Effective Brillouin Gain Spectra Broadening for SBS Suppression Based on Pseudo Random Bit Sequence Phase Modulation in Fiber System

Binglin Li, Meizhong Liu, Yifeng Yang, Yuqiao Xian, Bing He, and Jun Zhou

***Abstract*—We describe stimulated Brillouin scattering process in a fiber system with light field phase modulated by lowpass filtered and amplified pseudo random bit sequence (PRBS) using localized nonfluctuating source model. The effective Brillouin gain spectra and the ratio of normalized Stimulated Brillouin Scattering (SBS) threshold to RMS optical linewidth is used to characterize the SBS suppression capability of the PRBS phase modulation. The normalized effective Brillouin gain spectra for different modulation parameters are calculated to exhibit the Brillouin gain broadening process. Based on the theoretical model, we find that the SBS threshold reaches a maximum for the ratio of cutoff frequency to clock rate $r_c = 0.53$ and RMS modulation depth $k_{rms} = 0.55\ \pi$ for PRBS9. An effective Brillouin gain spectrum measurement setup is established, and the theoretical predictions are verified by the experiment.**

***Index Terms*—Effective Brillouin gain spectra, PRBS phase modulation.**

I. Introduction

STIMULATED Brillouin Scattering (SBS) is the lowest threshold nonlinear effect in narrow linewidth continuous-wave fiber system [1]. The SBS process can be treated as a SBS amplifier when the Stokes wave is injected externally or seeded by the Rayleigh scattering near the output end of the medium. In this case, a simple model demonstrated by Zel'dovich can give an exactly analytical expression, which is so-called localized nonfluctuating source model [2]. On the contrary, without seeding, the Stokes wave is initiated from spontaneous scattering of thermally excited sound waves or by random noise, which can be treated as a SBS generator. A more complicated model named distributed fluctuating source model proposed by Boyd *et al.* ascribes the SBS originated from Langevin noise [3]. Based on these two models, one can increase the SBS threshold through reducing the power density and interaction fiber length, adjusting the SBS gain distribution and mitigating the gain coefficient. Several techniques have been proposed to mitigate SBS effect in fiber system, such as optimizing fiber manufacturing parameters [4], [5], applying stress or thermal gradients along the fiber [6]–[9], multi-tone seeds injection [10], [11] and phase modulation [12]–[20]. Normally, the pseudo random bit sequence (PRBS) phase modulation is a promising SBS suppression candidate, which provides flexibly optical spectral line separation adjustment. By applying the lowpass filter and RF amplifier, the envelope of the phase modulated laser spectra can be modified, thus provide further SBS suppression improvement [21], [22]. In our earlier work, the dependent of SBS suppression capability on the parameters of the filtered and amplified PRBS such as pattern length, modulation depth, and the ratio of lowpass filter cutoff frequency to clock rate has been investigated [23]. However, the Brillouin gain spectrum characteristic with the optimized parameters has not been illustrated, and the theory has not been verified by experiments.

This is a straightforward extension of our earlier work. In this paper, we examine the effective Brillouin gain spectra broadening for filtered and amplified PRBS phase modulation in fiber system theoretically using localized nonfluctuating source model. The ratio of normalized SBS threshold to normalized linewidth is used to evaluate the SBS suppression capability of the PRBS signal. The dependence of the SBS suppression capability on parameters of the filtered and amplified PRBS phase modulation is investigated by this model. Optimized parameters are found theoretically and verified experimentally.

II. Theoretical Framework

The optics waves in fiber core can be represented as the amplitude addition of the forward propagating laser wave E_L and the backward scattered Stokes wave E_S with respectively angular frequency ω_L and ω_S. Normally, the effective Brillouin gain spectrum (BGS) $g_{eff}(\omega_S)$ provides a criterion to predict the

