Observation of strong stimulated Brillouin scattering in single-mode As_2Se_3 chalcogenide fiber

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Abstract: Strong stimulated Brillouin scattering in single-mode As_2Se_3 chalcogenide fiber is observed using a cw laser at 1.55 μm wavelength region. Brillouin threshold for a 5-m-long fiber is as small as 85 mW. The Brillouin frequency shift ν_B and the gain linewidth $\Delta\nu_B$ are 7.95 GHz and 13.2 MHz, respectively, measured with heterodyne detection and an RF spectrum analyzer. A Brillouin gain coefficient g_B of 6.0×10^{-9} m/W, about 134 times larger than that of fused silica fiber, is obtained for As_2Se_3 single mode fiber from measurements of Brillouin threshold power and the gain linewidth.

OCIS codes: (190.4370) Nonlinear optics, fibers; (290.5900) Scattering, stimulated Brillouin; (060.0060) Fiber optics and optical communications; (060.2400) Fiber properties;

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1. Introduction

When a narrow band laser radiation is propagated through optical fiber, a part of light is seen to scatter in the backward direction when the power exceeds a certain limit [1]. This phenomenon known as stimulated Brillouin scattering (SBS) imposes a limit to the amount of optical power that can be transmitted thorough an optical fiber and has been considered detrimental to optical communication systems and in many nonlinear fiber-optic applications involving cw light. However, the SBS can be useful to amplify a narrow band optical signal by propagating in a direction opposite to the pump, and this has lead applications in many places such as Brillouin amplifiers, lasers, distributed fiber sensors, as well as phase conjugators [2]. Using the intensity-dependent refractive index change associated with SBS process, tunable optical delays via slowing of light has been demonstrated in optical fiber [3], which has drawn considerable attention lately for its potential applications in optical networks. For applications involving SBS, it is desirable to have medium that has large Brillouin gain coefficient, g_B in order to reduce the threshold power and also the device length. Although many crystals and organic materials are reported to have large Brillouin gain coefficients [4], many are difficult to draw in the form of optical fibers. So far a number of non-silica based fibers are successfully drawn into optical fibers, which include tellurite, bismuth and chalcogenide glass fibers. These fibers are reported to have large nonlinear Kerr and Raman gain coefficients, and already found to have potential applications in high-speed optical signal processing [5,6].

The chalcogenide glasses contain S, Se that has transparency beyond 2 μm and nonlinear coefficients over two-three order of magnitudes larger than that of silica glass [6-9]. Within the As-S-Se chalcogenide glass family, As_2Se_3 glass is reported to have 500 times larger nonlinear coefficient n_2 than that of silica [7]. Low loss multimode As_2Se_3 fiber has been fabricated that exhibited large Raman gain coefficients [9,10]. Also optical regeneration in single mode As_2Se_3 fiber is also been demonstrated recently using the large Kerr nonlinearity [11]. Besides, Ogusu et al. estimated the Brillouin gain coefficient in As_2Se_3 glass using the phonon lifetime time and reported a value about 25 times large than that of fused silica [12]. However, to our knowledge so far no experimental observation of Brillouin scattering effect and its characterization in As_2Se_3 optical fiber has been reported.

This paper reports the first observation of SBS in single mode As_2Se_3 chalcogenide fiber in the 1.55 μm wavelength region. Strong SBS is observed from a fiber merely 5 m in length when pumped with a continuous wave (cw) laser with a threshold power of only 85 mW. The Brillouin frequency shift is 7.95 GHz that has a 3-dB linewidth of 13.2 MHz. A Brillouin gain

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coefficient g_B of 6.2×10^{-9} m/W, as much as 134 times larger than fused silica fiber is measured.

2. Experiment

The chalcogenide fiber was drawn at CorActive HighTech Inc. from high-purity material using double-crucible process [13], where the core was made from $As_{39}Se_{61}$ and the cladding from one that had slightly reduced As content [9]. The core diameter of the fiber was 6 μm and the NA was 0.18, which resulted in a V number of 2.2, and allowed the lowest mode to propagate through the fiber in the 1.55 μm wavelength. Because of the large refractive index of ~2.8 in chalcogenide glass, the fibers had large Fresnel reflection (22%), which was suppressed by antireflection coating for operation at 1.55μn. Two pieces of single mode silica fibers, tapered at their ends, were used to couple light into and out from the fiber.

