2006-01-01

# A Comparative Test of Brillouin Amplification and Erbium-doped Fiber Amplification for the Generation of Millimeter Waves with Low Phase Noise Properties

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## Recommended Citation

Junker, M. et al. (2006) A comparative test of Brillouin amplification and Erbium-doped fiber amplification for the generation of millimeter waves with low phase noise properties. *IEEE Transactions on Microwave Theory and Techniques*, June 2006,Volume: 54 , no. 4 , Part 1, 1576 - 1581. doi:10.1109/TMTT.2006.871321

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# A Comparative Test of Brillouin Amplification and Erbium-Doped Fiber Amplification for the Generation of Millimeter Waves With Low Phase Noise Properties

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***Abstract*—Measurements of phase noise of a 40-GHz carrier signal are presented. The carrier is generated by the amplification of harmonics due to stimulated Brillouin scattering. An analogy to a generation of millimeter waves by an erbium-doped fiber instead of the Brillouin amplifier is investigated and discussed. In our setup, both show a comparable behavior in respect to their noise characteristics.**

***Index Terms*—Brillouin scattering, millimeter-wave generation, phase noise.**

## I. Introduction

MILLIMETER waves are expected to be promising and important frequencies for future wireless communication systems. The frequency domain above 30 GHz offers an increase of the transmission bandwidth for radio links. The millimeter-wave frequency band overcomes the spectral congestion in lower frequency regions and offers an enormously large bandwidth. In the 60-GHz band, for instance, data transmission of 1.25 Gbit/s was shown [1]. Furthermore in [2], a wireless link with a data rate up to 3 Gbit/s and a carrier frequency of 120 GHz was verified. Short-range propagation systems in the 59–64-GHz frequency band that is set as a target frequency band has been developed [3]–[5] in Japan.

The requirements for carrier frequencies in wireless communications are, in fact, very high. Beside frequency stability, magnitude, and a narrow bandwidth, the most important property of a carrier signal is the phase noise. It describes the noise of the phase at a certain offset from the carrier measured in a 1-kHz bandwidth (dBc/Hz). It limits the application of carrier signals and is an important criterion for the use of different modulation formats in communication systems [6]. Phase noise degrades millimeter and microwave systems introducing a significant irreducible error rate. In [7], the 60-GHz region phase noise of $-59$ and $-85$ dBc/Hz at 10 and 100 kHz, respectively, offset from the carrier were measured. A millimeter-wave generation of 42 GHz was shown in [8] where a measurement of $-80$ dBc/Hz at 10-kHz offset was verified. By using the method of PM–IM conversion in chirped fiber gratings, a phase noise of $-87$ dBc/Hz at 10-kHz offset at a frequency of 28 GHz were measured [9]. Currently, Kawanishi *et al.* [10] reported on a 44-GHz signal generated by an integrated reciprocating optical modulator with a phase noise property of $-88.5$ dBc/Hz at 10-kHz offset from the carrier. In [11], the millimeter-wave generation of 33.87 GHz was realized by using hybrid mode locking of a monolithic distributed Bragg reflector (DBR) laser and a phase noise of $-70$ dBc/Hz was measured.

In this paper, we focus our discussions on the low phase-noise properties of the Brillouin amplification part. This gain can be seen as one of the most significant parts of signal generation in our system. This noise property is proven by a comparison to an erbium-doped fiber (EDF) amplification. It is realized by replacing the Brillouin amplifier in the setup physically. An alignment of all parameters to both amplification versions makes this possible.

In Section II, the experimental setup is briefly described. Theoretical results of the low phase-noise analyses are shown in Section III. In Section IV, experimental results focused on a comparison of Brillouin amplification and EDF amplification are evaluated. Finally, the conclusions and discussions are given in Section V.

## II. Experiment

Stimulated Brillouin scattering (SBS) is the nonlinear effect with the smallest threshold. SBS is an interaction between the material (optical fiber) and the incident light wave. The result is a density modulation of the refractive index, which can be seen as an acoustic wave. The pump wave is scattered at the grating resulting in a backward scattered wave, i.e., the Stokes wave. Owing to the Doppler effect, the Stokes wave is down shifted in frequency of 10.7 GHz. We measured a Brillouin gain bandwidth of 28.8 MHz. A similar experimental setup was discussed

Manuscript received October 10, 2005; revised December 8, 2005.