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SBS suppression. In a long fiber system, assuming the waves are linearly polarized, g_{eff} can be represented as [24], [25]

$$g_{eff}(\omega_s) = g_0(\Gamma_B/2)^2 \int_{-\infty}^{\infty} \frac{S(\omega)}{(\Gamma_B/2)^2 + (\omega - \omega_S - \Omega_B)^2} d\omega, \quad (1)$$

where $\Gamma_B = 2\pi\Gamma$ is the phonon decay rate, Γ is the full width at half maximum (FWHM) of spontaneous Brillouin gain. The symbol Ω_B is the resonant acoustic frequency of the medium, the peak of Brillouin gain $g_0 = (\gamma_e{}^2\omega_L{}^2/\rho_0 n_L c^3 \upsilon_s \Gamma_B)$, γ_e is the electro-strictive constant, ρ_0 is the fiber medium density, υ_s is the speed of sound, c is the speed of light, n_L is the refractive index of laser wave in the core, respectively. $S(\omega) = I(\omega)/\bar{I}$is the normalized power spectrum density (NPSD) of the laser wave. According to (1), it is clear that for single frequency laser, only the Stokes wave with frequencies near $\omega_S = \omega_L$-Ω_B with a range of $\pm\Gamma_B/2$ can obtain a relative high gain. On the contrary, for phase modulated laser wave, ω_L contains new sidebands generated by phase modulation, each sideband corresponds to an independent ω_S, which share the overall Brillouin gain. In this spectral broadened case, the SBS threshold will be mainly determined by the maximum value of broadened $g_{eff}(\omega_S)$. Here we use the normalized SBS threshold M to evaluate the SBS suppression, which is the ratio of phase modulated SBS threshold optical power to that of the unmodulated SBS threshold. Also, M is proportional to the ratio of unmodulated steady-state SBS gain to the phase modulated SBS gain [24], [26], viz

$$M \propto \frac{G_{CW}}{\max[g_{eff}\bar{I}L_{eff}]} = \frac{g_0}{\max[g_{eff}(\omega_S)]}, \quad (2)$$

where $G_{CW} = g_0\bar{I}L_{eff}$is the steady-state single-pass gain. In a real-world system, a sufficient SBS suppression with a smallest optical linewidth is always preferred. Accordingly, we define the ratio of the normalized SBS threshold to the normalized linewidth as

$$R_{ml} = \frac{M}{\Delta\nu_{rms}/\Gamma}, \quad (3)$$

where $\Delta\nu_{rms}$ is the root-mean-square (RMS) linewidth of the modulated spectrum. To some extent, R_{ml} represents the SBS suppression capability in unit optical linewidth.

The laser wave is phase modulated by PRBS signal. A PRBS signal can be easily generated by a Linear Feedback Shift Register (LFSR) and are described by primitive polynomials mathematically [27]. The PRBS has a pattern length of $N = 2^n$-1 (n is the bits number of the register) and a period of NT (T is the bits period). A pattern period of the PRBS contains every possible combination of n number of the binary ‘0’ and ‘1’ data bits, except the null pattern [17]. Normally, the normalized power spectrum density (NPSD) of the PRBS signal is given by [28]

$$S_{PRBS}(f) = \frac{1}{N^2}\delta(f) + \frac{N+1}{N^2}\text{sinc}^2\left(\frac{f}{f_{cr}}\right)\sum_{\substack{i=-\infty \\ i\neq 0}}^{\infty}\delta(f - i\Delta f). \quad (4)$$

Equation (4) exhibits a periodic and discrete frequency comb, where $f_{cr} = 1/T$ is the clock rate and the frequency separation is given by $\Delta f = f_{cr}/N$. We define the modulation depth of PRBS phase modulation as

$$k_{rms} = V_{rms}/V_\pi \cdot \pi, \quad (5)$$

where V_{rms} is the RMS voltage of modulation signal, V_π is the half-wave voltage of the electro-optic phase modulator (EOPM). Then the NPSD of the PRBS modulated laser wave can be written as

$$S_L(f) = \left(\tfrac{1+\cos 2k_{rms}}{2} + \tfrac{1+2\sin 2k_{rms} - \cos 2k_{rms}}{2N}\right)\delta(f) + \tfrac{1-\cos 2k_{rms}}{2}\,\tfrac{N+1}{N^2}\text{sinc}^2\left(\tfrac{f}{f_{cr}}\right)\sum_{\substack{i=-\infty \\ i\neq 0}}^{\infty}\delta(f - i\Delta f)\cdot \quad (6)$$