Since the index of chalcogenide glass is relatively large compared to silica, light that did not coupled into the core could partly reached the other end of the fiber. However, by coupling light at the output of AS_2Se_3 fiber using a lensed fiber, it was possible to accurately determine the light that travel in a single mode inside the core. Using a superluminescence laser source, the transmission spectra were measured for two pieces of As_2Se_3 fibers, 2 and 10 m in length, and were used for determining the transmission loss α in the 1360-1660 nm region and also the coupling loss.

The experimental setup used to study the Brillouin scattering in As_2Se_3 fiber is shown in Fig. 1. Light from an external cavity tunable cw laser operating at 1560 nm was amplified and launched into the fiber though am optical circulator, and light that was backscattered from the As_2Se_3 fiber was collected at the port #3 of the circulator and used for diagnosis. The intensity of Stokes component could be measured using an optical spectrum analyzer with a resolution of 0.01 nm. The pump power was gradually changed while the peak of the Stokes component was recorded using the optical spectrum analyzer. From the threshold power we determined the Brillouin gain coefficients using the small-signal steady-state theory of stimulated Brillouin scattering [14, 15].

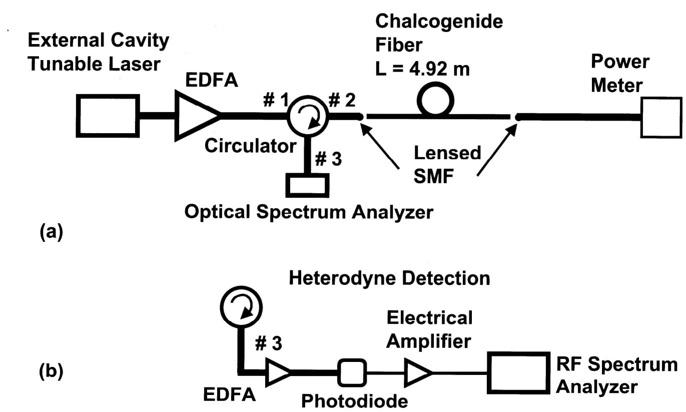

Fig. 1. Experimental setup used for observation of Brillouin Scattering in chalcogenide fiber (a) and linewidth measurement using heterodyne detection (b).

We also performed a heterodyne detection to measure the Brillouin shift with a higher resolution and also the gain linewidth [16]. The backscattered light was amplified using an erbium amplifier and detected using a fast photodiode and broadband electrical amplifier as shown in Fig. 1(b). The Stokes component and a fraction of light pump light reflected in the backward direction from the coupling optics caused optical beating, which could be observed in an RF spectrum analyzer. We could measure the Brillouin gain spectrum with high resolution (300 KHz), which yielded the gain linewidth.

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3. Results

Figure 2 shows the loss per meter versus wavelength, which indicates a loss lower than 1.0 dB/m over a wide wavelength range. The transmission loss at 1.55 μm is about 0.84 dB/m. The coupling loss between single mode fiber (SMF28) and the As_2Se_3 fiber was estimated to be 2.2 dB.

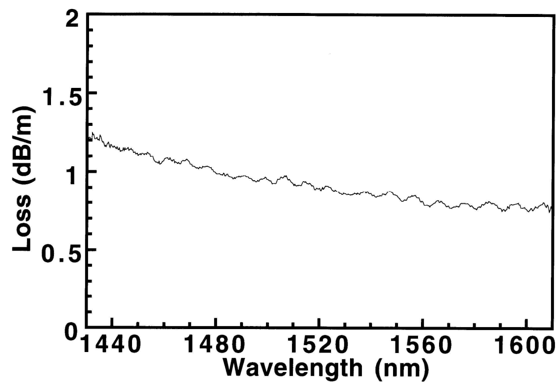

Fig. 2. Transmission loss of single-mode As_2Se_3 chalcogenide fiber.

Figure 3 shows the optical spectra of the back-scattered light from a 4.92-m (effective length L_{eff} is 3.2 m) long fiber observed with pump powers of 60 and 88 mW. A Stokes wavelength component at a separation of 0.06 nm in the longer wavelength side could be seen in the optical spectra. Figure 4 plots the power level of the light back scattered from the fiber as a function of the launched pump power. We could see the Stokes component with pump power as small as 6 mW. Brillouin threshold was observed at a power of 85 mW, when a sharp increase in the Stokes component could be seen.

