Broad-Band Transmitted Intensity Noise Induced by Stokes and Anti-Stokes Brillouin Scattering in Single-Mode Fibers

M. Horowitz, A. R. Chraplyvy, R. W. Tkach, and J. L. Zyskind

Abstract—**We experimentally investigate the optical noise induced by stimulated Brillouin scattering (SBS) in single-mode fibers. The noise, which is caused by the random nature of spontaneous Brillouin scattering, is induced in the transmitted wave as well as in the backward Brillouin wave. In fibers where the Brillouin gain spectra consist of several resonances, the induced intensity noise of the transmitted wave has a wide spectrum and it may be the dominant noise in the receiver for a broad radio frequency band (0–1 GHz). This unexpected result is explained by a multiple scattering process which is caused by stimulated and by thermally excited phonons. The SBS induced noise may cause a performance degradation in analog optical systems which require high optical powers and low noise. Using fibers with a single Brillouin resonance may limit the noise to lower frequencies.**

Index Terms—**Brillouin scattering, noise induced in fibers, nonlinear optics, optical links, analog optical systems.**

STIMULATED Brillouin scattering (SBS) is one of the dominant nonlinear effects which limit the performance of lightwave systems using single-mode fibers [1]. Due to its low threshold and its narrow gain bandwidth, the effect of SBS was considered as a power dependent loss mechanism [2], which limits the injected power. In previous work, the statistics of the intensity fluctuation of the backward propagating Brillouin wave in fibers with a single Brillouin resonance was measured and analyzed [3], [4] using a model which includes the initiation of the Brillouin scattering from a noisy spontaneous scattering. The noisy Brillouin wave also induces noise in the transmitted wave due to the depletion of the pump wave (which transfers part of its power to the Brillouin wave). A numerical integration of the equations which are used to model the SBS as well as the experimental results indicate that the bandwidth of such noise in the transmitted wave is two orders of magnitude narrower than that of the backward Brillouin wave because the transmitted noise is integrated along the fiber and therefore the high frequency components are averaged and attenuated. However, in [5], noise which causes a decrease of the carrier to noise ratio of an amplitude modulated vestigial sideband signal due to SBS was observed at a relatively high frequency (≈67 MHz).

In this work, we shall experimentally analyze the noise spectrum which is induced by Brillouin scattering in the transmitted wave and its dependence on fiber-type. We will show that this baseband noise may contain strong frequency components up to about 1 GHz and therefore it may impair the performance of analog optical systems. The SBS induced noise is especially important in optical systems which use fibers with complicated Brillouin gain spectra, consisting of several resonances. In previous work [6] it was shown that in such fibers the R.F. spectra of the beating between the backward Brillouin wave and the Rayleigh backscattered pump consists of several peaks. In this work we show that similar peaks may also be observed in the baseband of the RF spectrum of the transmitted wave (as well as in the baseband of the backward Brillouin wave). This coupling between the two counterpropagating waves (the transmitted and the backward Brillouin wave) which forms the peaks in the transmitted wave spectrum is unexpected because the frequency difference between the Brillouin resonances is much higher than the inverse of the main time constants of the Brillouin scattering. The new phenomenon is explained by a double scattering process which is based on both stimulated and thermally excited phonons. The use of fibers with a single Brillouin resonance in optical systems may improve the system performance.

The experimental setup for measuring the SBS induced noise is similar to the configuration in [6]. An erbium-doped fiber laser operating at a wavelength of 1.533 μm injected a maximum power of about 18 mW into the input end of the test fiber. The intensity spectra of the transmitted and backward Brillouin wave were measured using an R.F. spectrum analyzer. In the experiment we have used two types of fibers: a) 30-km-long silica core fiber with a SBS threshold of about 4.3 mW; b) 25-km-long dispersion-shifted fiber with a SBS threshold of about 3.8 mW. Fig. 1 shows the intensity noise spectrum of the backscattered Brillouin wave for the two fibers. The pump power was about 12 mW for the silica fiber and about 9 mW for the dispersion-shifted fiber. The spectra of the transmitted and of the backscattered Brillouin wave were highly dependent on the input power although the power dependence of the two counterpropagating noises was different. The RF spectrum of the backward propagating wave may be divided into two main regimes (around 0 Hz and and around 11 GHz). The peaks around 11 GHz stem from the

