Long-period fiber gratings spontaneously written by a mechanism markedly different from Hill grating formation

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Pumping a nonlinear germanosilicate fiber with intense near-infrared femtosecond laser pulses for supercontinuum generation may invoke multiphoton-assisted photosensitivity of glasses to write a long-period fiber grating. In sharp contrast to the spontaneous formation of a Hill grating that resonates with the writing wavelength through first-order diffraction, the long-period fiber grating resonates with the writing wavelength through second-order diffraction. This finding highlights the surprising light-matter interaction in a waveguide. © *2010 American Institute of Physics*. [doi:10.1063/1.3491842]

Fiber supercontinuum generation (SCG) employing near-infrared femtosecond laser has widespread applications in frequency metrology, spectroscopy, and biomedical imaging. However, the spectral broadening is ultimately limited by laser peak intensity corresponding to the photosensitivity of glasses.[1] Higher intensities may write a permanent long-period fiber grating (LPFG) in the fiber,[2] resembling the 1978 discovery of Hill grating (HG) formation.[3] The spontaneous formation of either the HG or the LPFG is accompanied by the transmission loss of the pump (writing) beam, reflecting the natural response of the fiber to counter the high-intensity irradiation by back-reflecting or scattering away the pump beam.

During HG formation, the interference of the core mode 488 nm beam with its Fresnel back-reflection from the fiber exiting end produces a sinusoidal intensity pattern for writing the HG (Refs. 4 and 5) through a two-photon-assisted photosensitivity.[6] Intuitively, the LPFG formation was attributed to the interference of the core mode 820 nm beam with a copropagating cladding mode 820 nm beam,[2] resulting in the sinusoidal intensity pattern for writing the LPFG through a five-photon-assisted photosensitivity.[7] However, new evidence rejects this intuitive interference-based interpretation of the LPFG formation, indicating that an evolving SCG fiber constitutes a unique prototypical system to study novel light-matter interaction.

Two step-index-type germanosilicate fibers (UHNA1 and UHNA3, Nufern, East Granby, CT) previously investigated[2] are revisited using a simple fiber-pumping setup intended for SCG (Fig. 1). The pump is a tunable (690–1020 nm) Ti:sapphire laser (Mai Tai HP, Spectra-Physics, Mountain View, CA) producing 80 MHz–100 fs pulses with ~10 nm bandwidth. An aspheric lens (C330TME-B, Thorlabs, Newton, NJ) is used to couple the pump into the fiber, and the coupling efficiency is determined by measuring the ratio of the maximized power exiting the fiber to the power incident on the aspheric lens. Immediately before and after the SCG, the fiber is probed across the 710–1020 nm spectral range to obtain the coupling efficiency spectrum (CES),[7] using the same aspheric lens while operating the laser in cw mode (Fig. 1). This operation produces cw tunable probe beam with a linewidth of ~1 nm.

Before and after the SCG and the measurements of the CES, the fiber is reversed so that its cleaved exiting end is used for light coupling while the cleaved entrance end serves as the exit (Fig. 1). In this arrangement, the far-field pattern of the exiting probe beam on a paper screen is examined using an infrared scope. Such sequence of probe-pump-probe procedure enables the characterization of the spontaneously written LPFG, which is localized within ~10 mm from the fiber entrance facet and can be completely removed by standard cleaving (Fig. 1).[2,7]

Following the above procedure, the UHNA1 fiber (~1 m) undergoing a typical SCG process (820 nm, 700 mW, 1.0 h) is investigated. The coupling efficiency of the pump drops from 65% to 28%, which cannot be compensated by optical realignment. Figure 2(a) compares the CES

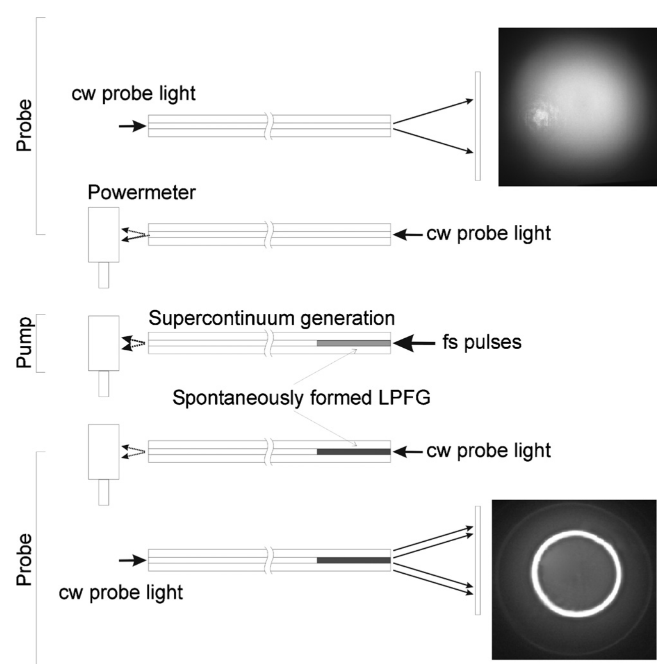

FIG. 1. Experimental procedures for spontaneous LPFG formation in an optical fiber, and exiting far-field pattern before and after SCG (insets).

