# Suppression of SBS-Induced RF Phase Noise in an RF-Photonic Link

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**Abstract—In this paper, we examine and suppress the effects of stimulated Brillouin scattering on the phase noise of a 10 GHz signal transmitted over an RF-photonic link. We demonstrate the appearance of interference peaks in the RF phase noise of a microwave signal transmitted through a 10 km optical fiber link. We attribute these peaks to double Brillouin scattering using a reduced model. We determine that there are at least three optical noise sources at optical powers relevant to RF transmission: shot noise, Rayleigh scattering, and stimulated Brillouin scattering. Furthermore, we demonstrate the suppression of noise from both Rayleigh and Brillouin scattering using frequency modulation. We demonstrate further suppression of phase noise from Brillouin scattering using a concatenation of fibers with different Brillouin frequency shifts.**

***Key words: RF-photonic link, Brillouin scattering, Optical scattering suppression***

## I. INTRODUCTION

Low phase noise transmission of analog signals is a vital technology for the precise transfer of frequency and time standards. Applications such as time standardization, radio astronomy and missile defense require extremely precise temporal and frequency synchronization that can only be achieved with such a low phase noise transmission scheme. One approach is to transmit the RF signal over optical fiber using an RF-photonic link to modulate the signal onto and remove it from a laser carrier beam.

In order to optimize the performance of signals sent through such an RF-photonic link, we must increase the power of the laser beam [1]. However, as we increase the optical power that travels through the transmission fiber, both Rayleigh and stimulated Brillouin scattering dominate the phase noise spectrum of the received RF signal [2, 3]. Consequently, we must also suppress optical scattering noise to reduce the phase noise of the final RF signal.

In this paper, we examine and suppress the effects of stimulated Brillouin scattering (SBS) on the phase noise of an RF-photonic link. First, we observe the appearance of interference peaks in the RF phase noise of a microwave signal transmitted through a 10 km optical fiber link. These peaks occur at offset frequencies proportional to the inverse of the delay incurred in the optical fiber. Thus, as transmission distance increases, the peaks appear at lower offset frequencies. We attribute these peaks to double Brillouin scattering using a reduced model.

We demonstrate that applying a frequency dither to the transmission laser suppresses both Rayleigh and stimulated Brillouin scattering-induced phase noise. We observe at least three optical noise sources at optical powers relevant to RF transmission: shot noise, Rayleigh scattering, and stimulated Brillouin scattering.

Finally, we demonstrate further suppression of the stimulated Brillouin scattering-induced phase noise using a concatenation of fibers with different Brillouin frequency shifts, as in [4,5]. This technique suppresses only Brillouin scattering. Because this method suppresses the RF phase noise for high laser powers, we conclude that the dominant noise in this regime must be caused by stimulated Brillouin scattering, in agreement with [3].

## II. CHARACTERIZATION OF RF PHASE NOISE

In this section, we examine the effects of SBS on the RF phase noise of a microwave signal transmitted through an RF-photonic link. We also identify the dominant noise sources in the transmission link. To accomplish this, we measure the RF phase noise spectrum of a microwave signal transmitted through fiber on a laser beam for a range of laser powers.

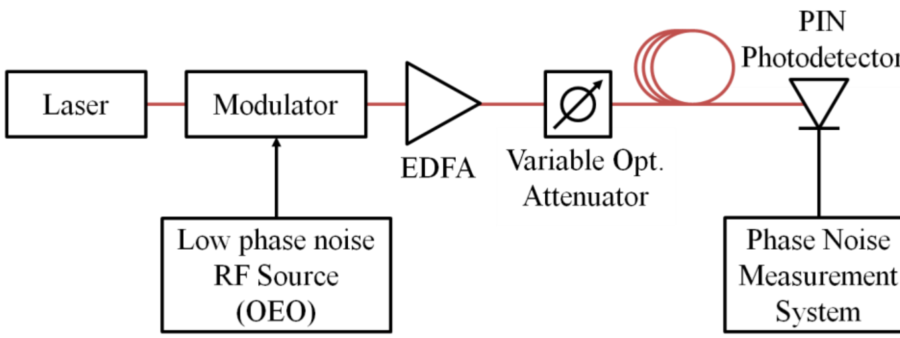


Figure 1. Experimental apparatus.

Figure 1 illustrates the experimental setup. First, an optoelectronic oscillator generates a low phase noise 10 GHz signal. The OEO uses a 6 km spool of fiber as a high Q resonator. An electro-optic modulator modulates the OEO signal onto the output of a DFB semiconductor laser. An erbium doped fiber amplifier amplifies the laser beam, and a variable optical attenuator controls the total optical power output of the EDFA. The signal then travels through a 9.4 km spool of optical fiber. Finally, the signal is detected in a PIN-structure photodiode and fed into a cross-correlation delay line phase noise measurement system similar to that described in [6].

