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Brillouin characterization of holey optical fibers

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We report the results of detailed measurements on the Brillouin frequency shift (BFS), gain bandwidth, and gain coefficients of several small-core holey optical fibers (HFs) of both uniform and axially varying structural characteristics and compare these with measurements on more conventional fibers. Our measurements show that the BFS of HFs is first-order proportional to the modal index for light propagating along the fiber and is thus extremely sensitive to its precise structural parameters. Our results highlight the possibility of using distributed Brillouin scattering measurements to perform nondestructive structural characterization of HFs, and the possibility of producing Brillouin-suppressed HFs using controlled structural variation along the fiber length. © 2006 Optical Society of America

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Holey optical fibers (HFs) can exhibit a variety of unusual optical properties that cannot be accessed using conventional optical fiber technology.[1] Of particular interest is the possibility for high-nonlinearity HFs with unique and highly tailorable dispersion characteristics. A number of nonlinear devices based upon such fibers have now been demonstrated. For certain Kerr-nonlinearity-based fiber devices, particularly those employing narrow linewidth optical signals, stimulated Brillouin scattering can adversely affect device performance, and the development of means to control the relative strengths of these often competitive nonlinear processes within a fiber are thus highly desirable.[2]

The Brillouin nonlinearity within HFs has previously been studied in the context of either Brillouin laser or sensor applications. A non-Lorentzian spontaneous Brillouin gain spectrum (BGS) exhibiting approximately a factor of 7 greater gain bandwidth than associated with conventional fiber was reported for a 40 m length of pure silica core HF.[3] It was postulated that the broadened linewidth (and the increased Brillouin laser threshold observed) was due to structural variation along the fiber length, although only limited quantitative data were provided to support this. More recently, a narrower linewidth of 66 MHz was measured for a 2 m long section of germanium-doped HF at 1.3 μm (Ref. 4) adding further support to this explanation, since the degree of structural variation along this much shorter fiber length would be expected to be less. To date, though, no detailed studies of how the structural parameters of a HF impact the Brillouin response have been undertaken.

In this paper, we experimentally investigate the Brillouin characteristics of various small-core HFs using a pump–probe technique[5] and then relate them to the structural properties of the fiber. We first compare the nonlinear properties of a pure silica HF drawn to have as uniform structural characteristics as possible along its length with those of conventional commercial fibers. We then characterized a small-core HF in which the fiber's structural properties are deliberately varied along the fiber length. By measuring the local variation of the BFS along the length of the fiber, and correlating these with the experimentally observed variation of fiber structure along the length, we are able to demonstrate that the Brillouin frequency shift (BFS) is first-order proportional to the modal index as in conventional fibers. We also show that, due to the large variation in modal index possible in small-core HFs, the BFS can be made extremely sensitive to any variation in the structural parameters of the fibers. Our results highlight the possibility of using distributed Brillouin measurements as a means of performing nondestructive, structural characterization of HFs, and that controlled variation of the structural parameters of a small-core HF can be used to design Brillouin suppressed fibers for specific Kerr-based nonlinear devices.

To characterize the Brillouin properties of our fiber, we adopted the approach used by Nikles *et al.*[5] (see Fig. 1). One feature of note within our experimental setup is the use of a high-precision fiber Bragg grating (FBG) filter (providing a 3 dB bandwidth of 6 GHz and a >40 dB extinction ratio) to extract the probe signal. This helped us reduce the beat noise between pump and probe beams within the system, thereby facilitating measurements on short-fiber samples. This technique has several advantages over the typical backscattering technique. First, far

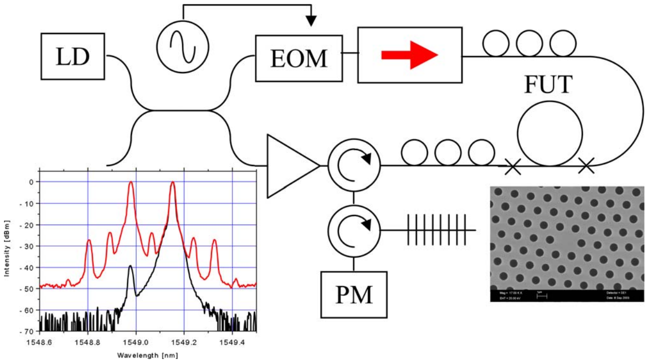

Fig. 1. (Color online) Schematic of the experimental setup. LD, laser diode; EOM, electro-optic modulator; FUT, fiber under test; PM, Powermeter. Bottom left inset, probe spectra after the EOM (top) and FBG (bottom). Bottom right inset, scanning electron micrograph image of the FUT.