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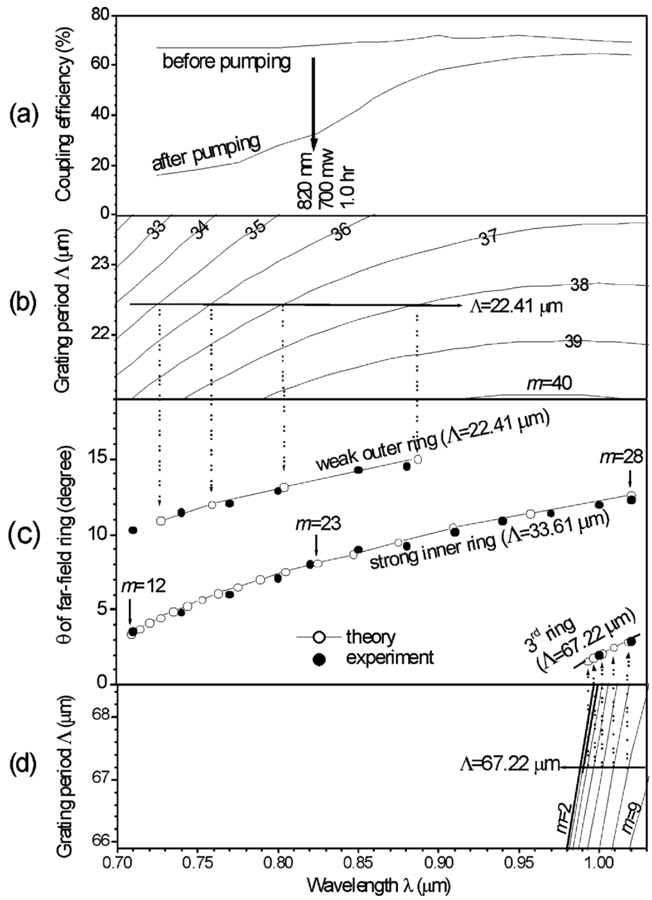

FIG. 2. CES before and after SCG (vertical arrow) (a), grating period Λ as a function of wavelength λ and index m of $LP_{0,m}$ cladding mode [(b) and (d)], and divergence angle θ of far-field ring as a function of wavelength λ (c), for the UHNA1 fiber.

measured before and after the process. The SCG induces noticeable transmission loss to the fiber, particularly at the short-wavelength end. The CES is typically measured with 10 nm increments. More accurate measurements with 2 nm increments do not resolve interesting fine structures.

The far-field patterns of the fiber at a probe wavelength (λ) of 760 nm are compared before and after the SCG (Fig. 1). While the Gaussian-like pattern of the core mode is expectedly observed before the process, a strong circular ring emerged from the pattern (shown as weak background) after the process. In our previous study,[2] the measured divergence angle θ of this ring as a function of λ was theoretically predicted from classical theory of cladding mode resonance by assuming the presence of a LPFG with a sinusoidal refractive index profile having a period (Λ) of 33.61 μm [Fig. 2(c)]. Thus, the observed modification of the CES [Fig. 2(a)] was attributed to the merged attenuation bands of the first-order (diffraction) resonance corresponding to a set of cladding modes $LP_{0,m}$ (m from 12 to 28 [Fig. 2(c)], note that the $LP_{0,m}$ mode is equivalent to $v=2m-1$ mode in Ref. 2. This assumption enables the intuitive interference-based interpretation of spontaneous LFPG formation[2] analogous to HG formation, because both the LPFG and HG resonate with the writing wavelength through first-order diffraction.

This interpretation is rather satisfactory except for the presence of an additional weak outer ring in the far-field pattern after the SCG (Fig. 1). The coexistence of the two rings across a wide range of λ [700–880 nm, Fig. 2(c)] suggests that the index profile of the LPFG is not strictly sinusoidal. The previous study did not take into account this additional outer ring,[2] and it is found out below that the inclusion of this ring in the theoretical analysis is indispensable for correct characterization of the LPFG, even though the intensity of the ring is weak.

