Guided entropy mode Rayleigh scattering in optical fibers

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Rayleigh scattering in optical fibers has the potential to degrade the performance of low-noise opto-electronic systems. In this Letter, we measure the Rayleigh gain spectrum of optical fibers. Our data show the gain bandwidth and the offset frequency of the Rayleigh gain peak. Both the gain bandwidth and the peak frequency are 3 orders of magnitude lower than the corresponding values for bulk silica. Our data suggest that the narrower gain bandwidth and frequency shift that we observe are due to guided entropy modes in the fiber. This effect is fundamental and will be present in any medium in which light is guided so that transverse intensity gradients exist.   © 2012 Optical Society of America

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Light traveling through an optical medium can induce density fluctuations that result in fluctuations of the permittivity. These permittivity fluctuations will then scatter light that is traveling through the medium. Density fluctuations can be due to either variations in the entropy or the pressure, i.e., [1] [Eq. (8.3.16)]

$$\Delta\tilde{\rho} = \left(\frac{\delta\rho}{\delta p}\right)_s \Delta\tilde{p} + \left(\frac{\delta\rho}{\delta s}\right)_p \Delta\tilde{s}, \qquad (1)$$

where ρ is the density, s is the entropy density, and p is the pressure. Fluctuations in the entropy lead to Rayleigh scattering, while fluctuations in the pressure lead to Brillouin scattering. Both scattering mechanisms are well studied in bulk materials [1,2]. Both scattering mechanisms lead to frequency shifts in the incident light. These processes have a characteristic bandwidth $\Gamma \sim C(4\pi/\lambda)^2$, where λ is the light's wavelength and the constant C depends on the material properties of the glass. For Brillouin scattering, it has been found that $\Gamma \sim 50$ MHz, while for Rayleigh scattering, it has been found that $\Gamma \sim 100$ MHz [1].

In optical fibers, the light is confined to a core that is a few micrometers in diameter. Hence, a transverse intensity gradient is present that induces both electrostrictive and electroabsorptive forces. These forces will generate combined thermal and acoustic modes that are confined within the glass and whose wavenumbers are oriented perpendicular to the core. These guided modes will generate density fluctuations whose interactions with the guided light will result in scattered spectra that differ significantly from the spectra that are generated in bulk media. Guided acoustic wave Brillouin scattering (GAWBS) in which guided pressure modes interact with the light is well understood [3,4]. The transverse forces that are due to the light's intensity gradient lead to a series of modes between 10 MHz and 1 GHz whose characteristic bandwidths equal $\Gamma = C/a^2$, where a is the radius of the fiber core and C is the same constant of proportionality that appears in the bulk glass. With light at 1.5 μm and a core of 4.0 μm, we find that the bandwidth is expected to be reduced by a factor of about 1000, corresponding to 10 kHz, which is observed.

Guided entropy mode Rayleigh scattering (GEMRS) is less well understood than is GAWBS. Zhu *et al.* [5] found a gain bandwidth of approximately 20 kHz, which is more than 3 orders of magnitude smaller than the gain bandwidth in bulk glass. Zhu *et al.* did not detect a frequency shift.

This effect is potentially important in applications where it is necessary to transfer a signal through an optical fiber with low phase noise. It plays an important role in the observed length-dependent flicker noise of opto-electronic oscillators and is likely to play a similar role in microresonators [6]. Moreover, this effect could explain the observed difference between duplex and bidirectional transport of frequency data [7].

In this Letter, we measure the incident and scattered intensity noise spectra in an optical fiber. From these intensity noise spectra, we determine the Rayleigh gain bandwidth and the frequency shift in the fiber. We observe Rayleigh bandwidths of about 50 kHz, which is consistent with the bandwidths that Zhu *et al.* observed. In addition, we measure for the first time the frequency shift of the Rayleigh gain spectrum. Both the bandwidth and the frequency shifts that we observe are consistent with a phenomenological explanation in which the Rayleigh scattering is due to longitudinal fluctuations in the fiber's index of refraction, and these fluctuations in the index of refraction are in turn driven by the transverse intensity gradient of the light.

Our experimental setup consisted of a cross-correlation relative intensity noise (RIN) measurement system [8] that we used to measure the incident intensity noise spectrum and a homodyne detection system that we used to measure the backscattered spectrum from the fiber under test. We then calculated the Rayleigh gain spectrum by dividing the backscattered spectrum by the incident RIN spectrum.