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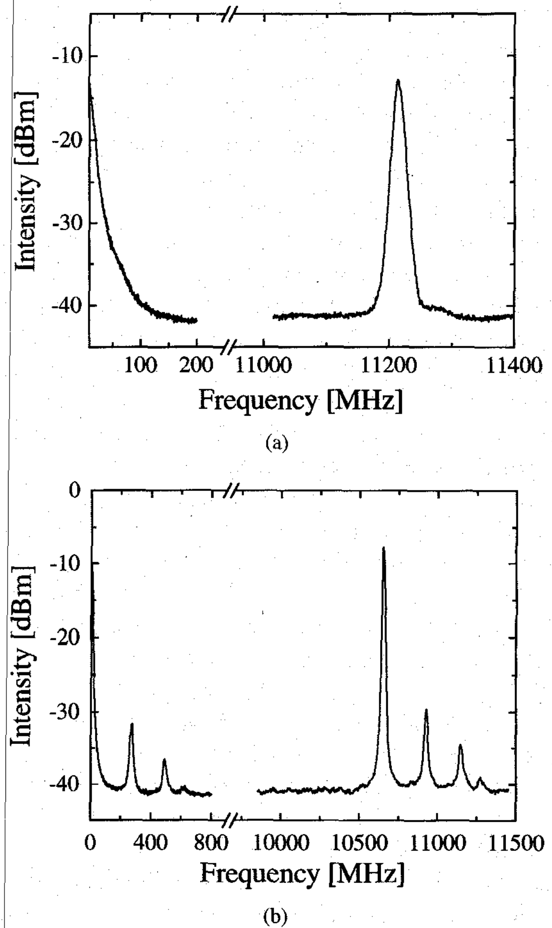

Fig. 1. RF spectrum of the intensity noise of the backscattered Brillouin wave for (a) a silica-core fiber and (b) for a dispersion-shifted fiber. The injected power was 12 mW for the silica-core fiber and 9 mW for the dispersion-shifted fiber.

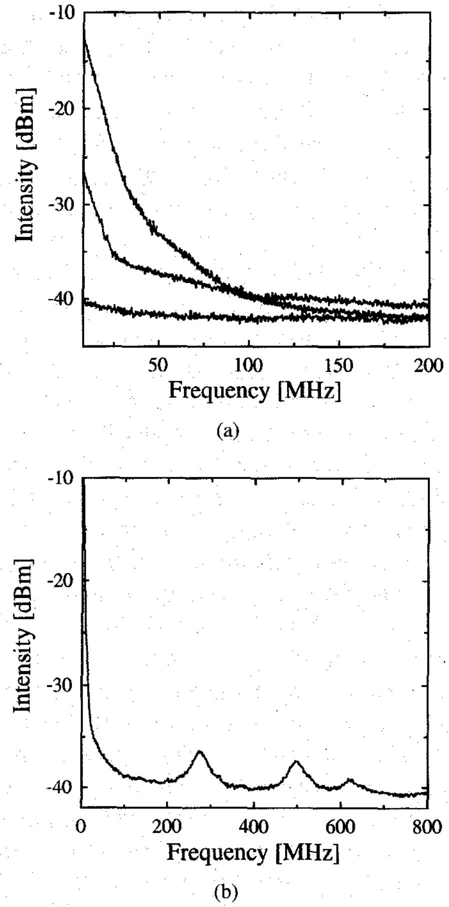

Fig. 2. Intensity noise of the transmitted wave for (a) a silica-core fiber and (b) for a dispersion-shifted fiber. The injected power is as in Fig. 1. For comparison, two curves were added to Fig. 2(a): the intensity noise spectrum in the baseband regime of the backward Brillouin wave (uppermost curve), and the thermal noise of the receiver (lowest curve).

interference of the Rayleigh backscattered pump wave and the Brillouin wave while the peaks at baseband are caused by the fluctuation of the Brillouin wave intensity (or the beating of the Brillouin wave with itself). In order to increase the sensitivity in the high-frequency regime of the spectrum (around 11 GHz) we have used heterodyne detection (the local oscillator was provided by a reflection from a mirror that was attached to the open end of the input coupler). The Brillouin gain spectrum for the silica fiber has a single resonance (as can be observed from the high-frequency regime of the spectrum) while the gain spectrum for the dispersion-shifted fiber consists of four different resonances due to the complex transverse structure of the fiber doping [6]. The complex Brillouin gain spectrum of the dispersion shifted fiber also causes the formation of four peaks in the lower frequency regime of the spectrum (baseband) (at about 0, 270, 490, and 620 MHz). The center frequencies of these peaks are equal to the difference between the frequencies of the Brillouin resonances, and the lineshapes are given by the cross correlation between the spectra of the Brillouin components.