If the index profile of the LPFG is not strictly sinusoidal but contains second-order harmonics of $\Lambda=16.81$ μm (i.e., half of the fundamental period of 33.61 μm), the weak outer ring may be attributed to the second-order resonance of some cladding modes without abandoning the intuitive interference-based interpretation of spontaneous LFPG formation. To test this assumption, the period Λ is determined from the θ versus λ relation corresponding to the weak outer ring, using the same method that deciphers the strong inner ring.[2] The assumption turns out to be invalid because the measured θ versus λ relation is consistent with $\Lambda=22.41$ μm, rather than $\Lambda=16.81$ μm [Figs. 2(b) and 2(c)].

The above analysis confirms the existence of LPFG(s) with $\Lambda=33.61$ μm and $\Lambda=22.41$ μm, which differ by a factor of 1.5. This unusual value strongly suggests that the two grating periods may correspond to the second and third harmonics of one LPFG with a nonsinusoidal index profile having a fundamental period of $\Lambda=67.22$ μm, which implies the existence of a third ring corresponding to this period. To test this new assumption, the θ versus λ relation of the third ring is calculated, predicting that the third ring is observable at λ above 970 nm [Figs. 2(c) and 2(d)]. The predicted third ring is experimentally observed while the predicted θ versus λ relation is quantitatively confirmed [Fig. 2(c)], convincingly validating the assumption. Thus, the three rings distinguishable by Λ (or equivalently, θ versus λ relation) alone can be attributed to the first-($\Lambda=67.22$ μm), second-($\Lambda=33.61$ μm), and third-order ($\Lambda=22.41$ μm) resonance of three distinct sets of cladding modes of one nonsinusoidal LPFG with $\Lambda=67.22$ μm [Figs. 2(b)–2(d)].

The emergence of such nonsinusoidal LPFG is highly counterintuitive considering that it scatters away the 820 nm writing beam from core mode predominantly into copropagating $LP_{0,23}$ cladding mode through second-order diffraction [Figs. 2(a) and 2(c)]. In sharp contrast, the emergence of HG reflects the writing beam from forward-propagating core mode into backward-propagating core mode through first-order diffraction. Unlike HG formation which originates from the simple interference between the two counter-propagating core modes, the spontaneous LPFG formation cannot be attributed to the simple interference between the copropagating core mode and $LP_{0,23}$ cladding mode, otherwise the writing wavelength would be coincident with the first-order diffraction of the LPFG corresponding to $LP_{0,23}$. Thus, the proposed mechanisms for HG formation[3–5] are invalid for the spontaneous LPFG formation.

At 820 nm writing wavelength, the $LP_{0,23}$ cladding mode is unique because it has the largest normalized coupling constant related to the core mode among all the cladding modes of the UHNA1 fiber, and is therefore termed as the dominant cladding mode (DCM).[2] Thus, the spontaneously formed LPFG resonates with the writing wavelength through the second-order diffraction of the DCM of the fiber, or equivalently, the writing wavelength is coincident with the second-order resonance of the LPFG corresponding to the DCM of