The Rayleigh gain spectrum is difficult to measure because the scattered light is small relative to the input intensity—varying between –90 dBc/Hz at 10 Hz from the carrier and –160 dBc/Hz at 1 MHz from the

carrier—and because the Rayleigh-induced frequency shift (~50 kHz) is smaller than the laser oscillating laser frequency (~200 THz) by more than 9 orders of magnitude. In order to generate high-resolution measurements of the Rayleigh gain spectrum, we used the homodyne detection system in Fig. 1. In this setup, an optical power splitter divides the laser output beam. Seventy-five percent of the laser output power then passes through a variable optical attenuator (VOA), followed by an optical circulator. The backscattered signal from the fiber under test travels from the third port of the circulator to an optical power combiner. Twenty-five percent of the laser output beam then goes into the other input of the power combiner. The two output beams of the power combiner go into the input ports of a pair of balanced photodetectors. An AC-coupled amplifier follows the photodetectors with a low frequency cutoff at 0.125 Hz. The output from the amplifier goes to an electrical spectrum analyzer.

We collected experimental data from lengths of optical fibers that varied from 40 m to 100 km. We varied the input power into each fiber spool using a VOA in order to keep the RIN spectra of the incident optical beams constant. In this section, we present backscattered data in the frequency range from 10 Hz to 1 MHz from the central laser frequency.

Figure 2 shows a plot of the backscattered intensity spectrum from a 6 km spool of single-mode fiber as well as the intensity noise spectrum of the input CW beam. The input optical power was 1 mW. To determine the Rayleigh gain spectrum, we divide the measured backscattered intensity spectrum by the incident laser intensity spectrum. Figure 3 shows a plot of the resulting Rayleigh gain spectrum for a 1 mW optical beam injected into a 6 km spool of single-mode optical fiber.

In order to compare our experimental data with the theoretically predicted Rayleigh gain spectra in bulk materials, we begin with the general form of the Rayleigh gain coefficient given by Boyd [1] [Eqs. (9.6.48) and (9.6.49)]:

$$G_R(\omega) = A_R \left[\frac{4\omega/\Gamma_R}{1 + (2\omega/\Gamma_R)^2} \right], \tag{2}$$

where A_R is a material coefficient and Γ_R is the gain bandwidth. We then vary the amplitude A_R and the
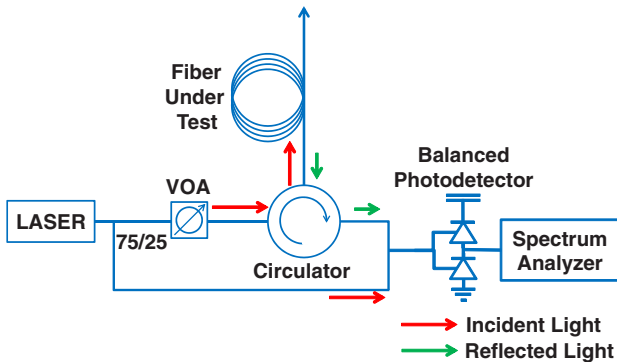

Fig. 1.   (Color online) Schematic diagram of the homodyne detection system used to measure the Rayleigh backscattered spectrum.
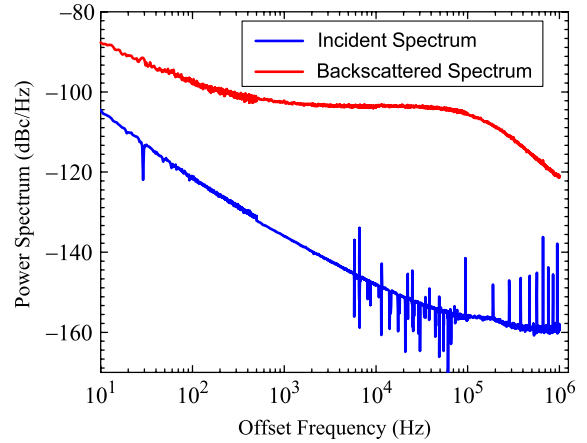

Fig. 2.   (Color online) A plot of the backscattered intensity spectrum from a 6 km spool of single-mode fiber as well as the incident noise spectrum of the input CW beam. The input optical power was 1 mW.

bandwidth Γ_R in order to minimize the mean square error between this theoretical curve and our experimental data. We show the resulting theoretical fit in Fig. 3.

Our experimental data match the general theoretical form in Eq. 2. The peak frequency is consistent with replacing $\lambda/4\pi$ with the core radius a in the definition of Γ_R and is lower than the peak that is observed in bulk silica by a factor of approximately 2000. The bandwidth is lowered by the same factor.