### *A. Interference Peaks*

Figure 2 shows the RF phase noise spectrum for several input powers. The sharp peaks at 33 kHz and 66 kHz are spurious modes of the microwave source and can be disregarded in this analysis. The unevenness in the spectra below 500 Hz is due to acoustic noise in the test area.

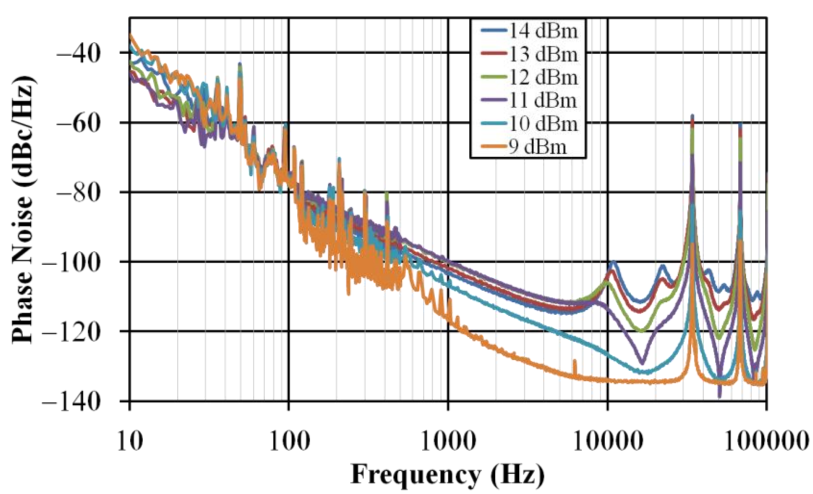


Figure 2. Phase noise of transmitted microwave signal for various optical powers.

In the pictured power regime, the phase noise at offset frequencies between 1 and 100 kHz grows with input power. As the input power increases, interference peaks appear at offset frequencies corresponding to twice the optical delay of the fiber. This indicates that the noise source is a double scattering process with effective mirrors at opposite ends of the fiber.

Figure 2 indicates that the interference peaks begin forming between 10 and 11 dBm (see also figure 3). This threshold power is approximately equal to the Brillouin threshold power for the transmission fiber. This indicates the influence of Brillouin scattering in the double scattering process.

### *B. Optical Noise Sources*

Figure 3 shows the average phase noise at 25 kHz as a function of the input optical power. This metric serves as a proxy to illustrate the general power dependence that is observable in figure 2 at offset frequencies greater than about 1 kHz. We will use this metric throughout the paper.

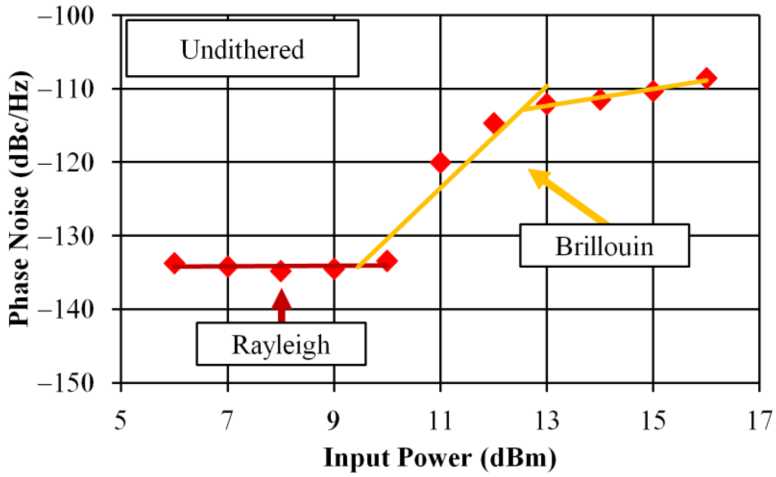


Figure 3. Average RF phase noise at 25 kHz vs. input optical power for standard fiber.

For low optical powers, the dominant noise source is constant with input power. This is consistent with linear optical scattering, and we attribute it to Rayleigh scattering. As the input optical power rises above a threshold power, the dominant noise source displays a positive slope. This indicates the presence of a nonlinear scattering process, such as SBS. Furthermore, figure 3 confirms the threshold power of the nonlinear process to be between 10 and 11 dBm which, as mentioned above, coincides with the SBS threshold power for our fiber.