Fig. 2 shows the baseband regime of the RF spectrum of the transmitted wave for the two tested fibers. The measured bandwidth (which is defined as the 3-dB cutoff frequency) of the noise in the transmitted wave is much narrower than that of the backward Brillouin wave. For example, by measuring the time dependence of the intensity for the silica-core fiber (with a detector and a sampling scope) we found that the transmitted noise bandwidth was approximately 90 kHz (while the bandwidth of the spontaneous backscattered Brillouin wave was about 21 MHz.) Noise with much higher frequency components could also be observed in the transmitted wave spectra. However, only the lowest frequency components in the transmitted wave are caused by the time dependent depletion of the pump wave due to stimulated phonons. The Brillouin wave may induce local noise in the transmitted wave with high-frequency components (as in the backward Brillouin wave) however because this noise is integrated along most of the fiber length the high-frequency components are averaged and attenuated. This result can be verified by solving numerically the equations which are used to model the Brillouin scattering or by comparing the measured bandwidth with an estimation of the effective integration time of the noise along the fiber. The pump depletion occurs mainly close to the input end of the fiber (where the intensity of the Brillouin wave is high), and therefore the effective integration length is much smaller than actual fiber length. The effective length can be estimated (under the undepleted pump approximation) as the inverse of the Brillouin gain coefficient (which depends on the pump power). For example, close to the Brillouin threshold the effective length is only about 1.5 km and therefore the integration of the transmitted noise will add an equivalent low pass filter with a cutoff frequency of about $c/ln \approx 10^5$ Hz (c is the velocity of the light, n is the refractive index and l is the effective fiber length). This result qualitatively fits our bandwidth measurements of the forward propagating noise for the silica-fiber (≈90 K/Hz). However, when the input power was greater than the Brillouin threshold, a different noise with much higher frequency components could also be observed (Fig. 2) for the silica fiber and particularly for the dispersion shifted fiber. Moreover, peaks that are similar to those measured in the baseband spectrum of the backscattered Brillouin wave could be observed in the baseband of the transmitted wave spectrum for the dispersion shifted fiber. The peaks in the transmitted wave cannot be explained by an interference between the Rayleigh scattered components of the Brillouin waves because even the beating between the strong transmitted pump and the Rayleigh scattered Brillouin wave gives only two peaks (around 10.6 GHz) and the power of the weaker peak is only 7 dB above the noise floor in our measurements. Moreover, the peaks in the transmitted wave spectrum can not be explained by the time dependent depletion of the pump wave because the frequency of those peaks is much higher than the cutoff frequency of the depletion process ($\approx 10^5$ Hz).

The multiple peaks in the baseband regime of the transmitted wave are caused by photons which were scattered from two phonons with different acoustic velocities. In fibers with a multiple-peaked Brillouin gain spectrum the phonons have a spectrum of acoustic velocities. Thus, photons which are backscattered by phonons with a specific acoustic frequency can be scattered again from phonons with a different frequency. The photons that generate the intensity noise are those that were formed by the stimulated Stokes scattering and were scattered again due to an anti-Stokes scattering (the optical frequency of the photons is increased by the second scattering event). After the two scattering events the photons propagate in the same direction as the pump wave (each of the scattering events invert the propagation direction of the photons) and their optical frequency is close to that of the pump. Although the number of such photons is small they can generate a significant noise in the receiver by interfering with the strong pump wave (as in coherent detection). The frequency of the induced noise will be equal to the difference between the acoustic frequencies of the two scattering phonons. In such a process, a phase mismatch exists and decreases the efficiency of the scattering; however, due to the relatively small effective interaction length and due to the noisy nature of the spontaneous anti-Stokes Brillouin scattering which is caused by phonons which are thermally excited, the effect of the phase mismatch is decreased. This multiple scattering process also couples the backward noise to the transmitted wave and hence increases the noise bandwidth in fibers with a single Brillouin resonance.

Our analysis is based on a mathematical model which will be published elsewhere; However, we can estimate the efficiency of such a multiple scattering process based on the measurements in [7], which indicate that the intensity ratio between the Rayleigh scattered wave and the two spontaneous Brillouin lines (Stokes and anti-Stokes) is approximately 13 dB in a bulk of fused quartz. From our measurements of the Brillouin gain spectra for the dispersion shifted fiber we can estimate that power ratio between the spontaneous scattering of the two strongest Brillouin lines is approximately 20 dB (the frequency difference between the two lines is approximately 270 MHz and the power of the main peak of the backward propagating Brillouin wave is about 4 dBm). Assuming that the intensity of the Rayleigh scattered wave is approximately 35 dB below the input intensity of the incident wave we can estimate that the optical power of the forward propagating noise peak whose optical frequency is lower by 270 MHz compared to that of the pump is approximately -63 dBm. Therefore, the optical power of the beating between this noise peak and the transmitted wave (with power of about 6 dBm) should be approximately -29 dBm. Such powers can be easily measured by our R.F. spectrum analyzer (the noise floor in our experiment can be estimated as -40 dBm). We note that forward light scattering by thermally excited guided acoustic wave was investigated by Shelby *et al.* [8]. However, such scattering does not depend on the optical power and it causes phase and polarization noises rather than intensity noise which was measured in our experiments and was formed by longitudinal phonons.

The noise induced in the forward direction can impair the performance of some optical systems. In our experiment, the equivalent input noise current of the receiver was about 24 pA/Hz$^{1/2}$. When the injected power to the dispersion-shifted fiber was about 9 mW the magnitude of SBS induced noise was about 4 dB stronger than that of the shot noise at 40 MHz and about 5 dB stronger at 272 MHz. Moreover, by using a more sensitive receiver we observed a significant increase of the noise floor of the receiver around 270 MHz for pump power as low as 6 mW.

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