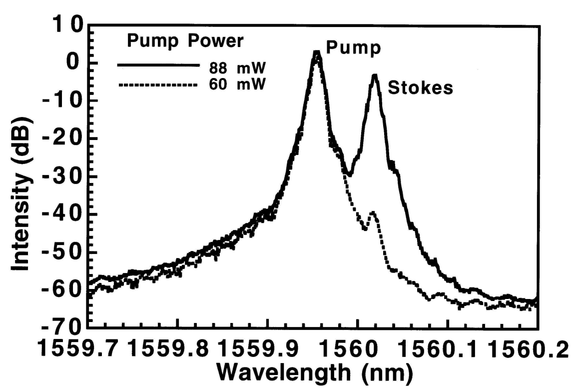

Fig. 3. Optical spectra of output from As_2Se_3 fiber in the backward direction for different pump power level.

According to the small-signal steady-state theory of stimulated Brillouin scattering [14], the pump power P_{th} required to reach Brillouin threshold in a single pass scheme is related to the Brillouin gain coefficient g_{B} by the following equation.

$$g_B K\left(P_{th} / A_{eff}\right) L_{eff} \cong 21 \tag{1}$$

Here P_{th} is power corresponding to the Brillouin threshold, A_{eff} is the effective cross sectional area defined as $A_{eff} = \pi\omega_o^2$ (ω_o is the $1/e^2$-intensity radius of a Gaussian distribution), L_{eff} is the

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effective length defined as $L_{eff} = \alpha^{-1}(1\text{-exp}[-\alpha L])$, and K is a constant that depends on the polarization property of the fiber which is 1 if the polarization is maintained and 0.5 otherwise [17]. Note that with this definition of A_{eff}, the exponential Brillouin gain along a fiber becomes $g_B L_{eff} P/A_{eff}$ (P is the incident pump power). Radius ω_o can be calculated from the core radius a and the V parameter using, $\omega_o \approx a(0.65+1.619/V^{1.5}+2.879/V^6)$ [18]

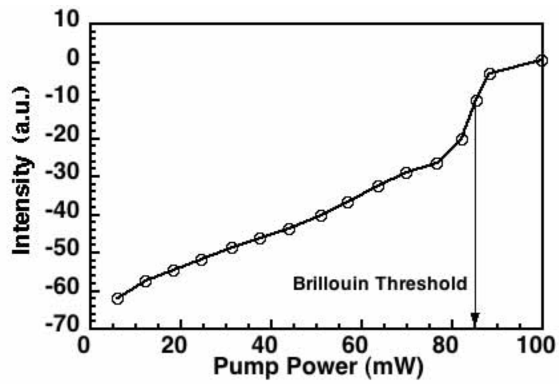

Fig. 4. Power of light backscattered from the 4.9 m long chalcogenide fiber.

Using, P_{th} = 85 mW, A_{eff} = 39 μm^2, L_{eff} = 3.17 m and K = 0.5 in Eq. (1) we obtained the peak Brillouin gain coefficient $g_B = 6.0 \times 10^{-9}$ m/W.

Brillouin shift and linewidth could be observed with a higher resolution from the heterodyne measurement. The RF spectra that resulted from the beating between the pump laser and the Stokes component is shown in Fig. 5. The Brillouin gain spectrum shows a peak at 7.95 GHz (ν_B) and a 3-dB linewidth of Brillouin scattering ($\Delta\nu_B$) of 13.2 MHz.

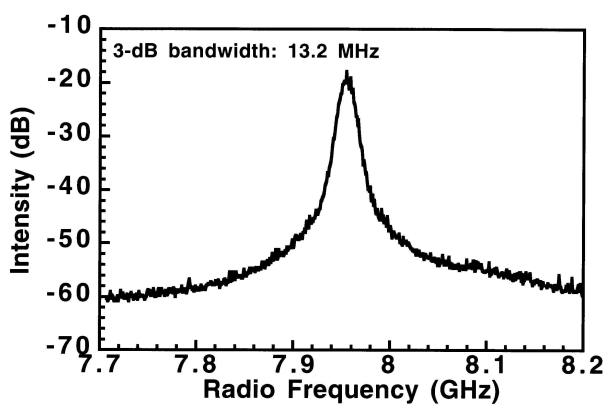

Fig. 5. RF spectrum of the beat signal obtained by heterodyne detection for a pump power of 71 mw.