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Digital Object Identifier 10.1109/TMTT.2006.871321

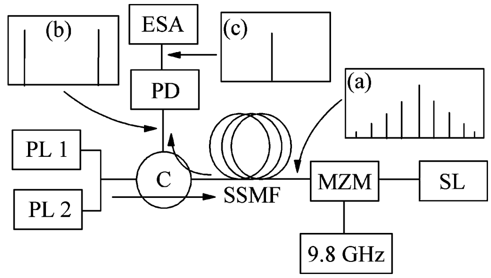


Fig. 1. Experimental setup for the generation of millimeter waves. (SL: signal laser, MZM: Mach–Zehnder modulator, PL: pump laser, PD: photodiode, ESA: electrical spectrum analyzer, C: circulator, SSMF: standard single-mode fiber.)

in detail in [12]. At this point, we want to give an overview about the system idea. A fiber laser is used as the signal laser with a narrow linewidth <2 kHz (Fig. 1), 20-mW output power, and a wavelength of 1550 nm. The linewidth of the signal laser should be as low as possible owing to the fact that it significantly defines the linewidth of the millimeter-wave signal. A polarization controller adjusts the polarization to its optimum for the Mach–Zehnder modulator (MZM). External modulation by an MZM driven in the nonlinear domain (upper/lower quadratic operation point) is performed to generate a frequency comb. The modulation frequency is 9.8 GHz, hence, the separation of the sidebands has a distance of 9.8 GHz [see Fig. 1, inset (a)]. By changing the operation point, switching between even- and odd-order sidebands is possible. The frequency comb is injected into a 50.43-km standard single-mode fiber (SSMF). The light of two DFB pump lasers combined in a 3-dB coupler is launched into the same fiber from the opposite side via a circulator. The frequencies of the pump lasers are adjusted in such a manner that the frequencies are 10.7 GHz higher than the frequencies in the comb. Due to this, only two wavelengths out of the comb are amplified by Brillouin scattering. The pump power is below the Brillouin threshold that we calculated to be around 8.1 mW. Hence, the Stokes wave is stimulated by the sideband and not by the noise in the fiber. The linewidth of the pump lasers is below 1 MHz.

Due to the natural attenuation, all other sidebands are attenuated while propagating in the fiber. The result at the output of the circulator is two strong frequency components with a separation depending on the order of the amplified sidebands: 19.6, 39.2, 58.8 GHz and so on [see Fig. 1, inset (b)]. The two amplified harmonics are then superimposed in a photodiode (PD) and the actual millimeter wave is generated by heterodyning [see Fig. 1, inset (c)]. The optical input power at the PD is 1 mW. The output frequency is $2n\ f\ with\ f$ being the frequency of the electrical generator and $n$ being the order of the sideband.

The modulation of the millimeter wave can be done quite simply by modulating the electrical generator, the signal laser, one of the pump lasers, or one amplified sideband.

## III. Theory

One of the simplest ways of generating millimeter waves is the heterodyning of two frequencies in a PD. The generation of two phase correlated waves can be done by double-sideband suppressed carrier (DSB-SC) modulation with MZMs. Due to the fact that both optical components are derived from a single source, their phases are totally correlated at the source [13]. If the optical component (sidebands) separation is in the tens of gigahertz region and fiber length of many tens of kilometers, the decorrelation effect owing to the fiber dispersion is negligible small. Hence, the millimeter-wave signal has a minimum of phase noise induced by the two heterodyned waves. In principle, the millimeter-wave generation of our setup follows the same restrictions as the generation by the heterodyning of two sidebands of an SSB-SC modulation in a PD [13]. If one assume no Brillouin amplification process in our setup, the resulting spectrum and the phase noise is the same. The only alternation in our setup is the adding of a Brillouin amplification process. The theoretical conditions for limiting the phase-noise induction to the millimeter wave are described in the following.

SBS as an amplifier, in general, induces many problems to the system. The Brillouin gain bandwidth is low and the spontaneous emission noise (SEN) can be 500 times larger than in a Raman amplifier [14]. Furthermore, a noise figure (NF) of 20 dB limits the system performance for preamplifiers.