The first part in RHS of (6) corresponds to the intensity of the carrier while the second part corresponds to the intensity of the sidebands. Apparently, both items are influenced by k_{rms} and N. For the lowpass filtered PRBS case, the NPSD of the PRBS signal can then be represented by $S'_{PRBS}(f) = S_{PRBS}\cdot H(f)$, where $H(f)$ is the frequency domain characteristic of the lowpass filter. Here we use a 6th-order Butterworth filter but with zero phase. According to the Wiener-Khinchin theorem [25], the lowpass filtered phase modulated optical spectrum $S'_L(f)$ can be written as

$$S'_L(f) = \left|F\left\{\exp\left[ik_{rms}\cdot F^{-1}\left\{S'_{PRBS}(f)\right\}\right]\right\}\right|^2, \quad (7)$$

where $F\{\cdot\}$ and $F^{-1}\{\cdot\}$ are the Fourier transform and inverse Fourier transform, respectively. However, we are not able to find an analytical expression of (7), instead, we calculate it numerically. Equations (6) and (7) can be substituted into (1-3) to evaluate the SBS suppression capability of the filtered and amplified PRBS with parameters k_{rms}, f_{cr}, and the filter cutoff frequency f_{co}. Here we define r_c as the ratio of f_{co} to f_{cr}. Some parameters and values used in our simulation are shown in Table I.

TABLE I
PARAMETERS FOR SIMULATION

Parameters	Quantity	Value of parameters
Γ_B	Phonon decay rate	2π/(17.5 ns)
Ω_B	Resonant acoustic frequency	$2\pi\cdot$(15.7 GHz)
f_{cr}	Clock rate	1.7 GHz
k_{rms}	RMS modulation depth	$\in[0, \pi]$
r_c	The ratio of cutoff frequency to clock rate	$\in[0, 1]$
N	Pattern length	2^9-1

III. Simulation Result

Based on the method mentioned above, we calculated the normalized SBS threshold as a function of k_{rms} and r_c, which is shown in Fig. 1(a). The local maxima for normalized SBS threshold follow a significant structure. We find two peak points at (r_c = 0.33, k_{rms} = 0.95 π) and (r_c = 0.53, k_{rms} = 0.55 π). In order to examine the dependence of optical linewidth to the modulation parameters, we calculated the RMS linewidth of the filtered and amplified PRBS phase modulated optical spectra versus k_{rms} and r_c, shown in Fig. 1(b). Normally, a larger linewidth does not necessarily correspond to a higher

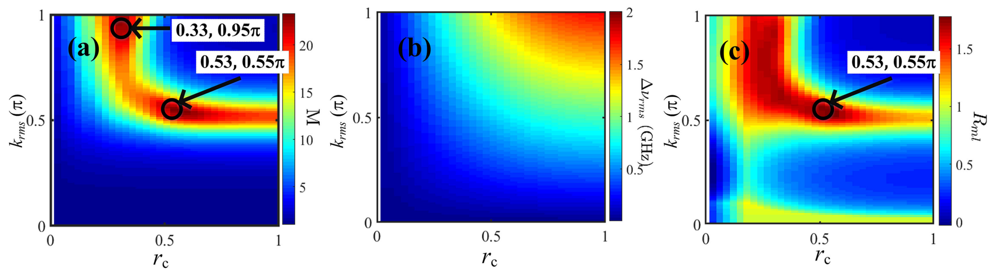

Fig. 1. (a) Normalized SBS threshold, (b) RMS linewidth of the phase modulated laser spectrum, and (c) the ratio of normalized SBS threshold to RMS linewidth as a function of k_{rms} and r_c.

