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Investigation of Brillouin effects in small-core holey optical fiber: lasing and scattering

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We demonstrate for what is believed to be the first time a Brillouin laser based on a holey fiber (HF). Using a simple Fabry–Perot resonator scheme containing a 73.5-m-long highly nonlinear HF with an effective area of 2.85 μm^2, we obtain a threshold of 125 mW and a slope efficiency of ~70%. Stimulated and spontaneous Brillouin scattering effects are investigated in the HF, and we show that the high lasing threshold is due mainly to reduction of the effective gain coefficient caused by structural nonuniformity along the fiber length.

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Holey fiber (HF) technology has progressed rapidly in recent years and is of great interest for fiber device applications because of the wide range of novel optical properties that it offers.[1,2] One particularly interesting class of HF combines a small-scale solid core with a large air-fraction cladding (i.e., closely spaced, large air holes). This type of fiber offers tight modal confinement and thus can provide an effective nonlinearity per unit length that is 10–100 times higher than that of a conventional fiber. Furthermore, when asymmetric structures are used, these HFs can offer high form birefringence.

A number of research groups have studied nonlinear effects in HF and demonstrated a variety of results, such as four-wave mixing,[3] soliton self-frequency shift,[4] and third-harmonic generation.[5] Recently we illustrated that HF technology could be a powerful way to realize a variety of practical nonlinear optical devices for fiber-optic communication systems. For example, we demonstrated the use of a nonlinear thresholding device based on the Kerr effect in just 8.7 m of HF with a mode area of ~2.93 μm^2 in a superstructured fiber Bragg grating–based 255-chip direct sequence optical code division multiple access system.[6] We also showed that it was possible to obtain ~42-dB signal gain in an L$^+$-band Raman amplifier based on just a 75-m length of the same HF.[7] Both demonstrations highlight the improvements that can be obtained in terms of reduced device lengths and (or) power requirements as a result of the high effective nonlinearity of the fiber.

In this Letter we show that HF technology can also be applied to another important class of nonlinear fiber-optic devices, namely, those devices based on the Brillouin effect. More specifically, we provide what we believe to be the first experimental demonstration of a HF-based Brillouin laser. Also, we investigate the Brillouin gain line shape within the fiber (for two different fiber lengths) and compare these measurements with the line shape of conventional dispersion-shifted fiber (DSF). Our results show that structural variations along the HF length give a substantial increase in Brillouin linewidth.

Our experimental setup is shown in Fig. 1. The pump source is based on an Er fiber distributed-feedback seed laser followed by a high-power Er/Yb amplifier. The source has a linewidth of ~35 kHz and a center wavelength of 1552.1 nm and provides a maximum output power of ~750 mW. The Fabry–Perot resonator incorporates a 73.5-m-long HF, a lens-coupled high-reflectivity cavity mirror, and a 96% output coupler defined by the Fresnel reflection from the cleaved fiber facet at the pump-launch end of the cavity. Both polarization controllers and a polarization-maintaining (PM) isolator were used so that the pump beam could be lens coupled onto one of the principal axes of the HF. A launch efficiency of ~50% was measured. We located a 92:8 beam splitter at the pump-launch end of the HF to monitor both the Brillouin laser output and the incident pump power. A mechanical chopper located in front of the high-reflectivity mirror facilitated alignment of the cavity.

The HF used in this experiment has a core diameter of ~1.6 μm and has a measured effective area of 2.85 μm^2 and a loss of 40 dB/km at 1550 nm. The effective length $\{L_{\text{eff}} = [1 - \exp(-\alpha L)]/\alpha$, where α is the fiber loss and L is the fiber length$\}$ of the fiber is 53 m.

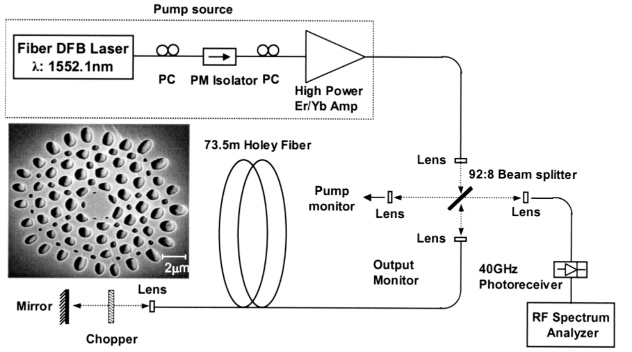

Fig. 1. Experimental setup. Inset, cross-sectional scanning electron microscope image of the HF used in this experiment. PCs, polarization controllers; DFB, distributed feedback.

