

Cancellation of Intensity Noise caused by Stimulated Brillouin Scattering in an Optical Fiber Transmission System

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Abstract: The primary source of broadband intensity noise on an SBS-degraded optical signal is found to be deterministic and depend on the imaginary part of the Brillouin loss spectrum. The noise is reduced by subsequent transmission through a Brillouin amplifier.

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1. Introduction

It is well known that the onset of stimulated Brillouin scattering (SBS) in an optical fiber transmission system leads to saturation of the average transmitted power and a dramatic increase in the relative intensity noise of the transmitted signal [1,2]. The source of the broadband intensity noise of the transmitted light has been attributed to a variety of sources: beating of the pump light with the anti-Stokes wave [2], filtering of the noise from thermally generated acoustic phonons [3], and a nonlinear phase shift at the optical carrier frequency due to asymmetry of the Brillouin gain spectrum [4]. A strong similarity was observed between the SBS-induced intensity noise spectrum (at frequencies greater than 50 MHz) and the intensity noise spectrum generated in a delayed self-homodyne measurement [5]. Because the delayed self-homodyne measurement simply mixes an optical signal with a time-delayed version of itself, it suggests that the broadband intensity noise induced by SBS is caused not by a random process in the SBS but rather a deterministic effect. Here we show experimentally that the primary source of the broadband intensity noise is filtering of the transmitted optical spectrum by the imaginary part of the Brillouin loss spectrum. The phase noise of the optical source is converted to intensity noise by the frequency-dependent nonlinear refractive index associated with the Brillouin loss (i.e., the imaginary part of the loss). We test this by passing the SBS-degraded signal that has large relative intensity noise through an optical system with a transfer function of the opposite sign: a fiber Brillouin amplifier. The intensity noise at the output depends strongly on the gain and frequency tuning of the amplifier. The tuning dependence suggests that the group delay, not the value of the nonlinear phase, at the optical carrier frequency determines the relative intensity noise power.

2. Theory

Broadband intensity noise is observed in a transmitted optical signal that undergoes stimulated Brillouin scattering. In the presence of an optical pump, SBS gain appears at the Stokes frequency. As the Stokes power becomes significant, SBS loss appears at the pump frequency. The spectrum is shown schematically in Figure 1. The SBS gain (loss) bandwidth is less than 50 MHz in standard single-mode fiber, and can lead to selective amplification or attenuation of an optical spectrum. The narrowband SBS optical loss has been used to suppress the optical carrier and thereby enhance the effective modulation depth of optically carried microwave signals [6-8].

Also shown in Figure 1 is the narrowband nonlinear refractive index (nonlinear phase) associated with the gain (loss) spectrum, which has been verified experimentally [9]. If modulation sidebands are outside the SBS bandwidth and the signal frequency tuned appropriately, the phase of the optical carrier can be changed relative to the sidebands. This has been used to counteract the effect of chromatic dispersion in an optical microwave link [6].

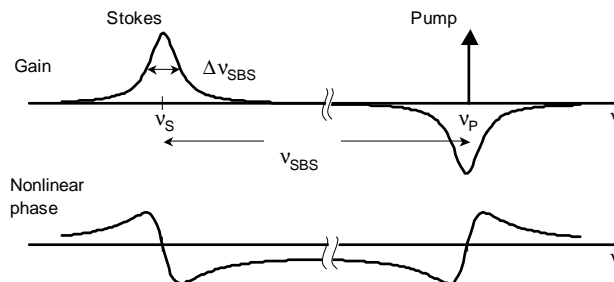


Fig. 1. Real and imaginary part of the SBS gain and loss spectrum. The imaginary part of the gain adds a frequency-dependent nonlinear phase to the signal. The optical spectrum of the pump typically has finite spectral width due to modulation, phase noise, and intensity noise.

