Narrow Spectral Response of a Brillouin Amplifier

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We investigate the spectral response of a Brillouin amplifier in the frequency regime within the SBS bandwidth. This is done by amplitude modulating the pump with a low frequency, and therefore, unlike previous studies, the spectrum of the modulated pump is, in all cases, smaller than the SBS bandwidth. We show both theoretically and experimentally that unlike phase modulation, which was reported in the literature, the amplitude modulation increases the Brillouin amplifier gain, and that this effect has a very narrow bandwidth. Only modulation frequencies that are lower than a certain cut-off frequency increase the gain. This cut-off frequency is inversely proportional to the fiber’s length, and can therefore be arbitrarily small.

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In long-distance optical communications in fibers the first nonlinear effect to appear is stimulated Brillouin scattering (SBS). Many investigations over the past decade have studied the influence of SBS on data transmission, either to evaluate the induced degradation of the optical signal or to utilize it for optical processing [1–4]. Clearly, the optical signal quality may be severely deteriorated due to SBS, since the signal experiences significant depletion over long distances. However, only a portion of the signal’s spectrum is depleted. It is well known, that depletion over long distances. However, only a portion of the signal’s spectrum is depleted. It is well known, that the Brillouin process is characterized by a finite spectral width, $\Gamma_B$, which is related to the phonon lifetime in the material (in glass fibers, for example, $\Gamma_B/2\pi \approx 20\text{GHz}$). Hence, every spectral component beyond the Brillouin spectral width will not take part in the Brillouin process, and will not be depleted.

Due to the practical importance of Brillouin scattering in long distance fiber communications, and its negative effect on the transmitted optical signal, most of the studies investigated the possibility of suppressing SBS. It was determined that SBS could be almost entirely suppressed by modulating the incident optical signal with a frequency that exceeds tens of MHz [5,6]. Due to the spectral width of the SBS, this is not a surprising finding.

Other works [7,8], which investigated the temporal response to lower frequencies, usually employed square-wave modulation (having a fast rise time), so that the lower portion of the spectrum did not receive enough attention. There were however, some indications [9] that the Brillouin amplifier can react in a non-trivial manner to modulation frequencies, which are considerably lower than the SBS’s spectral width. Eskildsen and co-workers [9] showed that SBS can be substantially suppressed by directly modulating a DFB laser with a frequency as low as 5kHz. However, in their experiment, the external low frequency modulation caused an extremely large (much larger than the SBS spectral width) wavelength dithering, i.e., a much larger broadening.

In this paper we investigate the spectral response of the Brillouin amplifier to modulation frequencies lower than the SBS bandwidth. This is done by amplitude modulating the pump with a low frequency, and therefore, unlike previous work [5,6,9], the spectrum of the modulated pump is, in all cases, smaller than the SBS bandwidth. We show both theoretically and experimentally that unlike phase modulation, which was reported in the literature, the amplitude modulation increases the Brillouin amplifier gain, and that this effect has a very narrow bandwidth. Only modulation frequencies, which are lower than a certain cut-off frequency increases the gain. This cut-off frequency value $f_c = c/(2nL)$, which depends only on the fiber’s length ($L$) and can be much smaller than the Brillouin spectral width.

In the slowly varying amplitude approximation [10]

$$\frac{\partial A_2}{\partial z} + \frac{1}{c/n} \frac{\partial A_2}{\partial t} = \frac{i\omega\gamma_e}{2nc\rho_0} \rho^* A_1$$

(1)

where

$A_1$and $A_2$ are the Stokes and pump amplitudes respectively, $n$ is the refractive index, and

$$\rho(z,t) = \frac{\gamma_e q^2 A_1 A_2^*}{4\pi \Omega_B \Gamma_B}$$

(2)

is the material density distribution, where $\gamma_e$ is the electrostrictive constant, $\Gamma_B$ and $\Omega_B$ are the Brillouin linewidth and frequency respectively, $q$ is the acoustic wave number, and $\omega$ is the optical angular frequency.