### *C. Double Brillouin Scattering*

In this section, we describe a reduced model of double Brillouin scattering that explains the appearance of the interference pattern in figure 2. This model is implicitly contained within the numerical model of [3]; it is our intent to provide a more explicit explanation of the process. We begin with a brief review of Brillouin scattering. There is a wealth of literature describing the Brillouin scattering process in greater detail, including [5, 7, 8].

Brillouin scattering is the scattering of light off of acoustic phonons. In optical fiber, we only consider light scattered 180° to the incident light, since all other scattered light will not couple into the fiber. The scattered light will experience a frequency shift in order to conserve energy in the collision. For a phonon which co-propagates with the incident light, the reflected light will have a lower frequency (Stokes scattering). For a phonon which counter-propagates to the incident light, the reflected light will have a higher frequency (anti-Stokes scattering). Figure 4 provides a visualization of this process. $\nu_L$ is the laser frequency, $\nu_B$ is the phonon frequency, $\nu_L - \nu_B$ is the Stokes frequency, and $\nu_L + \nu_B$ is the anti-Stokes frequency.

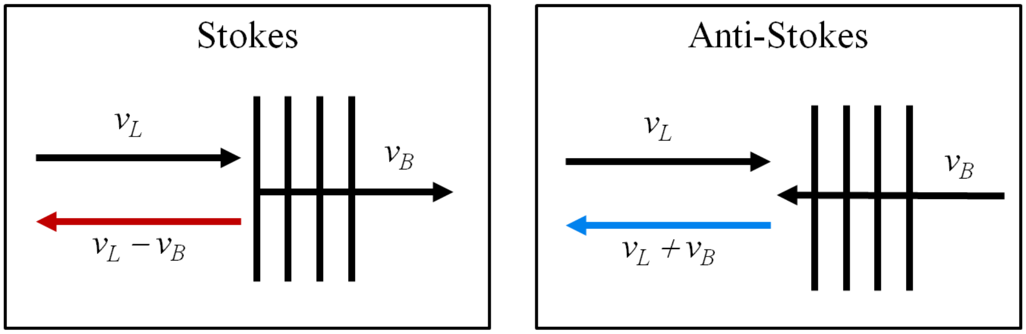


Figure 4. Stokes and anti-Stokes Brillouin scattering.

For light with a wavelength of 1550 nm propagating in an optical fiber, the frequency shift is approximately ±10.8 GHz. Because of this frequency shift, only light that experiences an equal number of Stokes reflections and anti-Stokes reflections will cause phase noise near the carrier frequency.

We can find the intensities of the Stokes and anti-Stokes beams by reducing the coupled mode equations to a set of equations for the intensities. The equations for the Stokes beam are given in eqs. (1), where $g$ is the Brillouin gain, $I_L$ is the intensity of the primary laser beam, and $I_S$ is the intensity of the Stokes wave. The equations for the anti-Stokes beam are analogous to eqs. (1) and can be found in [7].

$$\frac{dI_{\mathrm{L}}}{dz} = -gI_L I_S \tag{1a}$$

$$\frac{dI_S}{dz} = -gI_{\mathrm{L}} I_S \tag{1b}$$

Equations (1) describe a stimulated scattering process. Scattered light contributing to the intensity distribution in these equations will be in phase with light scattered from the end of the fiber. Thus, all light at the end of the fiber will effectively experience the same phase delay. We can interpret this as scattering from an effective mirror at the end of the fiber.

We can solve eqs. (1) to find the intensity distribution of the laser and Stokes beams as a function of position in the fiber. We specify the solution in terms of two initial conditions: the laser intensity at the entrance of the fiber, $I_{L0} \equiv I_L(0)$, and the Brillouin reflectivity, $\eta \equiv I_S(0)/I_{L0}$. Note that $0 \leq \eta \leq 1$ by energy conservation. We write the position dependent intensities in eqs. (2).

$$I_L(z) = \eta I_{\mathrm{L0}} \frac{1-\eta}{\exp[g(1-\eta)I_{L0}z]-\eta} + I_{\mathrm{L0}}(1-\eta) \tag{2a}$$

$$I_S(z) = \eta I_{L0} \frac{1-\eta}{\exp[g(1-\eta)I_{L0}z]-\eta} \tag{2b}$$

Figure 5 shows a plot of the intensity distribution of the laser and Stokes beams for high initial laser intensity. The abscissa corresponds to the position within the fiber, normalized to the total length, *L*.