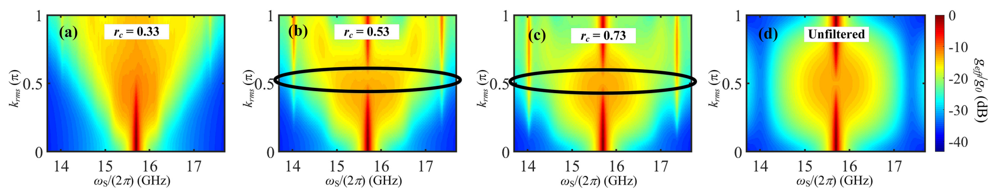

Fig. 2. The normalized effective BGS $g_{eff}(\omega_s)/g_0$ modulated by PRBS9 with k_{rms} at (a) r_c=0.33, (b) 0.53, (c) 0.73, and (d) unfiltered case.

SBS threshold. Only when the laser energy is evenly distributed among different frequencies of Stokes wave, each ω_S obtain the same gain factor so that the SBS can be optimally suppressed. Therefore, we calculated R_{ml} versus k_{rms} and r_c, shown in Fig. 1(c). Only one global maximum can be found at (0.53, 0.55 π), which indicated a maximized SBS suppression in unit optical linewidth.

To make further comprehension of the two peak points in Fig. 1(a), we calculate the variation of $g_{eff}(\omega_s)/g_0$ according to k_{rms} with several different r_c, shown in Fig. 2(a-c). As r_c increases, the g_{eff} value with center frequency ($\omega_s = \Omega_B$) gradually appears to be periodically modulated by k_{rms} with a period of π, which is similar with unfiltered PRBS modulation case shown in Fig. 2(d). This can be understanding like this: S'_L simples to (6) when the cutoff frequency tends to infinity ($r_c \to \infty$). Also, a larger k_{rms} will generate higher order side-lobes (see Fig. (b) and (c)) in the phase modulated optical spectra according to Jacobi-Anger expansion. When the laser energy is evenly distributed among different frequencies of Stokes wave, each ω_S obtain the same gain factor so that the SBS can be optimally suppressed. For $r_c = 0.33$ and 0.53, the sidebands are relatively weak when center frequency is suppressed, compared with the $r_c = 0.73$ case, so the global maximum points of *M* will appear at these two points in Fig. 1(a).

IV. Experiment Setup

We establish a filtered and amplified PRBS phase modulated fiber system, the schematic diagram is shown in Fig. 3. A 50-mW single-frequency laser (NKT Photonics, BASIK Y10) with a center wavelength of 1067 nm and a FWHM linewidth of <5 kHz is used as an oscillator. The bit signal is filtered using a 6^{th}-order Butterworth lowpass filter (Mini-circuits, SLP-1000+) with a cutoff frequency of 0.9 GHz. A 20 GHz RF amplifier (iXblue, DR-AN-20-HO) with a gain of 27 dB is used to boost power of the filtered signal. A $LiNbO_3$ electro-optic phase modulator

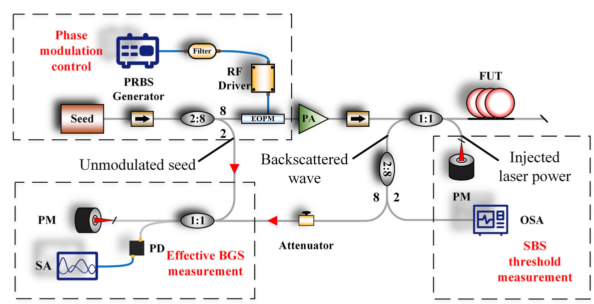

Fig. 3. Schematic diagram of fiber system and the self-heterodyne Brillouin gain spectrum measurement.

(EOPM) is used as a phaser with V_π @ 50 kHz = 3.6*V*. A three-stages pre-amplifier (PA) is implemented to amplify the modulated seed within 0.1∼18W and inject into the fiber under test (FUT, 1 km 1060-XP) through a 1:1 tap. The Brillouin gain spectra of FUT can be measured directly through a self-heterodyne measurement system. About 20% of the seed light is exported from a 2:8 tap and beat with the backward light through a 1:1 tap. An all-fiber variable attenuator is introduced to balance the power of the seed and the backward light to maximum the visibility of the beat signal, which transferred to the electric signal by a DC ∼ 45 GHz photodetector (Newport, 1014) and analyzed by a 2 Hz ∼ 43.5 GHz radio-frequency spectrum analyzer (Rohde & Schwarz, FSW43).

