

## **Fiber Bragg Grating Inscription in Highly Asymmetric HiBi PCF with a Low Intensity UV CW laser**

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*The transmission properties of Photonic Crystal Fibers (PCFs) can be tailored with unprecedented flexibility. This flexibility can be exploited to overcome current shortcomings of Fiber Bragg gratings (FBGs) for sensing applications. However, FBG inscription in PCFs is very challenging because the internal micro-structure of air-holes in the PCF cladding does not favour conventional FBG inscription techniques. In this report we show that it is feasible to use a low energy UV-Argon laser and a phase mask to inscribe FBGs in a highly birefringent Ge-doped core PCF, optimized for grating inscription.*

### **Introduction**

Since their discovery, Photonic Crystal Fibers (PCF) have attracted significant research interest owing to their unprecedented design flexibility and to their unique optical properties [1]. However, only few works dealt with combining Fiber Bragg gratings (FBGs) and PCFs in sensing applications. Highly birefringent (HiBi) PCFs are of interest for this purpose because their birefringence can be very high (one order of magnitude larger than in standard Hi-Bi fibers) and the temperature dependence can be limited (about  $1.11$  and  $-1.14 \cdot 10^{-4} \text{ K}^{-1}$ , corresponding to  $\pm 1.5\%$  of variation of the birefringence between  $-25^\circ\text{C}$  and  $800^\circ\text{C}$ ) [2] compared to usual bow-tie Hi-Bi fibers (about  $-7.05 \text{ K}^{-1}$ ). Therefore, FBG-based sensors in PCFs have great potential to serve as selective sensors that do not require temperature compensation mechanisms [2]-[3]. So far, femtosecond writing [4] in pure silica PCF and UV writing in PCFs with a Ge-doped core [5], [6] have been reported. However, the internal microstructure of PCFs tends to scatter the light of the laser writing beams, which compromises the interference pattern in the core that eventually forms the FBG [7]. To minimize this scattering, all existing FBG fabrications in PCF require a particular geometry of the fiber with only few holes [4]-[6] or index matching liquid filling the air holes [8] during the inscription process. Very high power lasers are often needed to fabricate FBGs with only a modest strength. In this study, we use a Hi-Bi PCF structure with a Ge-doped core that was designed for FBG writing with standard inscription techniques. We will show for the first time that high reflectivity FBGs can be recorded with the modest output power (few tens of mW) of a CW Argon laser at 244 nm.

### HiBi-PCF structure

Figure 1 shows the cross section of the Hi-Bi PCF structure considered in this study. The preform of the fiber was fabricated via a stack-and-draw technique. The diameter of the core region is about 2  $\mu\text{m}$  and is highly Ge-doped (7 mol %). The cladding microstructure is composed of the arrangement of only three layers of air holes with different sizes. One layer of small air holes with a diameter of 0.9  $\mu\text{m}$  is sandwiched between two rows of larger air holes with a diameter of about 3.6  $\mu\text{m}$ . This structure was shown to be single mode around 1550 nm, to have relatively low attenuation of the guided mode and to have high birefringence (about  $8 \times 10^{-4}$ ). During the inscription experiments conducted here, no particular care was taken on the angular orientation of the fiber versus the UV laser writing beam.

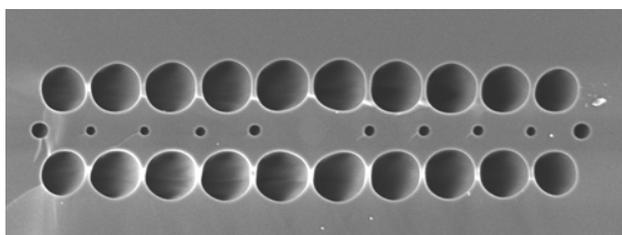


Fig. 1. Scanning Electron Microscope image of the Hi-Bi PCF cross-section. The Ge-doped core shows up in a slightly lighter color than the silica glass matrix.

### PCF Hydrogenation and FBG inscription

For the FBG inscription we relied on the phase mask technique with an Argon laser 'Beamlock' followed by a frequency doubler 'iTrain 244' of Spectra Physics, emitting at 244 nm. The principle of this technique is shown in figure 2. It consists of focusing the UV beam via a cylindrical lens on the core of the photosensitive fiber positioned behind a phase mask. The diameter of the UV beam is only 0.7 mm which limits the length of the inscribed FBG. To overcome this limitation, the UV laser beam is swept along the phase mask by a mirror positioned on a motorized translation stage. The velocity of the UV beam sweep and the laser output power can be modified to tailor the reflectivity profile of the inscribed gratings. The pitch of the phase mask is 1095.08 nm. An ASE source, a circulator and an optical spectrum analyzer are used during the writing process to monitor the reflectivity of the FBG.