It is clear from eqs. (2) and fig. 5 that the pump intensity is equal to the Stokes intensity plus a term that is constant along the fiber. Thus, we will analyze the form of eq. (2b). In the low intensity limit, where $g(1-\eta)I_{L0}z \ll 1$, the exponential term in the denominator of eq. (2b) is approximately 1, and (2b) reduces to a constant in $z$. This is shown in eq. (3a). In the high intensity limit, the exponential term dominates and eq. (2b) reduces to exponential decay, as shown in eq. (3b).

$$I_S(z) \cong \eta I_{L0} \qquad \text{for } g(1-\eta)I_{L0}\mathrm{z} \ll 1 \tag{3a}$$

$$I_S(z) \cong \eta I_{L0}(1-\eta)e^{-g(1-\eta)I_{\mathrm{L0}}z} \qquad \text{for } g(1-\eta)I_{L0}\mathrm{z} \gg 1 \tag{3b}$$

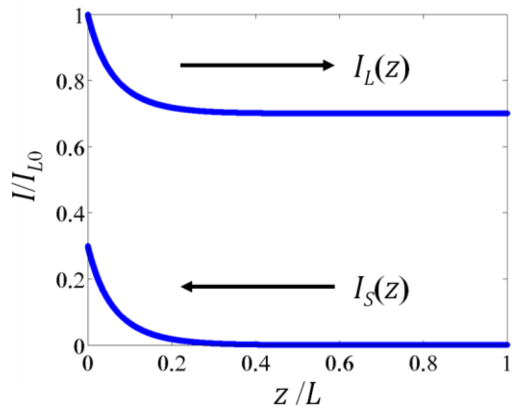


Figure 5. Spatial distribution of the intensity of the laser and Stokes beams at high initial intensity.

As shown in figure 5, in the high intensity limit the Stokes beam has high intensity only in a small region at the beginning of the fiber. Consequently, the second order anti-Stokes scattering (i.e. scattering from the Stokes beam) is localized to the same region. As $I_{L0}$ increases, the exponential becomes sharper, and the anti-Stokes region becomes smaller. This creates an effective mirror at the beginning of the fiber.

Thus, in the high intensity limit, stimulated Brillouin scattering creates effective mirrors at the beginning and end of the transmission fiber. There will be a double scattered beam that co-propagates with the transmission laser beam. The double scattered light will experience one Stokes and one anti-Stokes reflection, so its frequency will be equal to the transmission laser's frequency. The double scattered light will have a phase delay corresponding to twice the fiber length (i.e. transmission distance). When the transmission and double scattered light beams beat in a photodetector, interference peaks appear at frequencies corresponding to this phase delay. As fiber length increases, interference peaks will occur at lower offset frequencies. Assuming this model holds for much longer links, the first peak is predicted to occur at 1 kHz in a 100 km link and at 100 Hz in a 1,000 km link.

## III. SUPPRESSION OF SCATTERING

In the previous sections, we observed two regimes in the optical power dependence of the RF phase noise: one dominated by Rayleigh scattering-induced noise and one dominated by Brillouin scattering-induced noise. In this section we will demonstrate two methods to suppress Brillouin scattering-induced phase noise.

In the first method, we weakly dither the frequency of the laser beam. This technique has been demonstrated to suppress both Rayleigh and stimulated Brillouin scattering [2, 5]. By reducing the scattering noise, we observe a third optical noise source: shot noise.

In the second method, we replace the transmission fiber with an SBS-suppressing fiber of the same length. This technique will not suppress Rayleigh scattering, so noise that is suppressed by this technique must be SBS-induced.

### *A. Weak Dithering*

In this section, we introduce a weak frequency dither to the transmission laser. We confirm that frequency modulation suppresses not only the Rayleigh scattering-induced noise, but also the Brillouin scattering-induced noise.

The experimental setup is identical to that shown in figure 1, except that the laser source in the RF-photonic link is frequency dithered by a signal generator. The dither signal is a 20 kHz sinusoid with 100 MHz modulation depth.

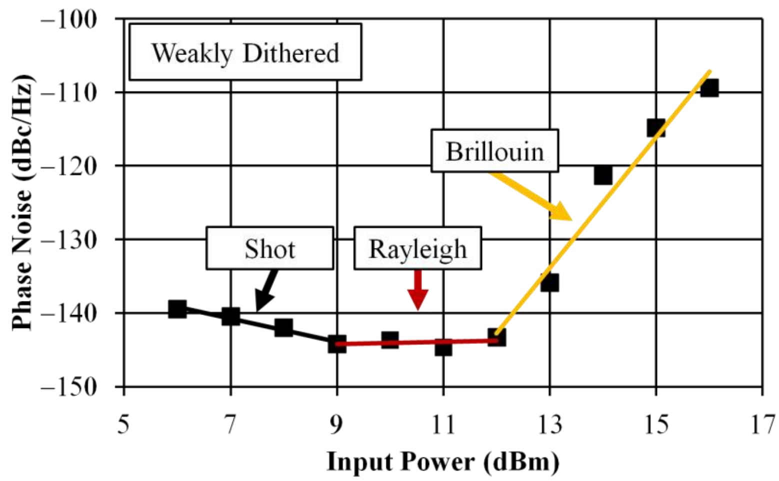


Figure 6. Average RF phase noise around 25 kHz for transmission using a weakly dithered laser.

