Investigation of Brillouin Scattering in Optical Fibers for the Generation of Millimeter Waves

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***Abstract*—Stimulated Brillouin scattering (BS) in optical fibers is investigated for the generation of millimeter waves (mm-waves) for radio over fiber systems. Predictions of a numerical simulation are compared to experimental results, and both are in good agreement with each other. With the numerical simulation, the optimum parameter for the technique is calculated. It will be shown that the optimum length of the fiber for BS depends on the signal rather than on the pump power. This gives us the opportunity to adjust the parameters for any given fiber length. The advantages and limits of the proposed method for mm-wave generation are discussed.**

***Index Terms*—Brillouin scattering, millimeter-wave communications, nonlinear optics.**

I. Introduction

FOR wireless communication links, gigabit per second data transmission is required in order to keep up with the remarkable speedup of local area networks [1]. A way to increase the bandwidth of wireless links is the exploitation of millimeter waves (mm-waves). The mm-wave frequency band offers a large transmission bandwidth, because it overcomes the spectral congestion in lower frequency regions. In the 60-GHz band, data transmission of 1.25 Gb/s was shown [2], for instance, and in [1], a wireless link with a data rate up to 3 Gb/s and a carrier frequency of 120 GHz was verified.

In order to reduce the complexity and the costs of wireless systems, a fiber-optic transport of the mm-waves between a central control station and remote base stations is very attractive. Optical fibers have many advantages over other propagation media—their capacity is very high [3], [4], they show low transmission losses, and standard components such as transmitters, receivers, filters, and amplifiers are available for low costs. At the same time, the generation of the mm-waves in the central control station reduces the complexity of each base station dramatically.

For the optical generation of mm-waves, many possibilities have been proposed so far. The easiest way is the direct modulation of a laser diode. However, high frequencies cannot be reached with this method. For a packaged 1550-nm distributed feedback (DFB) laser, 25 GHz [5] has been reported, whereas for unpacked 1100-nm lasers, 40 GHz [6] has been shown but only for small signal modulation and high bias currents [7]. Another problem accompanied with direct modulation is the unavoidable chirp of the laser diode output spectrum. This chirp is suppressed if the diode is externally modulated. External optical modulators able to modulate up to 100 GHz have been shown [8], [9]. On the other hand, such modulators are still not commonly available, and they are expensive. Furthermore, the dispersion in the fiber results in a beating between the carrier and the sidebands of the modulated signal. Hence, the received radio frequency (RF) power shows a periodical fading along the fiber due to different phase shifts between the lower and the upper sideband induced by the different group velocity dispersion [10]. A way to overcome such dispersion problems is the mid-span-spectral-inversion, where, in the middle of the span, the phase-conjugated signal is generated [11]. Another possibility is the single sideband modulation or the filtering of one of the sidebands. Single sideband modulation with Mach–Zehnder modulators (MZMs) can be achieved either in a suppressed carrier [12] or in a suppressed sideband configuration [13]. Filtering of one sideband can be done by optical filters or by Brillouin scattering (BS) [14].

A method that automatically generates single sideband signals is optical heterodyning. Heterodyning relies on the beating of two optical carriers in a photodiode. The frequency difference between both waves is the intended mm-wave. The efficiency of the optical-to-millimeter-wave conversion is high, and the frequency range that can be generated is only limited by the bandwidth of the photodetector [7].

If two independent lasers are used for optical heterodyning, the stochastic phase difference between them will lead to a phase noise of the generated mm-wave signal. In order to suppress this phase noise, many techniques have been proposed; for instance, an optical phase-locked loop [15], [16] or a dual-mode DFB laser [17]. Another possibility is optical injection locking, where one or two slave lasers are injection locked to an optical comb generated by a master laser [18], [19]. All of these methods are rather complicated. They require a specially designed equipment, and they are very sensitive to environmental influences. For optical injection locking, a temperature shift of a fraction of a degree is sufficient to cause the system to fall out of lock if standard DFB lasers are being used [7].

