Point-by-point inscription of apodized fiber Bragg gratings

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We demonstrate apodized fiber Bragg gratings (FBGs) inscribed with a point-by-point (PbP) technique. We tailor the grating phase and coupling amplitude through precise control over the longitudinal and transverse positions of each laser-inscribed modification. This method of apodization is facilitated by the highly localized, high-contrast modifications generated by focused IR femtosecond laser inscription. Our technique provides a simple method for the design and implementation of PbP FBGs with complex apodization profiles.

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Fiber Bragg gratings (FBGs) inscribed using the point-by-point (PbP) method are becoming increasingly popular for a variety of fiber laser and sensing applications due to the flexibility of the technique [1–4]. Although PbP FBG inscription was first demonstrated in 1993 using an excimer laser [5], the field received little interest until the advent of femtosecond (fs) laser materials processing. The use of fs pulses enables the inscription of highly localized microvoid modifications via nonlinear photoionization processes [6]. Coherent Bragg scattering from each of the microvoid modifications in a PbP FBG produces high-quality grating reflection spectra with low loss [7,8]. The fs laser–material interaction enables grating inscription into almost any fiber material without requiring photosensitivity. A further advantage of this technique is the high-temperature stability of the gratings due to the structural modification of the glass [9].

The sideband reflection peaks typical of uniform FBG spectra can be problematic for many applications, causing cross talk in WDM systems, instabilities in Q-switched fiber lasers, and linewidth broadening in high-power fiber lasers [2,10]. To eliminate these unwanted sidebands, it is necessary to fabricate gratings with an apodized profile, where the grating strength varies as a function of position. Various techniques have been developed for fabricating apodized FBGs using holographic inscription, such as phase-mask dithering [11]; however, these methods are specific to holographic inscription and do not translate directly to PbP inscription. To apodize PbP gratings, one might consider modulating the laser pulse energy during inscription; however, this is likely to be very challenging due to the highly nonlinear laser–material interaction processes.

In this Letter, we report apodized FBGs inscribed using a PbP technique. Our apodization approach is to tailor the local coupling amplitude of the gratings through precise control over the transverse position of each laser-inscribed refractive index modification (RIM), thereby varying the overlap of the RIM with the core mode. We achieve further flexibility in the apodization profile by introducing discrete phase shifts in the grating. This technique may, in principle, be used to achieve apodization profiles of arbitrary complexity. Because of the sensitivity of apodized gratings to the precise coupling-strength profile, it is critical to incorporate the intensity profile of the core mode in the design of the variation in the transverse position of the RIMs. We demonstrate the versatility of our technique by fabricating gratings with Gaussian and sinc apodization profiles. We chose to demonstrate gratings with these apodization profiles as Gaussian-apodized gratings are standard among traditional UV-inscribed FBGs, while sinc-apodized gratings yield spectra characterized by steep band edges and a relatively flat-top peak [12].

The FBG fabrication technique incorporating a fiber-guiding system with submicrometer transverse control and fs laser inscription is described in detail elsewhere [8]. The pulse energy of the fs laser was constant throughout each grating inscription. We fabricated second- and third-order gratings in Corning SMF-28e optical fiber with target wavelengths λ_B in the range of 1520 to 1570 nm (corresponding to periods of approximately 1.1 and 1.6 μm, respectively). The gratings were analyzed in reflection and transmission using a high-resolution (3 pm) swept wavelength system (JDSU 15100).

The coupling amplitude κ of an FBG is proportional to the overlap of the RIM with the intensity profile of the core mode [$\kappa \propto \int \Delta\varepsilon(x,y)|\mathbf{E}(x,y)|^2 \mathrm{d}x\mathrm{d}y$, where $\Delta\varepsilon(x,y)$ is the change in the dielectric constant and $\mathbf{E}(x,y)$ is the electric field]. Therefore, we can control the local coupling amplitude of the grating by varying the transverse offset of the RIMs from the center of the fiber core [8]. This was achieved by applying a voltage to one axis of the piezo-controlled translation stage. We translated the fiber within the focal plane of the objective, as the RIMs have the smallest dimensions in this plane due to the ellipsoidal focal volume of a focused Gaussian beam [13].

The intensity profile of the fiber core mode is approximately Gaussian, and the size of the RIM in the axis of translation ($\sim$1 μm) is small with respect to the $1/e^2$ width of the guided mode (10.4 μm). It follows that the coupling strength of the grating varies approximately as a Gaussian function of the offset $x(z)$ of the RIM from the center of the core. Therefore, to inscribe a

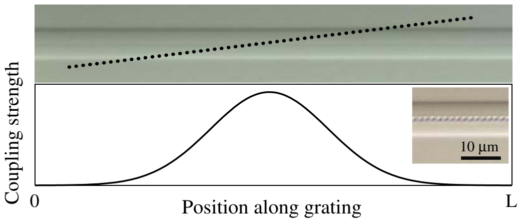

Fig. 1. (Color online) Illustration of the Gaussian apodization technique: a linear translation of focus across the core produces a Gaussian apodization profile. Inset, micrograph of a PbP FBG in SMF-28e fiber.