Based on the theoretical prediction, r_c∼0.53 is realized experimentally by PRBS9 with a clock rate 1.7 GHz and a filter cutoff frequency of 0.9 GHz. Then the SBS threshold with different k_{rms} is measured in the experimental system. The SBS threshold is defined as the injected power when the Stokes and Rayleigh wave have the same spectral components in backscattered wave monitoring by an optical spectrum analyzer (YOKOGAWA, AQ6370B). For the unmodulated case, the SBS threshold is 80 mW. By changing the output power of the PRBS generator,

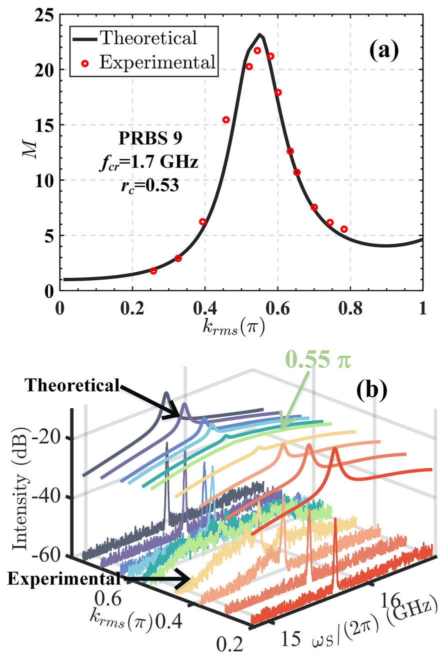

Fig. 4. (a) The normalized SBS threshold and (b) the effective BGS as a function of k_{rms} with f_{cr}=1.7 GHz, r_c=0.53, PRBS9 in experimentally and theoretically.

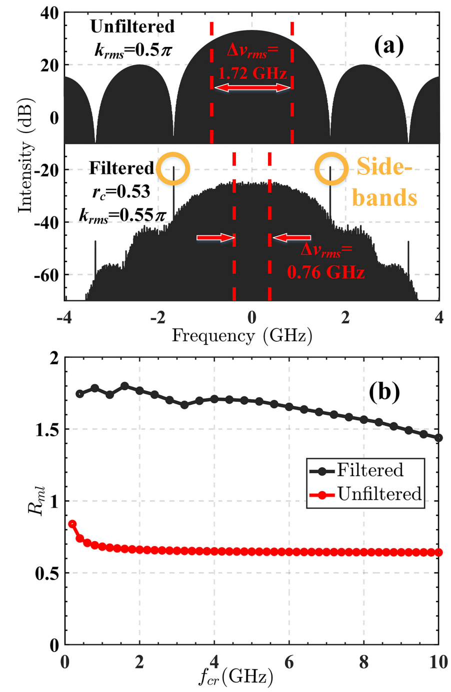

Fig. 5. (a) The optical spectra of unfiltered and filtered and amplified PRBS phase modulation cases and (b) the R_{ml} as a function of clock rate for unfiltered and filtered PRBS9 modulation.

V_{rms} of modulation signal is changed and measured by Oscilloscope (Keysight, DSO-S 254A). Then the k_{rms} can be obtained by (5). The comparison of the theory simulations and the experiments is shown in Fig. 4(a). The experimental measurement has a good agreement with the theoretical prediction. Fig. 4(b) shows the measurement of the effective BGS with corresponding k_{rms}. The theoretical prediction is also shown above to make a comparison. Since the self-heterodyne measurement system cannot give the exact value of the g_{eff}, here we mainly concern the relatively density. With the increasing of k_{rms}, the broadened effective BGS makes more Stokes frequency components amplified and reaches the widest around $k_{rms} = 0.55\ \pi$, which also makes a good agreement with theoretical prediction. However, it should be noted that the intensity peaks in the experiments appear narrower compared to the theory in Fig. 4(b). This can attribute to the gain narrowing of the Stokes output spectrum [3]. For the experimental results of the gain spectra around $k_{rms} = 0.55\ \pi$, the envelope of the gain spectra become top-hat shape, and the signal-to-noise ratio is reduced. Under this circumstance, some of the accidental noise pulses may be mistaken for the gain spectra peaks.