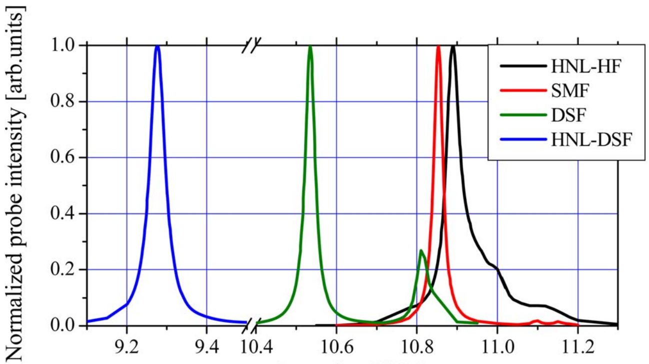

Fig. 2. (Color online) Normalized BGS spectra for the fibers listed in Table 1.

shorter sections of fiber can be characterized. Second, there are no experimental ambiguities concerning Fresnel reflections from fiber end facets. Third, the power requirements are greatly reduced (typically ~10 mW is all that is required for the pump beam), allowing for the use of conventional core-pumped amplifiers with low-noise performance. Finally, when distributed measurements are employed, the tradeoff between spatial and spectral resolution can be relaxed considerably.[6]

We characterized a range of different fibers including a HF of nominally uniform structural characteristics along its length made of pure silica and both conventional dispersion-shifted fiber (DSF) and highly nonlinear (HNL)–DSF fibers. The pitch Λ and the air hole diameter d of this particular HF are 2 and 0.8 μm, respectively. The observed BGS are shown in Fig. 2. A few satellite peaks are observed for DSF and HNL–DSF as expected from their core structure. For the purpose of this paper, we concentrate on the properties of the primary gain peak. The results are summarized in Table 1. Note that the A_{eff} values here are derived from separate measurements of the Kerr nonlinearity per unit length.[7] The BFS of a given fiber can be expressed as $v_B=2n_{\mathrm{eff}}v_A/\lambda$, where n_{eff} is the modal index, v_A is the acoustic velocity, and λ is the wavelength.[8] A high germanium concentration decreases v_A,[5] and in conventional fibers, particularly for HNL–DSF, the effect of this greatly outweighs that of the increased n_{eff} due to the raised core index. The measured BFS for HNL–HF is ~250 MHz (~2.2%) smaller than the value extrapolated from the conventional fibers (11.2 GHz). We attribute this to the relatively small n_{eff} of this particular HNL–HF, which we numerically estimated to be ~1.425 (~2.3% smaller than that of pure silica). Thus the significant reduction in n_{eff} obtained for small-core HFs results in a noticeable shift in the BFS.

The FWHM value of the gain bandwidth for the 100 m long HNL–HF was 43 MHz, which although slightly greater than that of SMF is still comparable with that of conventional fibers. The gain profile itself is asymmetric, with a tail that extends over ~150 MHz to the high-frequency side without any peaks. When we characterized a short section of the same HNL–HF (~1 m), the gain profile was essentially the same. Therefore we concluded that this is inherent to this particular fiber and that the fiber is as expected highly uniform. The existence of this broad tail may be attributed to the fact that the pure silica core HFs represent an acoustic antiguide structure.[5] We also note that the high birefringence often observed for small-core HFs may broaden the BGS of HFs when both axes are excited. The measured beat length of ~1 mm (modal birefringence of $\sim 5\times 10^{-4}$) corresponds to an ~20 MHz difference in BFS. Although we attempted to launch light onto a single polarization axis, successive splicing between the small-core HF and conventional fibers within the setup may well have degraded the polarization purity of both pump and probe.

To study the structural dependence of the Brillouin properties, we characterized a HF with structural variation deliberately imposed along its length. This fiber was produced by applying a step change in the fiber draw speed during the pulling process. The core of this particular fiber was doped with germanium (~3 mol.%), which also contributes to the decrease in the BFS. The total length of the fiber over which transient effects were investigated was 40 m. We cut this 40 m length of the fiber up into 20 pieces and characterized the individual structural parameters of each 2 m fiber sample using a scanning electron micrograph, as shown in Fig. 3(a). It is seen as a result of the drawing perturbation that d/Λ temporarily increases due to the increased tension and then returns to its original value (~0.5) as the draw speed settles to a constant value, and that Λ oscillates before converging to a stable drawing regime. Despite the substantial changes in these parameters, the transverse structures were retained without significant deformation. We then measured the BFS of each 2 m sample (note that this length is sufficient to obtain a reasonable signal-to-noise ratio in our measurements partly owing to the high nonlinearity of our fiber). Although we observed multiple peaks due to the germanium doping,[4] we again focused our analysis on the properties of the primary gain peak, which exhibited a typical bandwidth of ~50 MHz. In Fig. 3(b), we plot the results for each 2 m sample along the fiber length together with a theoretical estimate of the modal index obtained using the plane-wave expansion method based on structural data measured above. Clearly, the modal index and the BFS are strongly correlated. The BFS reduces by more than 100 MHz over the

Table 1. Summary of the Experimental Results

	SMF	DSF	HNL–DSF	HNL–HF
L [m]	100	96	490	100
A_{eff} [μm^2]	83	48	10.3[a]	7.3
N_2 [x10^{-20} m^2/W]	2.20[b]	2.35[b]	2.99[a]	2.16[b]
v_B [GHz]	10.881	10.56	9.31	10.925
Δv_B [MHz]	34.8	37.7	44.5	43
g_B/A_{eff} [W^{-1} m^{-1}]	0.13	0.26	1.33	1.23
g_B [$\times 10^{-11}$ m/W]	1.08	1.25	1.37	0.898

[a] Quoted value from the manufacturer.