To determine the power dependence of the Rayleigh gain spectrum, we varied the power that is injected into a 6 km spool of single-mode fiber and we measured the resulting backscattered spectrum. We then divided the backscattered spectrum by the laser RIN spectrum. Figure 4 shows plots of the resulting Rayleigh gain spectra. Our data show that the peak Rayleigh gain does not vary appreciably with incident optical power, indicating that the backscattered power increases approximately linearly with input power. However, the peak frequency and bandwidth do decrease somewhat as the power increases, suggesting that the material properties of the fiber change as the incident power increases.
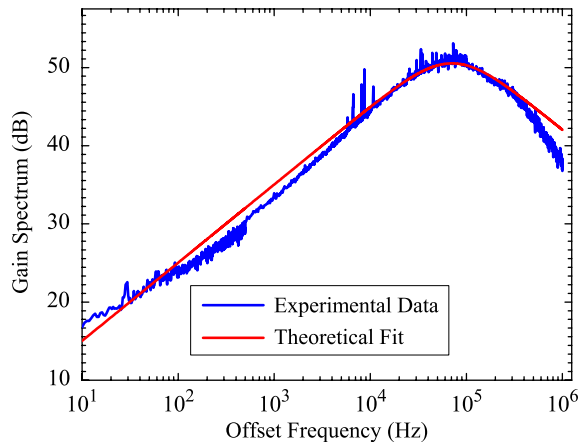

Fig. 3.   (Color online) Plot of the Rayleigh backscattered gain spectrum from a 6 km spool of single-mode fiber with a 1 mW incident optical beam. A theoretical fit to experimental data is included for comparison.
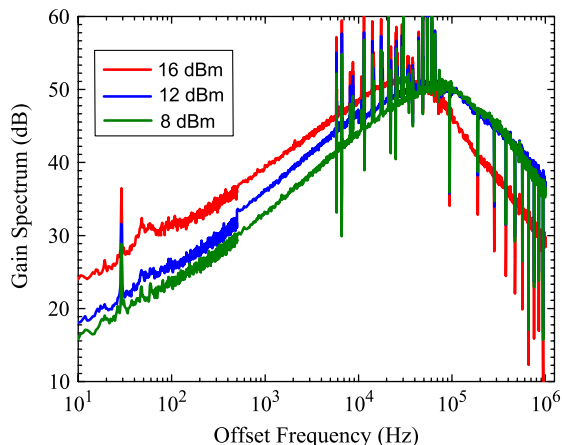
Fig. 4. (Color online) Plots of the Rayleigh backscattered gain spectra from a 6 km spool of single-mode fiber.

Fig. 5. (Color online) Plots of the Rayleigh backscattered spectra from single-mode optical fibers for a 1 mW incident beam.

To determine the fiber-length dependence of the Rayleigh gain spectrum, we applied a fixed 1 mW incident beam to single-mode fiber spools of different length. Figure 5 shows plots of the Rayleigh gain spectrum for 40 m, 500 m, 6 km, and 100 km of single-mode fiber. Our experimental data show that the peak gain varies linearly with fiber length up to 6 km, after which it saturates.

The data suggest that the coherent interaction length of the Rayleigh scattering along the length of the fiber is much shorter than the fiber lengths that we used in our experiments. A coherent interaction would lead to exponential growth as a function of fiber length. From 6 to 100 km, the Rayleigh gain only increases by 5 dB

We attribute the observed saturation to standard (longitudinal) stimulated Brillouin scattering, which clamps the signal power that is available for Rayleigh scattering.

A phenomenological explanation that is consistent with our observed results follows: in an optical fiber, the optical mode has a large transverse intensity gradient that generates large transverse electrostrictive and electroabsorptive forces. These forces induce thermal gradients. Optical intensity fluctuations due to incident laser RIN lead to thermal fluctuations. The dimensions and boundary conditions of the core/cladding system lead to thermal resonances. These thermal resonances lead to density fluctuations that oscillate at frequencies on the order of 50 kHz. Longitudinally traveling light scatters from these resonant guided entropy modes. This behavior is analogous to the scattering of photons from guided acoustic phonons in the case of GAWBS [4]. As with GAWBS, the bandwidth of this GEMRS effect is on the order of 50 kHz.
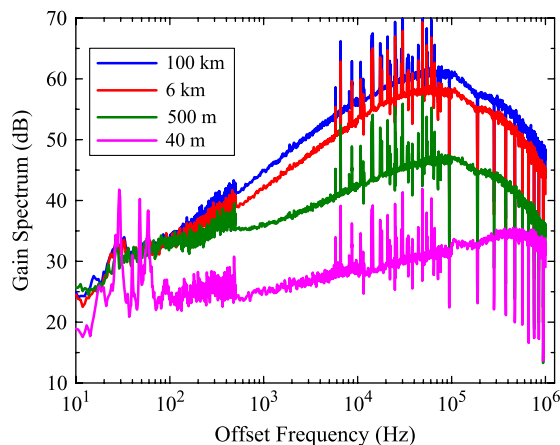
In conclusion, we have measured the backscattered Rayleigh scattering spectrum in optical fibers. Our data show the gain, frequency shift, and bandwidth of the scattering. The bandwidths and frequency shifts that we observed are a factor of 2000 smaller than those observed in bulk silica. Our data suggest that the narrower gain bandwidth and frequency shift that are observed are due to guided entropy modes in the optical fiber.

This effect is fundamental and will be present in any medium in which light is guided so that transverse intensity gradients exist. GEMRS will affect any guided light wave applications in which it is necessary to transmit an optical signal with low noise.

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