In contrast to that, Ferreira *et al.* [15] reported that driving the amplifier in the saturation regime could significantly reduce the SEN. A short amplifier length can provide considerable improvement on the gain of the signals and decreases the SEN as well. Furthermore, the noise power increases with signal detuning. Hence, if the detuning between the pump and signal wave is minimized, the noise power can be notably reduced. Another way for decreasing the amplified spontaneous noise power is the setting of relatively high input signals powers when the Brillouin amplifier is operated in the saturation regime.

To maintain the phase-correlated state during their propagation in the fiber and while amplifying by two independent lasers, one has to consider two properties of the system. They are described below. A basis for simulating the amplification of two frequencies was shown in [16] where nonlinear effects accompanied with the susceptibility $\chi^{(3)}$ and the phase shift due to Brillouin amplification were considered. A part of a differential equation system, which describes the amplified sidebands at the circulator output, is shown in (1) and (2) as follows:

$$\begin{aligned}\frac{\partial E_{S2}}{\partial z} &= \frac{g_B}{2A_{\text{eff}}}\Delta k_1 E_{s2}P_{P2} + \frac{\alpha}{2}E_{S2}\\ &\quad + j\left[\frac{g_B}{2A_{\text{eff}}}\Delta k_2 E_{s2}P_{P2}\right.\\ &\qquad\left. + \gamma(P_{S2} + 2P_{P1} + 2P_{P2} + 2P_{S1})E_{s2}\right] \qquad (1)\end{aligned}$$

$$\begin{aligned}\frac{\partial E_{S1}}{\partial z} &= -\frac{g_B}{2A_{\text{eff}}}\Delta k_1 E_{s1}P_{P1} + \frac{\alpha}{2}E_{S1}\\ &\quad + j\left[\frac{g_B}{2A_{\text{eff}}}\Delta k_2 E_{s1}P_{P1}\right.\\ &\qquad\left. + \gamma(P_{S1} + 2P_{P1} + 2P_{P2} + 2P_{S2})E_{s1}\right] \qquad (2)\end{aligned}$$

where $P_s$ is the power of the signal wave, $P_P$ is the power of the pump wave, $\Delta k_2$ is the phase matching factor, $\alpha$ is the attenuation in the fiber, $\gamma$ is the nonlinear coefficient, and $A_{\text{eff}}$ is the effective core area. Equations (1) and (2) show the first and second amplified sideband, respectively, with their amplification by SBS and the attenuation in the real part. The imaginary part (in squared brackets) describes the phase shift due to nonlinear processes accompanied by $\gamma$ like cross phase modulation (XPM) and self phase modulation (SPM) (in brackets). Furthermore, the phase shift due to the Brillouin gain coefficient $g_B$ is considered.

If we assume that the signal waves $(P_{S1} = P_{S2})$ and pump waves $(P_{P1} = P_{P2})$ have the same power, the phase shift due to SPM and XPM of both amplified sidebands is equal. Furthermore, the Brillouin gain $g_B$ and the effective area $A_{\text{eff}}$ have the same values in (1) and (2), respectively. Hence, the phase-matching factor $\Delta k_2$ is variable and is described by

$$\Delta k_2 = \frac{\Delta k}{\left(\frac{\alpha_a}{2}\right)^2 + \Delta k^2} \tag{3}$$

and

$$\Delta k = \frac{1}{v_a(\omega_s - \omega_{s\text{MAX}})} \tag{4}$$

where $v_a$ is the velocity and $\alpha_a$ is the attenuation coefficient of the acoustic wave. $\omega_S$ is the signal wavelength and $\omega_{s\text{MAX}}$ is the wavelength for maximum amplification. If there is no detuning between the signal wave and pump wave $(\omega_S = \omega_{s\text{MAX}})$, the phase shifts of both amplified sidebands are equal [16].

Concluding the theoretical part: the influence of phase decorrelation of two waves derived from one source is negligible. A high signal power, a low detuning, a short fiber length, and driving the amplifier in the saturation regime can significantly reduce the noise. If the power of both sidebands is nearly equal, the phase change due to SPM and XPM is the same. If the detuning between the pump and the signal wave is minimal, the phase shifts for both sidebands are also equal. Hence, the SBS influences on the millimeter wave is small. All theoretical derived system and setup settings have been considered with the exception of the short fiber length.

