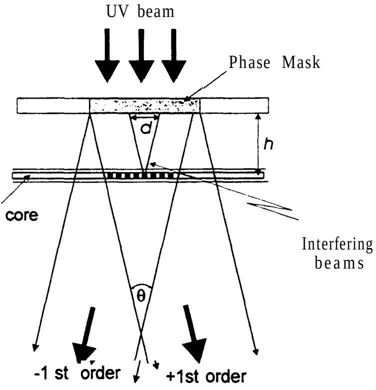

Fig. 2. A schematic of the phase mask geometry for inscribing Bragg gratings in optical fibers. The plus and minus first-order diffracted beams interfere at the fiber core, which is placed at a distance h from the mask.

This experiment was then repeated with the excimer laser modified to incorporate an intracavity aperture and an air-spaced etalon to improve spatial coherence (preliminary work demonstrated a slight improvement in spatial coherence when the etalon was incorporated within the laser cavity). Taking advantage of the extended spatial coherence of the modified excimer laser we were able to demonstrate tunability of the inscribed Bragg grating center wavelength using a phase mask. This was achieved simply by placing the fiber at an angle relative to the phase mask. In other words, one end of the exposed section of the fiber was positioned right against the mask and the other end was set at different distances (ranging from O-500 μm) from the mask (see inset in Fig. 3) As the angle relative to the phase mask was varied, the Bragg grating center wavelength varied accordingly (a tuning range of approximately 2 nm is demonstrated).

III. RESULT AND DISCUSSION

Fig. 1 shows the peak reflectivities of Bragg gratings written with the fiber core at various distances from the phase mask. Clearly, the modulation of index of refraction induced in the fiber was larger when the modified excimer laser was utilized. In addition, the distance at which the Bragg grating reflectivities were still higher than 50% increased by a factor greater than four. Since the *fluence* and the exposure were kept constant throughout, we believe that this dramatic improvement is attributed to the improved spatial coherence.

To understand this let us consider a simple schematic of the phase mask geometry (Fig. 2). Ideally, the fiber should be placed right against the phase mask, this way the spatial coherence requirement will be minimum. Consider the fiber core to be at a distance h from the phase mask. The transmitted plus and minus first orders that interfere to form the fringe pattern on the fiber emanate from different parts of the mask (referred to as distance d in Fig. 2). Since the distance of the fiber from the phase mask is identical for the two interfering beams, the requirement for temporal coherence is not so critical for the formation of a high contrast fringe pattern. On the other hand, as the distance h increases, the separation, d, between the two interfering beams emerging from the mask, increases. In this case, the requirement for good spatial coherence is critical for the formation of a high contrast fringe pattern. As the distance h extends beyond the spatial coherence of the incident UV beam, the interference fringe contrast will deteriorate, eventually resulting in no interference at all. The importance of spatial coherence was also demonstrated by Dyer et *al.* [7] where they used a KrF laser irradiated phase mask to form gratings in polyimide films.

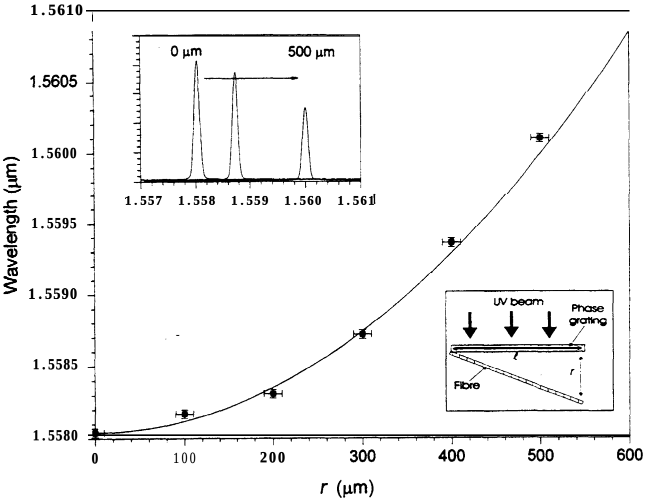

Fig. 3. Bragg grating center wavelength tuning as a function of distance r (lower inset). The experimental results which are represented by the square points are in good agreement with the calculated values shown as the solid curve. The upper inset shows the reflective spectra of several Bragg gratings as a function of r (the arrow shows r increasing).

The extent of the spatial coherence may be estimated from our results in Fig. 1. Simple trigonometry (see Fig. 2) gives the following expression $d = 2h \tan(\theta/2)$, where θ is the angle between the plus and minus first orders (for this particular phase mask this is 27°). The extent of the spatial coherence (at the point where Bragg gratings with reflectivities stronger than 50% are inscribed) is estimated to be d = 45 μm for the normal excimer laser and d = 210 μm for the modified excimer laser.

One of the advantages of not having to position the fiber right against the phase mask is the freedom to be able to angle the fiber relative to the mask. As explained in the experimental section, placing one end of the exposed fiber section against the mask and the other end at some distance from the mask, we were able to change the induced Bragg grating center wavelength [9]. Again, from simple geometry (see inset in Fig. 3), one can derive a general expression for the tunability of the Bragg grating center wavelength, which is given by:

$$\lambda_b = 2n\Lambda\sqrt{1+\frac{r^2}{l^2}}$$

where A is the period of the *fiber* grating, r is the distance from one end of the exposed fiber section to the phase mask, and l is the length of the phase grating. Therefore, for a fixed phase mask period, changing r will result in a different Bragg center wavelength. For the phase mask utilized in these experiments (Λ = 0.531 μm, l = 10 000 μm), at r = 0 (the fiber is placed parallel to the phase mask) l_b = 1.5580 μm. Fig. 3

shows the theoretical curve for the tunability of the inscribed Bragg grating as a function of distance r. In this figure the experimental values for the peak reflectivities of the Bragg gratings are also shown for different r values. We should point out that these gratings are blazed at small angles.

IV. CONCLUSION

We demonstrated the importance of spatial coherence for inscribing Bragg gratings in optical fibers using the phase mask technique. We showed that an improvement in the spatial coherence of the UV source results in relaxing the requirement of the fiber being in contact with the phase mask for inscribing high quality Bragg gratings. We also demonstrated fine tuning of the induced Bragg grating center wavelength using the phase mask technique.

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