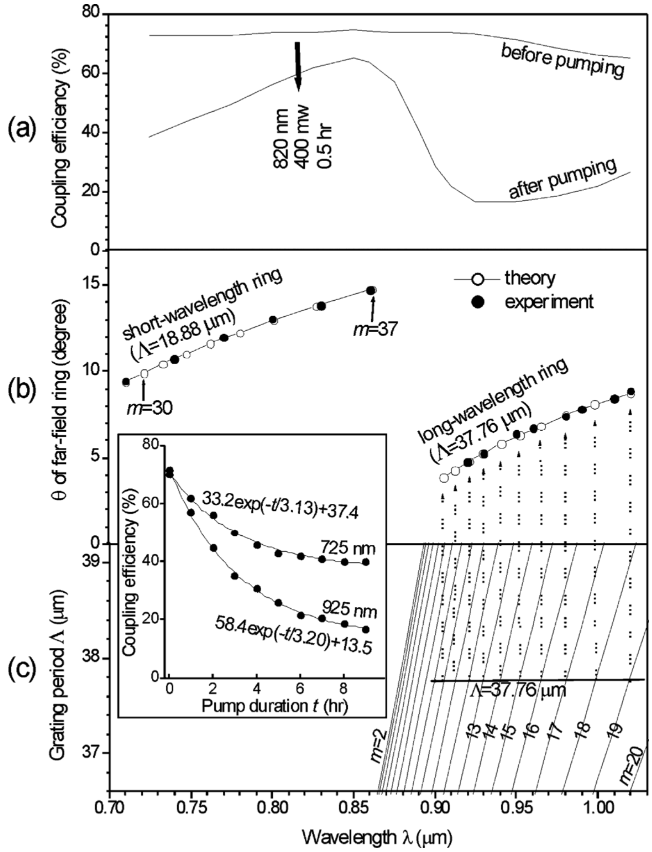

FIG. 3. CES before and after SCG (vertical arrow) (a), divergence angle θ of far-field ring as a function of wavelength λ (b), and grating period Λ as a function of wavelength λ and index m of $LP_{0,m}$ cladding mode (c), for the UHNA3 fiber; the inset shows coupling efficiency decay at 725 and 925 nm at discrete times when SCG (800 nm, 200 mW) is interrupted (dots), and the corresponding fits of exponential decay (lines).

the fiber. This assertion is sufficient to predict the Λ of the nonsinusoidal LPFG at a given writing wavelength for a fiber with known dielectric structure. To see whether this is valid for other writing wavelengths, the dependence of the DCM on the writing wavelength is evaluated. At 750 nm (or 910 nm) writing wavelength, the DCM is attained at $LP_{0,19}$ (or $LP_{0,26}$) according to the previously reported method,[2] yielding $\Lambda=65.6$ μm (or $\Lambda=67.3$ μm). This weak dependence of Λ on the writing wavelength has been experimentally confirmed by SCG using pump wavelengths across 750–910 nm.

The above assertion is further tested in a different fiber. The CES of the UHNA3 fiber before and after a SCG process (0.82 μm, 400 mW input for 0.5 h) is plotted in Fig. 3(a). In contrast to the UHNA1 fiber, only one far-field ring can be observed at λ across 710–1020 nm. On the other hand, the observed θ versus λ relation clearly reveals two rings of different origin. One is observable at λ below 870 nm, termed as the short-wavelength ring, while the other is observable above 900 nm, termed as the long-wavelength ring [Fig. 3(b)]. According to the assertion, the short-wavelength ring should represent the second-order diffraction of certain cladding modes because it includes the writing wavelength of 820 nm. At this wavelength, the DCM of the UHNA3 fiber is found out to be $LP_{0,35}$ (or $LP_{0,36}$) mode, which results in $\Lambda=18.88$ μm for the short-wavelength ring [Fig. 3(b)].[2] Thus, the long-wavelength ring can be attributed to the first-order diffraction of some other cladding modes associated with $\Lambda=37.76$ μm. The θ versus λ relation of this ring is calculated accordingly, and is found to be in excellent agreement with the observed relation [Figs. 3(b) and 3(c)]. This extraordinary coincidence thoroughly validates the above assertion. Despite the difference of the two fibers in terms of the modified CES [Figs. 2(a) and 3(a)] and far-field rings [Figs. 2(c) and 3(b)], the physics underlining the spontaneous LPFG formation is the same.

The differentiation of the two rings is necessary for understanding the observed bandpass filterlike CES of the LPFG centered at 850 nm [Fig. 3(a)].[7] The attenuation bands of the first-order (second-order) resonance of the cladding modes associated with the long-wavelength (short-wavelength) ring overlap with each other to form the continuous transmission loss band above (below) 850 nm. The transmission maximum at 850 nm corresponds to the transition between these two effects, which gives rise to the bandpass filterlike CES [Fig. 3(b)]. This straightforward explanation was not available from a previous study in which the long-wavelength ring was not taken into account.[2]

A key question pertinent to the spontaneous LPFG formation is whether the nonsinusoidal index profile is produced by the saturation of an otherwise sinusoidal index profile[8] formed at the early stage of SCG. If this is the case, the CES decay spanning the short-wavelength ring should begin after the CES decay spanning the long-wavelength ring is largely completed. The pump process in the probe-pump-probe sequence (Fig. 1) can be periodically interrupted by the probe processes to monitor the dynamics of the LPFG formation at certain pump duration and peak power,[7] so that the coupling efficiency decay as a function of the pump duration are measured at λ of 725 and 925 nm [Fig. 3(c), inset]. The decay kinetics can be well fitted to an exponential decay for both wavelengths while the corresponding decay constants differ by 5%. Thus, the initially formed LPFG simply grows in strength but maintains the similar nonsinusoidal index profile throughout the SCG. This evidence rules out the saturation nature of the nonsinusoidal LPFG formation. The absence of a sinusoidal index profile even at early stage of the LPFG formation further verifies the irrelevance of the LPFG formation to HG formation.

To conclude, an intrinsically nonsinusoidal LPFG is spontaneously written in a fiber to resonate with the writing wavelength through the second-order diffraction of the DCM of the fiber, exhibiting novel light-matter interaction in a waveguide that is worth future investigations.

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