The fiber is PM by virtue of the structural hole asymmetry that is evident in the cross-sectional scanning electron micrograph shown in the inset of Fig. 1 and has a measured beat length of ~0.4 mm near 1550 nm. This fiber is more fully described in Ref. 7.

We first investigated the performance of the fiber under laser operation (i.e., with feedback from the HR mirror end of the cavity). We confirmed that laser operation rather than stimulated scattering occurred by modulating the cavity loss by use of the free-space chopper and looking for correspondingly modulated laser output (see the inset of Fig. 3 below). Figure 2 shows experimental data of the Brillouin laser output power as a function of the input pump power. The laser threshold was found to be 125 mW, and the slope efficiency was ~70%. The rf spectrum of the beat signal between the laser output and the pump beam was measured with a rf spectrum analyzer, which showed that the frequency of the Brillouin laser output was downshifted by 10.6 GHz relative to the pump frequency, as shown in Fig. 3.

We next investigated the stimulated Brillouin scattering (SBS) threshold within the HF. Feedback from the HR mirror was removed, and any possibility of Fresnel reflection from the terminated fiber at this end of the cavity was eliminated by immersion of the fiber in index-matching liquid. We experimentally observed a SBS threshold of ~280 mW (as shown in Fig. 2).

This stimulated threshold value, and indeed the laser threshold, was substantially higher (by roughly an order of magnitude) than we had expected from simple estimates based on the established Brillouin gain coefficient for pure silica and the measured values of HF mode area and loss. We postulated that this was due to structural variations along the HF, since it is well established in conventional fibers that Brillouin shift is strongly dependent on the fiber structure and that any variation in structure along a fiber can result in effective Brillouin line broadening and reduced Brillouin gain.[8] This particular HF was drawn without active diameter control during the drawing process and was known to have a (slow) variation of as much as ±3-μm diameter along its length, a far greater variation than is usual for conventional commercial fiber types (and indeed for other HFs that we have drawn).

Theoretically, if the pump-laser linewidth is negligible relative to the Brillouin gain bandwidth, the SBS threshold can be approximated by the following equation as suggested by Shiraki *et al.*[8]:

$$P_{\mathrm{th}} \cong 21 \frac{K A_{\mathrm{eff}}}{G(\nu_{\max})} \,. \tag{1}$$

The effective gain coefficient, $G(\nu)$, is expressed as

$$G(\nu) = \int_0^L g_B(\nu, z) \exp(-\alpha z) \mathrm{d}z \,, \tag{2}$$

where K and A_{eff} are the polarization factor ($K = 1$ for a PM fiber) and the effective area of the fiber, respectively. $\nu_{\max}$ represents the frequency at which $G(\nu)$ is maximized. $g_B(\nu, z)$ is the Brillouin gain spectrum whose Lorentzian profile is given by

$$g_B(\nu, z) = \frac{g_0}{1 + \left[\dfrac{\nu - \nu_B(z)}{\Delta \nu_B / 2} \right]^2} \,, \tag{3}$$

where $\nu_B(z)$ is the Brillouin frequency shift at the location of z, $\Delta \nu_B$ is the intrinsic Brillouin gain bandwidth, and g_0 is the peak Brillouin gain coefficient. A fiber with structural variations shows a smaller effective gain coefficient than a uniform fiber [$G(\nu_{\max}) = g_0 L_{\mathrm{eff}}$ for uniform fiber] because of the irregular Brillouin shift distribution along the fiber, as can be understood through the relation $g_B(\nu, z) \leq g_0$.[8] Thus the Brillouin threshold increases while the effective gain coefficient $G(\nu_{\max})$ decreases in a structurally nonuniform fiber.

To confirm our suspicions we measured the spontaneous Brillouin scattering line shape for two different lengths (73.5 and 40 m) of the fiber, using a hetrodyne-detection technique that relies on beating the spontaneously scattered light with the pump beam.[9] We also compared the result to that with a standard DSF fiber. Our Brillouin gain bandwidth measurements are summarized in Fig. 4.