V. Discussion

In this section, we examine the optical spectra for both unfiltered and filtered PRBS phase modulation scheme. Fig. 5(a) shows the optical spectra of unfiltered and filtered PRBS9 phase modulation. We choose optimized SBS suppression parameters (i.e., $k_{rms} = 0.5\ \pi$ for unfiltered case and $k_{rms} = 0.55\ \pi$, $r_c = 0.53$ for filtered case), and f_{cr} is 1.7 GHz. For the unfiltered case, the spectrum of laser wave is infinite extension as a sinc^2 shape (see Fig. 5(a)), and the concentration of energy will be lower than Gaussian or Lorentz shape [16]. The high-order sidelobes will cause the degradation of the coherence of the fiber system, thus reduce the combination efficiency for coherent combining systems [29]. On the contrary, for the filtered case, the spectrum is truncated and redistributed to have a top-hat shape within the linewidth (dash lines in Fig. 5(b)). Though there are relatively strong sidebands at $\pm$1.7 GHz (shown in yellow circles in Fig. 5(a)), the integrated energy here is low for discrete spectral lines. Moreover, the linewidth of the filtered case is 0.76 GHz, which is less than half of the unfiltered case. Furthermore, the optimal parameter combination of $k_{rms} = 0.55\ \pi$, $r_c = 0.53$ can be generalized to different f_{cr}, since the shape of spectrum will be the same with only different Δf. Fig. 5(b) shows the simulation results of R_{ml} as a function of f_{cr} with unfiltered and filtered PRBS9 modulation to examine the scalability of these optimal parameters. The R_{ml} of the filtered case is 2 times larger than that of the unfiltered case, which means the SBS suppression capability of filtered case will be more than 2 times of the unfiltered case with the same linewidth around GHz-level.

However, the theoretical predictions of M and R_{ml} no longer accurate if the interaction length (fiber length) is relatively short. In a commonly used 10-m level fiber system, the round-trip time is 80 ns-level, which is shorter than the period of a PRBS waveform with GHz-level clock rate (e.g., 511 ns period for PRBS9 with 1 GHz clock rate). On this condition, the SBS suppression capability for a specific PRBS waveform would be degraded [24]. In addition, small frequency separation introduces the cross-interaction of phase mismatched terms, which will further decrease the SBS threshold [10], [30]. The localized nonfluctuating source model we use here neglects these two factors and will consequently cause overestimation of SBS threshold. Nevertheless, the principle of SBS mitigation of filtered and amplified PRBS phase modulation estimated by the proposed model agrees well with the experiments and our earlier simulation results using triply coupled wave model [23].

VI. Conclusion

In summary, we describe SBS process in a fiber system with laser wave phase modulated by filtered and amplified PRBS using localized nonfluctuating model. The effective Brillouin gain spectra, M and R_{ml} are used to evaluate the SBS suppression capability of PRBS modulation. Parameters of the filtered and amplified PRBS such as RMS modulation depth and the ratio of filter cutoff frequency to clock rate are optimized numerically. The simulation indicated that for PRBS9, the effective Brillouin gain spectra will be broadened evenly and the SBS threshold reaches the maximum at $k_{rms} = 0.55\ \pi$, and $r_c = 0.53$. This result agrees well with our previous work which investigate the SBS suppression capability by solving triply coupled set of nonlinear partial differential equations. We also establish an experimental setup to verify the theory. The experimental results of SBS threshold and effective Brillouin gain spectrum are in good agreement with the theoretical prediction. With these optimized parameters, the spectrum of filtered PRBS modulated laser wave is reshaped to be more concentrated and has less variation within the linewidth compared with unfiltered PRBS modulation case. With the same linewidth around GHz-level for PRBS9, the SBS threshold of filtered case will be 2 times than that of unfiltered case. This research may provide a new understanding of lowpass filtered PRBS modulation scheme and make a further advance on phase modulation SBS mitigation of narrow linewidth fiber amplifier.

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