## IV. Experimental Results

In order to prove the high signal performance of the generated carrier, it is necessary to analyze the stability, spectrum, and phase-noise properties. Due to the fact that our equipment (spectrum analyzer and PD) is frequency limited to 40 GHz, all measurements have been done in this domain. Theoretically, the system (Fig. 1) is able to generate up to 160 GHz depending on the MZM used in the setup. Other possible frequency comb-generation techniques would have only the bandwidth of the PD as a limitation, which is 330 GHz [17]. This could be a Fabry–Perot laser or a comb generation due to four wave mixing (FWM). Fig. 2 shows the carrier signal at a frequency of 39.199989 GHz with a bandwidth of 300 Hz. Due to the resolution limitation of the electrical spectrum analyzer (ESA), it was not possible to measure the real bandwidth of the carrier. The ESA has a resolution bandwidth (RBW) and a video bandwidth (VBW) of 300 Hz. Note that the actual bandwidth is possibly lower, but not measurable. The signal was measured with an ESA at the output of the PD. As one can see, it has very good spectral purity. The detuning of the signal wave and pump wave is minimized and the amplified sidebands have the same magnitude.

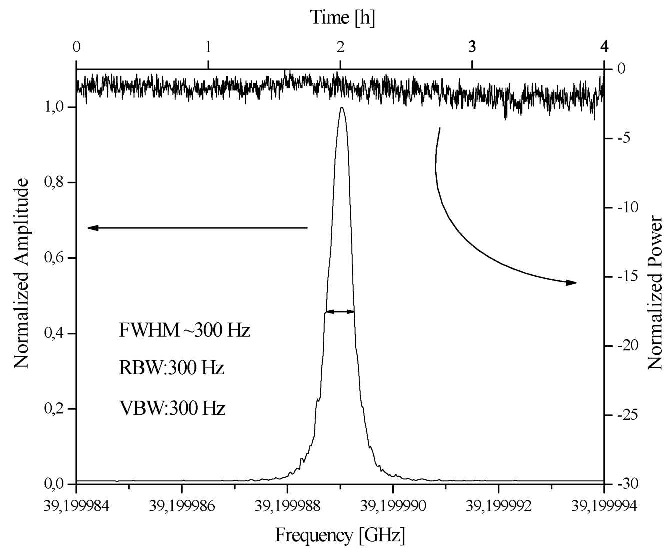


Fig. 2. Carrier signal at 39.199989 GHz at the output of the PD (bottom and left) and long-term stability of itself (top and right).

Fig. 2 shows also a power time measurement over a range of 4 h and it is proven that the signal is indeed constant. The short-term fluctuations in the plot are a result of the temperature controllers of the pump lasers. Due to a thermistor setting resolution of minimal 1 $\Omega$, which is approximately 42 MHz, the frequency of the pump lasers changes within this range. This fluctuation causes a frequency shift of the Brillouin gain and, thus, a change of the amplitude of the amplified harmonic. Owing to the fact that two sidebands are amplified, the fluctuations are doubled. Distortions of this kind can be easily and significantly reduced by using temperature controllers with a higher setting resolution.

The temperature stability depends significantly on the components used in the system. The 9.8-GHz generator has frequency stability of $< \pm 5 \cdot 10^{-8}$ Hz/°C. The pump laser wavelength is adjusted by a control loop to stay fixed at the wavelength of the sideband that should be amplified. The electro/optical frequency conversion in the MZM is temperature independent as well. The only parameter, which is a function of the temperature, is the Brillouin shift. In [18], it is shown that the Brillouin shift is 1.36 MHz/°C in an SSMF at 1.32 $\mu$m. If we assume that the Brillouin shift at 1.55 $\mu$m is nearly equal and the Brillouin bandwidth is 28.8 MHz, there is a need of $\pm 10.6$ °C temperature change for a total detuning of the Stokes wave and sideband. Due to the fact that the detuning of both amplified sidebands would be the same, a temperature shift affects only the power of the millimeter wave, but not the phase. This problem can be reduced, on the one hand, by a control loop, which regulate the pump laser wavelength to the maximum amplification and, on the other hand, the Brillouin bandwidth can easily be broadened by an external phase modulation [19]. This increases the Brillouin bandwidth and, hence, the system independence on the temperature. Note that there was no connection