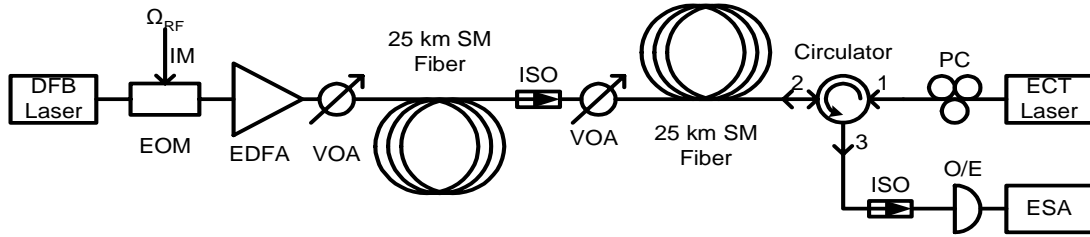


Fig. 2. Experimental set-up. The source is a 1550-nm DFB laser with measured linewidth of about 10 MHz. The first 25 km of standard single-mode fiber is Stage 1, where the input signal acts as a pump for SBS generation. For the SM fiber, the SBS gain linewidth was measured as $\Delta\nu_{\text{SBS}} = 35$ MHz and Brillouin shift as $\nu_{\text{SBS}} = 10.87$ GHz. The second 25-km length of fiber is Stage 2, a fiber Brillouin amplifier reverse-pumped by an external cavity tunable (ECT) laser. At Port 3 of the circulator, the spectrum of the output intensity is resolved on an electrical spectrum analyzer (ESA). EOM is an electro-optic modulator, VOA is variable optical attenuator, PC is polarization controller, and ISO is optical isolator.

The primary source of increased broadband intensity noise in the transmitted pump appears to be spectral modification of the pump optical spectrum by the nonlinear phase associated with the SBS loss spectrum. The frequency-dependent nonlinear phase shift converts the phase noise of the laser source to intensity noise. If the signal is passed through an optical system with the opposite transfer function, the SBS-induced intensity noise should be canceled. We test this by passing the SBS-degraded signal through a tunable fiber Brillouin amplifier.

3. Experiment and Discussion

Figure 2 shows the experimental setup to measure the intensity noise at the output of a fiber transmission system. The first stage is 25 km of standard single-mode fiber and the source is a DFB laser with linewidth approximately equal to 10 MHz. The SBS threshold power is approximately 9 dBm. The second stage, the Brillouin amplifier, is isolated from the first stage and is reverse-pumped by a tunable laser. Figure 3 shows the intensity noise spectrum in the presence of SBS loss (1), SBS gain (2), and cascaded gain and loss (3). In the presence of either SBS amplification or SBS loss, the intensity noise is much higher than when no SBS loss or amplification is present (4). The latter is measured by launching 8 dBm into the 50 km length of fiber and turning off the amplifier pump of Stage 2. The results show that the SBS-induced intensity noise cannot arise from selective power change of the optical carrier. If this were the primary mechanism, enhancement of the optical carrier relative to the sidebands in the case of SBS gain would reduce the intensity noise. The opposite is observed. The difference between enhancement and suppression of the optical carrier could, however, explain the difference in the relative intensity noise power between traces 1 and 2 in Figure 3. A second important observation is that the noise for the cascaded system (Stage 1 followed by Stage 2, gain = loss) is lower than for either stage alone. If the SBS processes in the two stages generate uncorrelated random fluctuations, the noise power of the cascaded system should be the sum of the two. Instead the noise is less than for either gain or loss alone. Therefore, the primary contributor to the intensity noise must be a deterministic effect of the stimulated Brillouin scattering.

The reduction of the intensity noise by Brillouin amplification was further studied to determine the dependence

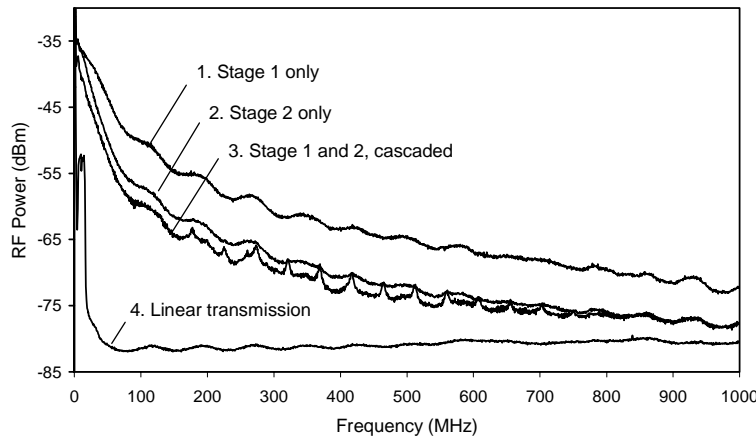


Fig. 3. Intensity noise spectra of output. Trace 1 is the noise after transmission through Stage 1 with average power input of 14 dBm (nonlinear loss = 4 dB). Trace 2 is the noise when Stage 1 is bypassed and the signal is amplified through the fiber Brillouin amplifier (nonlinear gain = 4 dB). Trace 3 is the noise when Stage 1 and Stage 2 are cascaded. Trace 4 shows the intensity noise when the signal is transmitted through 50 km at low power and there is no measurable SBS gain or loss (launch average power is 8 dBm). For all spectra the received average optical power is -5 dBm.