Figure 6 shows the average RF phase noise at 25 kHz for different input powers. For low optical powers, the dominant noise source of our system has a slope of -1.5. This is consistent with shot noise in the photodetector. For optical powers between 9 and 12 dBm, the noise is approximately constant. Again, this is consistent with Rayleigh scattering-induced phase noise. The frequency dithering has reduced the noise level of the Rayleigh scattering by about 10 dB (see fig. 3). For input powers above 12 dBm, the dominant noise source has a sharply positive slope consistent with SBS-induced noise. The frequency dithering has increased the threshold of SBS dominance by about 2 dB.

*B. SBS-Suppressing Fiber*

In this section we suppress the noise at high optical powers using a concatenation of fibers, as in [4, 5]. Figure 1 illustrates the basic experimental setup. We maintain the dither signal from the previous section (a 20 kHz sinusoid with 100 MHz modulation depth) and replace the fiber in figure 1 with an SBS-suppressing fiber.

To make the SBS-suppressing fiber, we concatenate two fiber spools with different Brillouin frequency shifts, as in [4, 5]. This prevents the SBS in the end fiber from building in phase with the SBS in the initial fiber. The SBS-suppressing fiber has a total length of 10 km and the SBS frequency of the two constituent spools differs by 9 MHz. The first spool is 4.5 km long and the second is 5.5 km long.

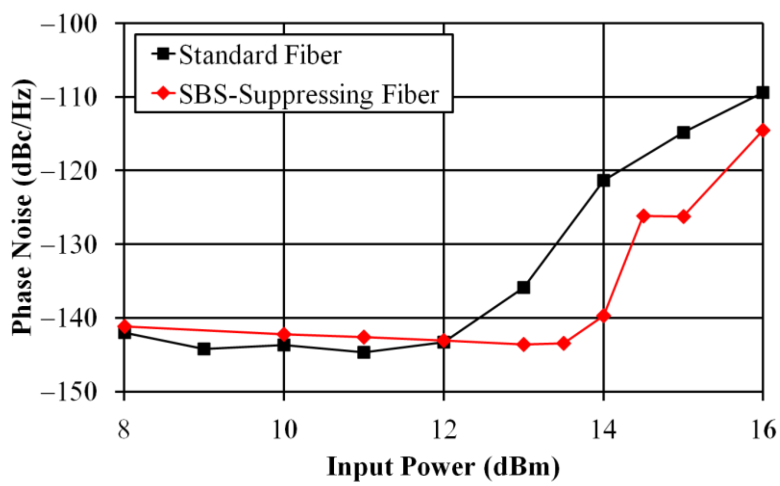


Figure 7. Average RF phase noise around 25 kHz for standard (red) and SBS-suppressing (blue) fibers.

Figure 7 shows the average RF phase noise at 25 kHz as a function of input power for the standard and SBS-suppressing fibers. The SBS suppressing fiber increases the threshold power by at least 1 dB, indicating that the dominant noise source at high input powers is caused by SBS.

The SBS-suppressing fiber suppresses SBS while leaving Rayleigh scattering unaffected. We observe suppression of the noise at high laser power, while the phase noise at lower optical powers is unaffected. This result is consistent with the noise classifications in fig. 3 and fig. 6, as well as the results of [3].

## IV. CONCLUSION

We have presented an experimental characterization of the effects of Brillouin scattering on the RF phase noise of a microwave signal transmitted over a 10 km RF-photonic fiber link. Double Brillouin scattering leads to interference peaks at offset frequencies corresponding to twice the delay of the fiber. Further data is necessary to characterize the stimulated Brillouin-induced phase noise in longer transmission links, but the reduced model that we have presented indicates that the interference peaks will appear at lower offset frequency.

We have demonstrated that the Brillouin-induced phase noise can be suppressed by frequency dithering the laser signal and by replacing the standard fiber with a concatenation of fibers each with a different Brillouin frequency shift.

Finally, we have shown that the phase noise is dominated by three optical effects: shot noise, Rayleigh scattering, and Brillouin scattering.

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