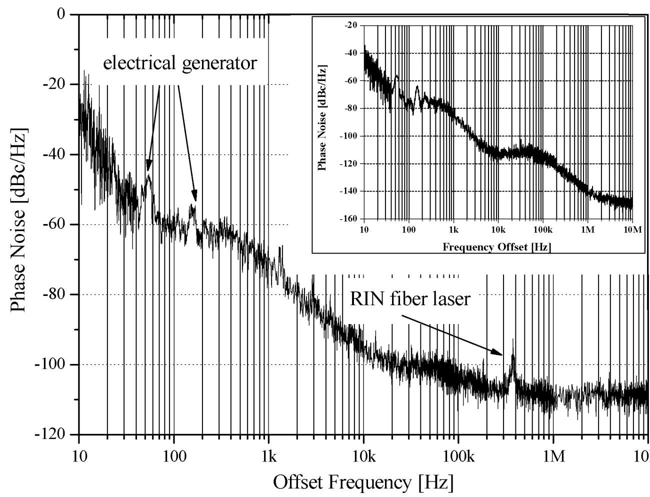


Fig. 3. Phase-noise measurement of the 39.199989-GHz signal. At 10-kHz offset from the carrier, the phase noise is −94.8 dBc/Hz. The inset shows the phase noise property of the 9.8-GHz oscillator.

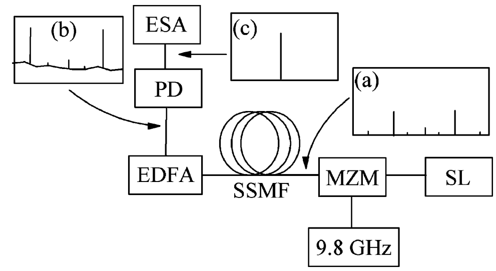


Fig. 4. Modified setup for comparison SBS-EDFA gain. (EDFA: erbium-doped fiber amplifier.)

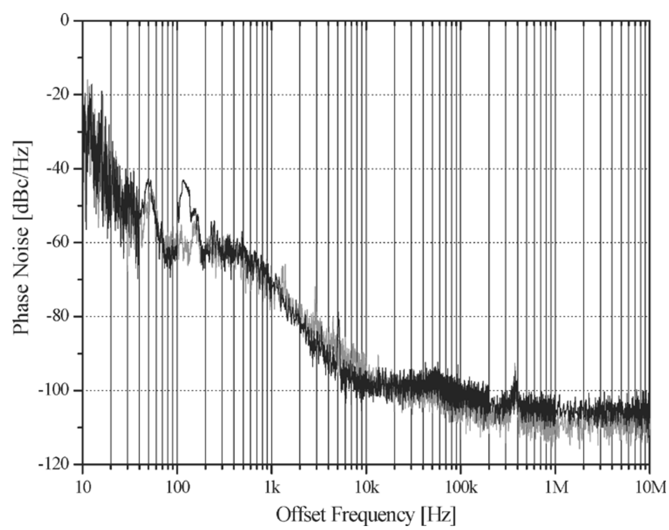


Fig. 5. Phase-noise measurement of the 39.199989-GHz signal generated by an EDFA (dark curve). At 10-kHz offset from the carrier the phase noise is −95 dBc/Hz. The bright curve is phase-noise measurement of the 39.199989-GHz signal generated by SBS (see Fig. 3).

between the temperature and millimeter-wave frequency realized during the measurements.

The phase noise of the generated signal is shown in Fig. 3. The noise at a frequency separation above 10 kHz from the carrier is −94.8 dBc/Hz, although the method is not yet optimized. This is a remarkably small value compared to other investigations on millimeter waves [7]–[11]. If one considers a Brillouin amplification process in the system, this result is even more impressive. Due to the inefficient opto-electronic conversion, the magnitude of the measured signal is −26.5 dBm. The input power at the PD is 1 mW. By optimizations of the fiber length shown in [15], one can assume a further decrease of the phase noise. The peaks at 55 and 150 Hz have their origin in the 9.8-GHz signal generator, which provides the MZM with the necessary power. The total phase noise of the millimeter wave is induced, on the one hand, by the noise of each component used in the system and, on the other hand, the phase noise induced by the SBS has to be added logarithmically together with the noise of the components. The peak at 300 kHz is the relative intensity noise (RIN) oscillation peak that is typically around 250–300 kHz in the fiber laser (signal laser).