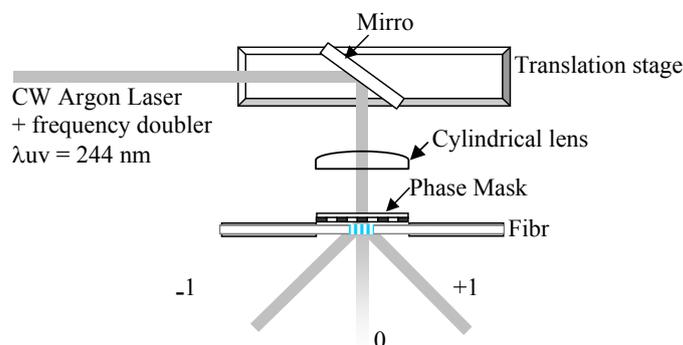


Fig. 2. Schematic of the FBG inscription setup based on the phase mask technique

Hydrogenation of the PCF was required prior to the inscription to increase the photosensitivity of the Ge-doped core. For this purpose the fiber was placed in a hydrogen chamber at 70°C under 200 bar during 3 days.

In earlier attempts to inscribe an FBG in this PCF, the power of the output UV beam was increased from 20mW, which is typically used for hydrogenated standard step-index fibers in this setup, up to 150mW and the exposure time was increased from a few seconds to 1 hour. However FBG inscription showed to be impossible under these conditions. Indeed, the hydrogen diffuses out of the fiber via the air holes around the core within only a few minutes after removing the fiber from the hydrogen chamber. To overcome this problem, sealing of the fiber ends before the hydrogenation was needed [9]. The PCF was spliced on both ends to a conventional single mode Corning SMF28 fiber. This collapses the fiber end holes which prevents the hydrogen from outgassing and maintains the photosensitivity of the fiber.

### Experimental Results

In Figure 3 we present the reflection and transmission spectrum of the FBG obtained in the Hi-Bi PCF fiber with 22 mW of UV output power and a sweep velocity of 50  $\mu\text{m/s}$ . The FBG was 6 mm long, corresponding to an exposure time of 120 s.

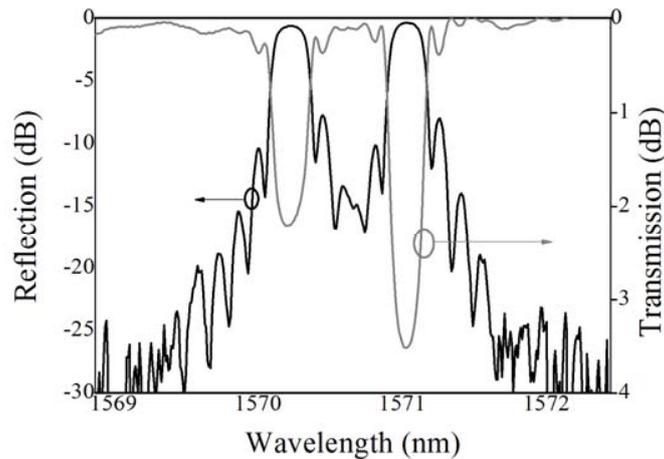


Fig. 3. FBG reflection and transmission spectrum in Ge-doped HiBi-PCF fiber.

Since the fiber is birefringent, one FBG yields 2 Bragg peaks. These peaks correspond to the eigenmodes of the fiber i.e. polarization modes of the slow and the fast axes of the fiber. The Bragg peak wavelengths corresponding to these two modes are given by:

$$\lambda_{\max,s} = 2(n_{\text{eff},s} + \delta n)\Lambda \quad \lambda_{\max,f} = 2(n_{\text{eff},f} + \delta n)\Lambda \quad (1)$$

$$\text{with } n_{\text{eff},s} = n_{\text{eff}} + \frac{B}{2} \quad n_{\text{eff},f} = n_{\text{eff}} - \frac{B}{2} \quad (2)$$

where  $\Lambda$  is the grating period,  $n_{\text{eff}}$  is the effective refractive index of the fiber,  $\delta n$  is the index modulation and  $B$  is the fiber birefringence. The subscript  $s$  and  $f$  denote fast and slow, respectively.

From the spectra shown in figure 3, we can see that the maximum reflectivity is reached (almost 100% for both peaks) and that the top of the peaks is flattened. This is the

signature of the saturation regime i.e. the refractive index modulation maximum  $\delta n_{\max}$  is reached [10]. The Bragg peak wavelengths were determined with the peak detection function of the ANDO Optical Spectrum Analyzer and are located at 1570.22 nm and 1571.03 nm. Using equations (1) and (2), the modal phase birefringence of the HiBi PCF fiber is about  $7.6 \times 10^{-4}$ . This value is in good agreement with the theoretical value ( $1 \times 10^{-3}$ ) obtained from the full vectorial FEM mode solver simulation [11].

## Conclusion

We have shown the possibility to use a low power UV-Argon laser and a conventional phase mask technique for FBG inscription in a Hi-Bi Ge-doped core PCF. Owing to the specific geometry of the microstructure and to the unusual hydrogenation procedure a very strong FBG was successfully inscribed in the fiber with modest UV laser power. The peak separation of the Bragg peak wavelengths allowed estimating the phase birefringence of the fiber which is one order of magnitude higher than in standard Hi-Bi fibers. This high birefringence offers potential for FBG-based sensing applications.

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