[b] After Ref. 11.

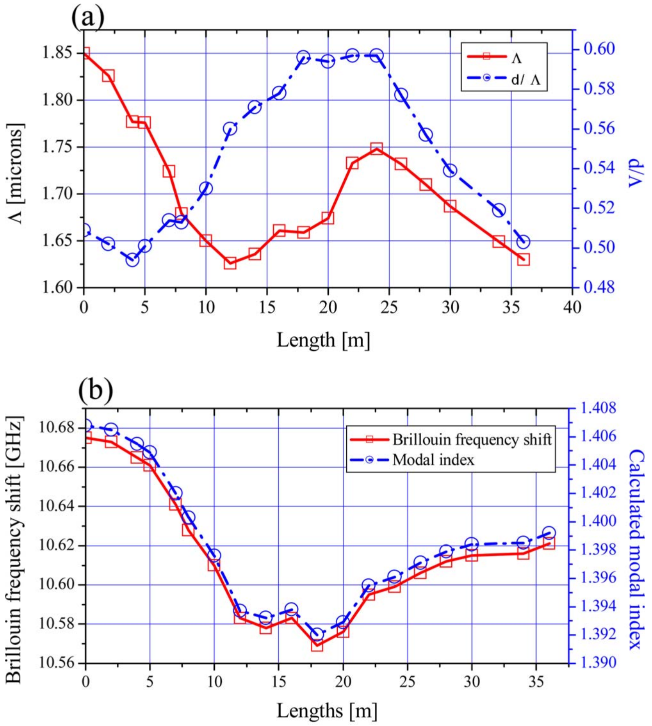

Fig. 3. (Color online) (a) Variation in the HF structural parameters along the fiber length and a scanning electron micrograph of the fiber structure, and (b) the correlation between the measured Brillouin frequency and modal index calculated from the numerical model along the fiber length.

first 20 m and then recovers to ~10.62 GHz while the modal index varies from 1.407 to 1.392 over its length. This results in a BFS variation of $\sim 2.5\Delta v_B$ (~106 MHz) over the full fiber length, implying that v_A is ~5600 m/s. This suggests that to prevent any broadening of the BGS in this design regime (say within ~5 MHz), Λ and d/Λ must be maintained to within 1% and 0.7%, respectively, along the full fiber length. Note that this sensitivity is enhanced for designs with small Λ and/or large d/Λ.

This high sensitivity may, however, be used to investigate the variation in modal properties along a length of HF. Since the Brillouin gain is inversely proportional to A_{eff}, and the BFS is proportional to n_{eff}, local information about both A_{eff} and n_{eff} can simultaneously be obtained by employing distributed Brillouin gain measurements using the frequency modulation technique.[6] Since these two quantities are uniquely related to the structural parameters d and Λ, distributed Brillouin measurements allow, in principle, retrieval of these structural parameters along the fiber length in a nondestructive fashion. Although due to the short lengths used and the uncertainty in coupling efficiency between samples, it was difficult to compare the absolute magnitude of the Brillouin gain coefficient for each discrete fiber sample in this experiment, this should prove far easier using a distributed measurement along a single fiber. Our numerical simulations predict that the effective area of this HF varied from 5.9 to 4.2 μm^2 along the full fiber length, and that this structural variation would lead to an increase in the Brillouin threshold by a factor of ~2.2, compared with a uniform fiber with the same nonlinear coefficient. Further numerical simulations highlight the possibility of producing Brillouin suppressed high-nonlinearity fibers with low (uniform or path-average) dispersion by carefully controlling the longitudinal variation.[9]

In conclusion, we report the results of a systematic study of Brillouin properties of HFs. We found that a uniform HF with a length of 100 m can exhibit a narrow gain bandwidth (~43 MHz), comparable with that of conventional fibers. By studying a HF with deliberate structural variation along its length, we found that the BFS in small-core HFs is strongly affected by the modal index, which can vary over a significantly wider range than in conventional fibers. We anticipate taking advantage of this high sensitivity to perform nondestructive structural characterization using distributed Brillouin measurement. Furthermore, our results also highlight the interesting possibility of producing Brillouin suppressed high-nonlinearity HFs in which the dispersion variation is simultaneously controlled by a suitable choice of structural modulation profile along the fiber length.

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