The generation of millimeter waves by Brillouin scattering (Fig. 1) is a closed system. Hence, the output signal is the object that needs to be analyzed. On the other hand, we want to show that SBS is still of interest as an amplifier for special applications. Therefore, it is necessary to evaluate the characteristics of the Brillouin amplifier.

An important property of conventional amplification systems is the NF. The NF is the ratio of actual output noise to that which would exist if the device itself did not introduce noise.

Due to the fact that all other devices in our system have an unknown phase noise portion, it is not possible to draw a conclusion from it to the Brillouin amplification part. The NF analysis of the Brillouin amplifier in our setup is only possible by a comparison test. Two setup changes are necessary to realize this comparison.

First we change the MZM operation point in such a manner that only even-order sidebands are generated (carrier, 2, 4, 6, 8) by changing the bias voltage [see Fig. 4, inset (a)]. Hence, all other harmonics are suppressed. The second harmonics have the highest magnitude and are adjusted in such a manner that they have the same value as before the change. Due to the natural attenuation in the 50-km fiber, the optical power is decreased. In order to have the same output power, there is a need to amplify the modified frequency comb with a gain of 32 dB by an erbium-doped fiber amplifier (EDFA) [see Fig. 4, inset (b)]. The EDFA has a maximum NF of 6 dB at a gain of 32 dB.[1] The optical power of the EDF amplified sidebands is 1 mW, which is the same as in the measurement in Fig. 3. Hence, the optical input power at the PD is 1 mW as well. At the output of the PD, again the 39.199989-GHz carrier signal is detected [see Fig. 4, inset (c)].

The amplification of the sidebands by an EDFA allows a comparison between the two amplification systems because all other parameters are unchanged. Although the phase spectrum at 10-kHz offset is nearly equal (−95 dBc/Hz) to the SBS gained signal, the quality has decreased near the carrier.

As can be seen in Fig. 5, the influence of the electrical generator increases as one can see at 130 Hz due to the EDFA amplification. It proves that the Brillouin amplifier driven in our regime

[1]Personal contact with the EDFA manufacture/results of simulations.

induces a low amplified spontaneous emission (ASE) noise to the signal, as does an EDFA.

We have shown that the impact to the phase of a signal by a Brillouin amplifier can be significantly reduced. We focus our future research to the modulation of the signal and the optimization in respect to the noise.

## V. Conclusion

New phase-noise measurements of a millimeter waves have been presented. The values show very low phase-noise properties in the frequency domain at 40 GHz. A phase-noise value of $-94.8$ dBc/Hz prove the high quality of the signal. This low phase noise is even more impressive if one considers Brillouin amplification in the setup. We also discussed the comparison between the application of a Brillouin amplifier and an EDF amplifier in our setup. It is realized by replacing the Brillouin amplifier with an EDF amplifier and aligning all parameters to the reference (EDFA). It shows a high-quality NF performance.

Although the EDF amplification has shown similar phase-noise results, it is unusable for the generation of millimeter waves up to 160 GHz. The EDF amplifies all sidebands in the same way, which limits the millimeter-wave frequency to 40 GHz depending on the operation point of the MZM [see Fig. 4, inset (a)]. In our setup, we used the SBS as a filter as well. The selective Brillouin amplification amplifies just the sidebands that correspond to the desired carrier signal. An amplification of the eighth sideband is possible by SBS that is not using an EDFA. The EDF amplification is only a comparison parameter in this paper.

## Acknowledgment

The authors would like to acknowledge the assistance of C. Schäffer and G. Staats, both of the Technische Universität Dresden, Dresden, Germany, and the help with the phase-noise measurements. The authors further acknowledge the donation of the phase-noise equipment by the Technische Universität Dresden.

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