on average gain and frequency tuning of the Brillouin amplifier. For this, the intensity of the input laser is modulated with an RF tone at 300 MHz and the output signal-to-noise ratio (SNR) measured. This normalizes out any improvement due to relative gain of the optical carrier. Figure 4 shows the SNR of the cascaded system as a function of the power and optical frequency of the pump of the Brillouin amplifier. The average optical power input to Stage 1 is constant at 14 dBm, yielding an SBS loss of 4.0 dB, and the SNR with no amplification (pump off) is 89 dB (referred to 1-Hz bandwidth). In Fig. 4(a), the frequency of the tunable laser is constant at the value that maximizes the average power gain of the signal. As the pump power and Brillouin gain increase, the SNR improves to a maximum of about 95 dB at 3.1 dB Brillouin gain (compare to 4.0 nonlinear loss of Stage 1). Above this, the SNR decreases and becomes worse than the baseline SNR (dashed line) when the Brillouin gain is greater than 6 dB.

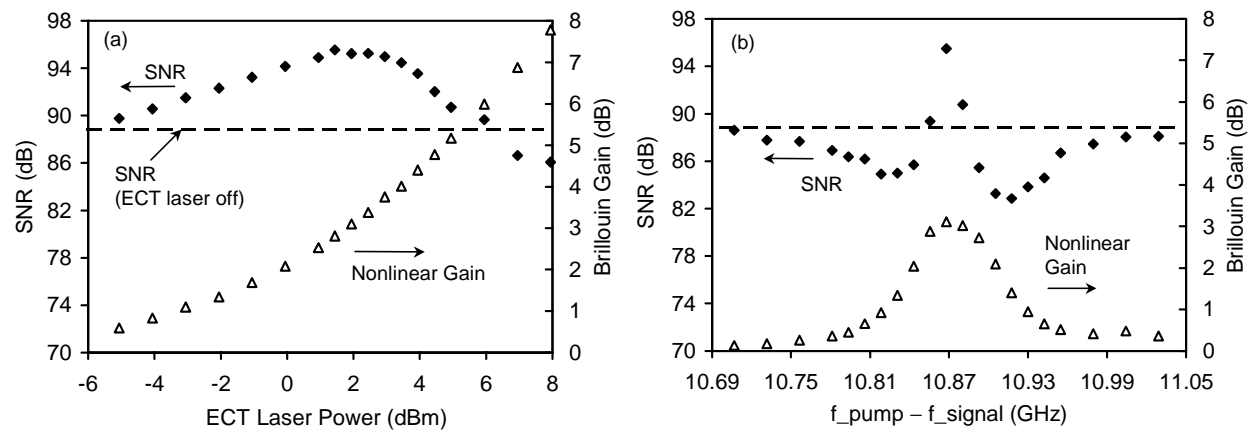


Fig. 4. Signal-to-noise ratio (1-Hz bandwidth) of RF tone at 300 MHz and modulation depth 1.8% in cascaded system. a) Versus amplifier pump power at port 2 of circulator in Figure 2. The wavelength of the pump is set to maximize the average power gain of the signal. b) Versus frequency difference between signal and ECT pump laser (pump power at Port 2 is 2 dBm). The Brillouin gain of the Brillouin amplifier is shown on the right scale.

Figure 4(b) shows the effect of tuning the pump frequency (the pump power is constant, 2 dBm). The improvement appears to be greatest when the gain peak is centered on the signal frequency, zero when it is detuned 15 MHz, and degrades the worst at ± 45 MHz detuning. The contrast between the tuning dependence of the signal gain and the SNR shows that the improvement in SNR does not depend on the real part of the SBS gain. It correlates closely, however, to the slope of the nonlinear phase (group delay) of the cascaded system, at the carrier frequency. This contrasts with previously published theory in which the authors attribute the relative intensity noise to the value of the nonlinear phase at the signal carrier frequency [4].

We have shown that amplification by a Brillouin amplifier can improve the SNR of an SBS-degraded signal by more than 6 dB. The improvement depends on both the magnitude of the gain and—more critically—the detuning of the gain peak from the optical carrier frequency. The relevant parameter is the net group delay at the signal carrier frequency. These results have important consequences for understanding systems that suffer signal degradation by stimulated Brillouin scattering or use SBS for signal processing.

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