Eq.(1) can be rewritten in terms of the intensities [10]

$$\frac{\partial I_2}{\partial z} + \frac{1}{c/n} \frac{\partial I_2}{\partial t} = g_0 I_1(z,t) I_2$$

(3)

where the line center gain factor is

$$g_0 \equiv \frac{\omega^2\gamma_e^2}{2ncv\rho_0 \Gamma_B}$$

(4)

$v$ is the acoustic velocity and $\rho_0$ is the mean density of the medium.
In the non-depleted pump approximation we can describe the modulated pump as

\[ I_1(z,t) = I_1(L) \{ 1 + \cos [2\pi f (zn/c + t)] \} \]  \hspace{1cm} (5)

and then the solution to eq.3 for the amplified Stokes will satisfy

\[
\ln[I_2(z,t)] \propto C_1 \sin [2\pi f (zn/c + t)] + C_2 \sin [2\pi f (zn/c - t)] + C_3 \cos [2\pi f (zn/c - t)] + C_4 (zn/c + t) + C_5 (zn/c - t)
\]  \hspace{1cm} (6)

(the first and the fourth terms correspond to the specific solution while the other terms correspond to the homogenous ones), where due to the boundary condition \[ I_2(z = 0) = I_2(0) \], \( C_2 = C_1, C_3 = 0 \) and \( C_4 = C_5 \), and the final solution at \( z = L \) is

\[ I_2(L) = I_2(0) \exp \left\{ G \left[ 1 + \cos (2\pi f t) \frac{\sin (2\pi f nL/c)}{2\pi f nL/c} \right] \right\} \]  \hspace{1cm} (7)

where \( G \equiv g_0 I_1(0) L \) (in our experiment \( G \approx 1 \)).

This solution oscillates in time. The difference between the maximum and minimum intensities corresponding to the oscillatory portion of the signal is

\[ \Delta I_2 = 2I_2(0) \exp (G) \sinh \left[ G \frac{\sin (\pi f / f_c)}{\pi f / f_c} \right] \]  \hspace{1cm} (8)

where

\[ f_c \equiv c/2nL \]  \hspace{1cm} (9)

is the cut-off frequency (the first frequency where \( \Delta I_2 = 0 \)).

This solution suggests that the Brillouin effect in the fiber reacts to frequencies, which depend solely on the fiber’s length. For long fibers, these frequencies can be considerably smaller than the Brillouin spectral width.

It should be noted, that this effect is not necessarily specific to the Brillouin process. Other nonlinear, distributed optical amplifiers, when pumped by an amplitude-modulated beam, will present a similar spectral response. The reasoning behind this is as follows. Since the amplification is a nonlinear function of the pump intensity, the impact of the temporal maxima and minima of the modulated pump do not cancel each other; the maxima have an excess gain (their gain increase is larger than the gain decrease at the minima), and therefore the Stokes beam experiences a net increase in gain. However, when the fiber length is larger than the modulation wavelength the effective gain averaged over the spatial maxima and minima converges to the unmodulated gain value.

The experimental set-up is shown in Fig. 1. Light from a narrow-band (∼200kHz) laser (NetTest Tunics Plus) at 1550nm is split by a coupler. A portion is amplified by an EDFA and sent into Fiber 1, to generate a Brillouin Stokes beam with a bandwidth of about 30Mhz, which is then guided into Fiber 2 as the seed for the Brillouin amplifier. The other portion is also amplified and then modulated by a LiNbO3 electro-optic modulator, before being sent into the other side of Fiber 2, to act as the pump for the Brillouin amplifier. The amplified Stokes exits through the circulator.

We investigated two different lengths of single-mode fiber for the Brillouin amplifier: ∼1km and ∼2km. In both cases, the pump power entering Fiber 2 was approximately 10mW, and the Stokes power was about three orders of magnitude lower. The amplified Stokes consisted of an amplified dc component as well as an ac component due to the presence of the modulated pump. We measured the peak-to-peak amplitude of the amplified Stokes as a function of the modulation frequency. The experi-
mental results and theoretical prediction are shown in Figs. 2 and 3.

![Image of graph showing frequency response of the AC part of the amplified Stokes signal, where Fiber2 was 2km long.](image)

**FIG. 3.** The frequency response of the AC part of the amplified Stokes signal, where Fiber2 was 2km long.

For the 1km amplifier, the cut-off frequency is 100 kHz, and for the 2km amplifier it is 50kHz, in perfect agreement with theory.

In general, where the pump in eq.5 has a general form $I_1(z,t)$ it can always be separated into its Fourier components $I_1(z,t) = I_1(L) \int df \alpha_f [2\pi f (zn/c + t)].$ Clearly, a generalization of 6 will still be valid, and, as a consequence, only the low frequencies components will contribute to the amplification. We therefore conclude that the Brillouin amplifier can behave like a narrow band amplifier, whose cut-off frequency is inversely proportional to its length, and can be considerably narrower than the Brillouin spectral width.

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