We also calculated the peak value of Brillouin gain coefficient from the linewidth of Brillouin gain using the following equation [15].

$$g_B = \frac{2\pi n^7 p_{12}{}^2}{c\lambda_P{}^2 \rho v_a \Delta v_B} \tag{2}$$

where n is the refractive index, p_{12} is the longitudinal elastooptic coefficient, c is the velocity of light, λ is the wavelength, ρ is the material density, v_A is the acoustic velocity, $\Delta\nu_B$ is the

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linewidth of spontaneous Brillouin scattering. Using the measured value of $\Delta\nu_B$ = 13.2 MHz, and also the published values of n = 2.81, $\rho = 4.64 \times 10^3$ kg/m^3, v_A= 2250 m/s, p_{12} = 0.266, g_B for As_2Se_3 was determined to be 6.08×10^{-9} m/W.

3. Discussion

The Brillouin gain coefficients measured experimentally using linewidth and threshold of single pass Brillouin scattering are in agreement with each other. The following table compares the Brillouin gain coefficients for As_2Se_3 and silica glass fiber and the parameters that are used to calculate the gain coefficients. As shown in the table the Brillouin gain in As_2Se_3 single mode fiber is about 134 times larger than that of fused silica.

Table 1. Brillouin shift, linewidth and gain coefficients of As_2Se_3 and fused silica at 1.56 μm

Material	n	ρ (kg/m^3)	v_A (m/s)	p_{12}	$\Delta\nu_B$ (MHz)	ν_B (GHz)	g_B (m/W)
As_2Se_3	2.808[a]	4640[b]	2250[b]	0.266[c]	13.2[d]	7.95[d]	6.08×10^{-9}
Fused silica	1.45	2200[b]	5960[b]	0.286[e]	16[f]	11.1[g]	4.52×10^{-11}

[a] Refractive index data supplied by the manufacturer.

[b] Ref .19.

[c] Ref. 20.

[d] Measured in this work.

[e] Ref. 21.

[f] Calculated for 1.56 μm pump wavelength using data from Ref. 15.

[g] Ref. 2

It is worth comparing the experimental value of g_B with that estimated recently by Ogusu et al. for bulk As_2Se_3 glass in Ref. 12. They calculated the Brillouin gain coefficient from phonon lifetime T_B, which was estimated from the attenuation coefficient α_A reported for acoustic wave at 200 MHz for bulk As_2Se_3 [20] and the acoustic velocity v_A [19]. As the experimental data α_A of acoustic waves in the 11 GHz range was not available, it was approximated from α_A measured at 200 MHz through an extrapolation made under the assumption that $\alpha_A \propto v_B^2$. They obtained a g_B in bulk As_2Se_3 that was 25 times larger than that of bulk silica.

We can think of several possible sources that might have caused this discrepancy between the estimated g_B for bulk As_2Se_3, and experimentally determined g_B for single mode As_2Se_3 fiber, which include differences in the exact guided nature of optical modes (transverse distribution of the electric field) and damping time of acoustic waves between bulk sample and cylindrical optical waveguide [2, 22], exact composition (e.g. $As_{39}Se_{61}$ in the core of the fiber we used) of the core and clad, the purity of material, and also any possible deviation in the estimation of attenuation coefficient for higher acoustic frequency using $\alpha_A \propto v_B^2$. For example the g_B estimated for fused silica (2.24×10^{-11} m/W) in Ref. 12 from α_A is about half of what measured in fused silica fiber [1]. Also equation 2 is derived under the assumption of no reflections from the Brillouin fiber. However, there can exist some weak feedback due to residual reflections from the fiber ends despite the ends being antireflection coated, which might effect the threshold power measurements [23] and the calculated value of the gain coefficient. These effects are currently under investigation.

4. Summary

In conclusion, we report our observation of a strong SBS from As_2Se_3 single mode optical fiber. The threshold power for single Brillouin scattering from a 4.92 m long fiber was about 80 mW. The Brillouin shift was measured to be 7.95 GHz, which has a bandwidth of 13.2 MHz. A Brillouin gain coefficient of 6.0×10^{-9} m/W, about 134 times larger than that of fused silica fiber, was obtained from both the gain linewidth and Brillouin threshold measurements.

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