Gaussian-apodized FBG, we simply applied a linear translation of the laser focus across the core during the grating fabrication (see Fig. 1).

The measured reflection spectrum of a Gaussian-apodized grating and a comparable uniform FBG are presented in Fig. 2. The Gaussian-apodized FBG had a peak reflectivity of 85%, and the uniform FBG had a peak reflectivity of 86%. The Gaussian-apodized FBG was inscribed with 300 nJ pulses and was 15 mm long with a period of 1.605 μm (third-order resonance at 1549.5 nm). It began and ended with a −7.35 μm and a 7.6 μm offset from the center of the core. The $1/e^2$ length of this grating was 7.4 mm (the length of grating over which the coupling strength is greater than $1/e^2$ of the peak). The uniform FBG, inscribed with 300 nJ pulses, was 6 mm long and had a period of 1.588 μm (third-order resonance at 1533 nm). The Gaussian-apodized FBG exhibited an 8 dB improvement in sideband suppression compared to the uniform FBG. This is a significant improvement in spectral quality for such a simple fabrication step and could readily improve the performance of fiber laser systems based on PbP FBGs [2,3].

While Gaussian-apodized gratings provide greatly improved sideband suppression over uniform gratings, many applications demand a more tailored spectral response, which can only be realized using sophisticated apodization profiles. Sinc-apodized gratings are an example of such a grating, exhibiting a characteristic top-hat reflection spectrum, which is highly desirable for applications such as band filtering and optical switching.

In order to fabricate FBGs with a sinc apodization profile, it is necessary to introduce $\pi/2$ phase shifts in the grating to change the sign of the coupling amplitude,

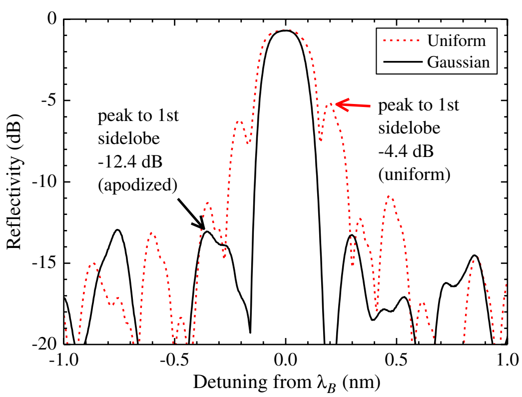

Fig. 2. (Color online) Reflection spectrum of a Gaussian-apodized FBG and a comparable uniform FBG written with similar inscription parameters.

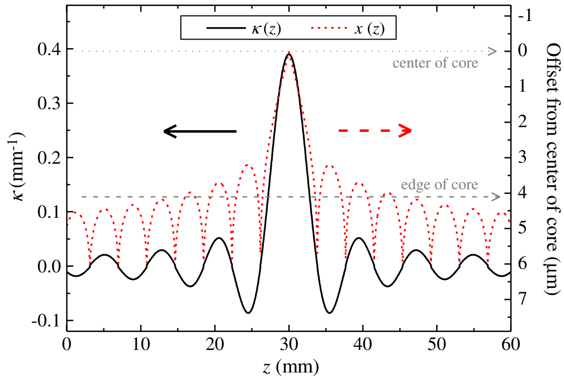

Fig. 3. (Color online) Coupling amplitude (κ) profile (black curve) and translation function (red curve) for a sinc-apodized PbP grating.

as shown in the target κ profile in Fig. 3. Thus the desired apodization profile is achieved by combining a translation function $x(z)$ that defines the absolute value of the coupling amplitude, with $\pi/2$ phase shifts at each of the zero crossings. We directly control the phase of the grating via the timing of the fs pulse train. To introduce a phase shift in the grating, we switch between two clock signals for triggering the pulses from the fs laser. The two signals both operate at 1 kHz, but they are offset in time by an amount corresponding to the $\pi/2$ phase shift.