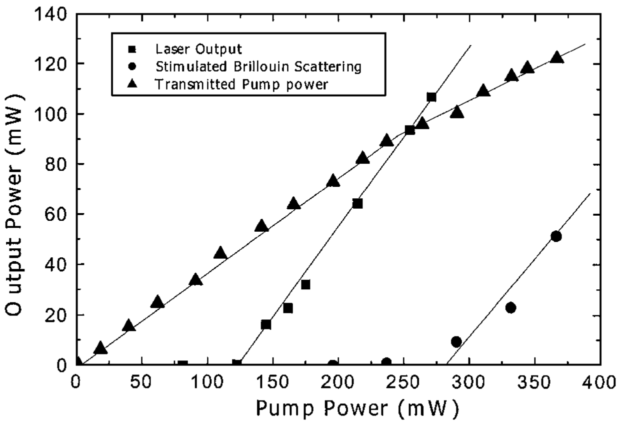

Fig. 2. Laser output, stimulated Brillouin scattering (backward), and transmitted pump power as a function of launched pump power (stimulated scattering only).

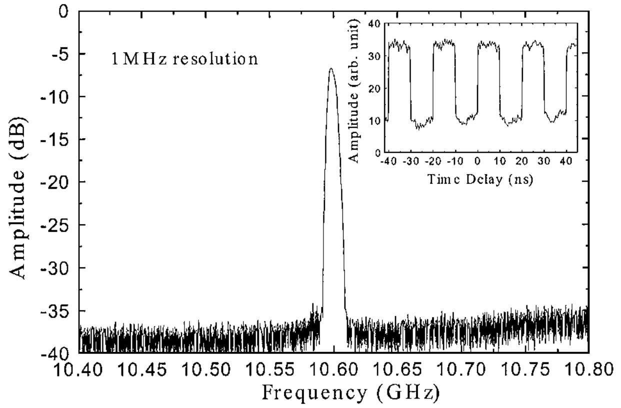

Fig. 3. rf frequency trace of the beat signal between the Stokes and the pump beams. Inset, oscilloscope trace of output square-shaped pulses from the Brillouin laser under cavity modulation with the chopper.

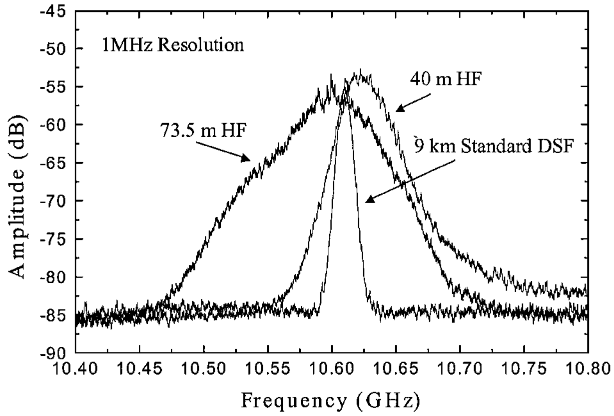

Fig. 4. rf frequency trace of the beat signals between the spontaneous Brillouin-scattered beam and the pump for 73.5-m HF, 40-m HF, and a 9-km standard DSF.

The spontaneous Brillouin linewidth of the 73.5-m-long HF is seen to be approximately an order of magnitude greater than that of pure silica and has a non-Lorentzian shape. More specifically, the 73.5-m HF has an approximately seven times broader bandwidth than DSF silica fiber in terms of the 3-dB bandwidth. Our theoretical prediction of the threshold of the HF based on the observed line broadening is ~240 mW, which is in reasonable agreement with the measured value of 280 mW mentioned above. The Brillouin gain bandwidth of a 40-m length of the same HF ($L_{\mathrm{eff}} = 33$ m) was also measured, and we observed a bandwidth of approximately half the value found in the 73.5-m length and in addition a small increase in the Brillouin frequency shift (see Fig. 4). This thus represents compelling evidence that structural variation along the fiber is indeed responsible for the variation in Brillouin frequency shift and corresponding linewidth broadening and consequently for the increased SBS threshold. It will certainly be possible to obtain much lower SBS thresholds in HF in which greater attention is paid to reducing the diameter fluctuations along the length. Note that the 40-m HF was measured to have a SBS threshold of 290 mW, which is comparable to that of the 73.5-m HF.

In conclusion, we have experimentally demonstrated a cw Brillouin laser based on a highly nonlinear HF. A good laser power conversion efficiency of ~70% and a Brillouin-shifted output power of 110 mW were readily achieved at a wavelength of 1552.18 nm by use of a simple Fabry–Perot resonator scheme. We also investigated the stimulated Brillouin scattering characteristics of the HF and established that structural variation along this particular HF was responsible for broadening the Brillouin gain line shape. With better control of the HF diameter during drawing it will be possible to reduce this line broadening, allowing the full benefits of the tight mode confinement within these fibers to be exploited more fully in terms of reduced device lengths and (or) power requirements for a variety of Brillouin-effect-based optical devices.

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