The desired coupling amplitude profile was $|\kappa_S(z)| = \kappa_0|\mathrm{sinc}(2\pi z/(L/N_0))|$ (where L is the length of the grating and N_0 is the number of sinc oscillations in the grating). Through the Gaussian form of the guided mode, the actual local coupling amplitude in these PbP gratings is dependent on the offset of the RIMs from the center of the core according to

$$|\kappa(z)| = \kappa_0 \exp[-(4x(z)/w)^2], \tag{1}$$

where w is the $1/e^2$ width of the core mode (10.4 μm). Thus by substituting $\kappa_S(z)$ into Eq. (1), we obtain the translation function

$$x(z) = \frac{w}{4}\sqrt{-\ln|\mathrm{sinc}(2\pi z N_0/L)|}, \tag{2}$$

which must be truncated to some maximum value because in the limit as $\kappa \to 0$, $x \to \infty$. However, a truncation of 6 μm or more in this fiber has a negligible effect on the grating response. The translation function $x(z)$ and resultant coupling amplitude profile $\kappa(z)$ are shown in Fig. 3.

We used 220 nJ pulses to inscribe a sinc-apodized grating of length 60 mm and period 1.065 μm (second-order resonance at 1541 nm). Figure 4 shows the measured reflection spectrum of the grating, the target spectrum (based on the target κ profile shown in Fig. 3), a simulation of the fabricated grating, as well as the modeled spectrum of a uniform FBG with equivalent peak reflectivity and FWHM bandwidth. The modeled spectrum of a uniform FBG highlights the typical spectral characteristics of uniform FBGs, whereas the fabricated grating exhibits all the key qualities of a sinc-apodized FBG: steep band edges with a relatively wide reflection peak (0.33 nm FWHM) and excellent sidelobe suppression (15.2 dB, peak to first sidelobe). However, by observing

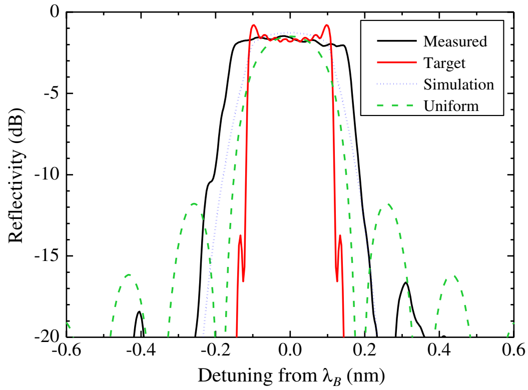

Fig. 4. (Color online) Measured reflection spectrum of the sinc-apodized grating (solid black curve), target spectrum based on $\kappa(z)$ shown in Fig. 3 (solid red curve), simulated spectrum of the fabricated grating (dotted blue curve), and modeled spectrum of a uniform FBG (dashed green curve).

the grating with a microscope, we found that the amplitude of the translation waveform supplied to the piezo stage was too large, which uniformly stretched the translation function $x(z)$ over a range of $8.4\,\mu$m, rather than the intended $6\,\mu$m. This resulted in a slightly distorted κ profile, hence the discrepancy between the target (solid red curve) and measured spectrum (solid black curve). The simulation of the fabricated grating shown in Fig. 4 (dotted blue curve) is based on the measured translation function of the fabricated grating, and it shows improved agreement with the measured spectrum, particularly with regards to the slope of the band edges. This confirms the contribution of this fabrication error to the experimental results, as well as highlighting the sensitivity of apodized gratings to the coupling-strength profile and the importance of matching the translation function to the intensity profile of the core mode. Furthermore, we found that simply using a sinc translation function (as in our previous work on sampled gratings [8]) produced gratings that either included strong sidelobes or did not exhibit the desired square shape and steep band edges.

In our simulations, we assumed that the average refractive index remained constant throughout the grating, as this produced the best agreement with the experimental results. We believe this to be due to the unique morphology of the PbP modifications, which consist of a microvoid ($-\Delta n$) encased in a compacted shell ($+\Delta n$) [13]. Our investigations into this phenomenon will be the subject of future work.

In conclusion, we have demonstrated apodized FBGs fabricated using a PbP technique. We tailor the coupling amplitude by varying the overlap of the microvoid modifications with the core mode, and we produce phase shifts in the grating by introducing discrete time delays to the fs laser pulse train. We fabricated a sinc-apodized FBG that highlights the strength and the flexibility of our apodization technique. In each of the gratings presented here, the out-of-band insertion loss was between −0.7 and −0.9 dB, which is within the typical range for PbP gratings inscribed with high pulse energies. The polarization-dependent difference in peak reflectivity for both the uniform and Gaussian-apodized FBGs was 0.8 dB, and that of the sinc-apodized FBG was 0.6 dB. This indicates that the apodization technique does not produce any significant additional scattering loss or polarization sensitivity beyond the intrinsic characteristics of PbP gratings [13].

The ability to inscribe apodized FBGs greatly extends the functionality of the PbP technique. These gratings have immediate application to fiber lasers based on directly inscribed FBGs for high-power narrow-linewidth operation [2] and all-fiber Q-switched operation [3,10], and indeed any fiber laser or sensing application that requires gratings in non-photosensitive fibers [4] or gratings with high-temperature stability.

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