If the two frequency components are derived from only one optical source, they will have the same phase, and, hence, no additional equipment is needed for the control of the phases. One possibility is the generation of higher harmonics, for instance, with pulsed semiconductor lasers, where the microwave spectrum of the pulsed output is a comb of frequencies with a high harmonic content [20]. Two of these sidebands can be selected by optical filtering—for instance, with a Fabry–Pérot

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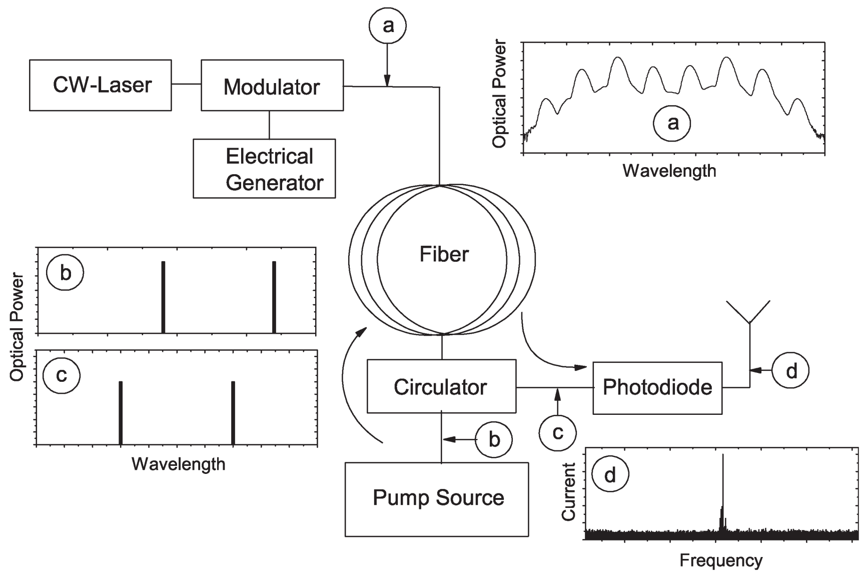

Fig. 1. Basic components of the experimental setup for the generation of mm-waves with BS. Insets (a) and (d) are measured results.

filter—to beat together in a high-speed photodiode [21]. The advantage of these techniques is that they can generate mm-wave signals with 100% modulation depth [22]. Only one optical source is used and so the phase noise of the laser modes is correlated, which results in very low phase noise electrical signals [21]. In [23], four-wave mixing in a dispersion-shifted fiber was used for the frequency comb generation, and arrayed-waveguide gratings filtered the required sidebands. With this technique, a 60-GHz optical fiber link over a distance of 108 km was shown. With an amplified fiber loop optical frequency comb generator, more than 100 lines over a 1.8-THz bandwidth in the 1.55-μm band are possible [24]. However, the optical power of the sidebands is rather low and will be further reduced by optical filtering, so additional optical amplifiers are required for this method, which introduce noise to the system and make it more complex and less reliable.

Recently, we have presented a very simple method for the tunable generation and amplification of mm-waves, which only uses standard components of optical telecommunications [25]. Our technique relies on the generation of sidebands of a continuous wave (CW) laser by the nonlinear modulation of an optical modulator. Two of these sidebands will be amplified by BS in an optical fiber, whereas the rest will be attenuated due to the natural attenuation in the fiber. The two amplified sidebands are then superimposed in a photodiode. Due to the fact that both sidebands come from the same source, there will be no problem with a phase noise. Furthermore, the system inherent amplification produces very strong sidebands that can be propagated over large distances. A frequency tuning and a modulation of the mm-wave can be done quite simply.

In this paper, we will investigate the proposed method for mm-wave generation in more detail. We will discuss the generation of higher harmonics and the advantages and limits of BS for the amplification of the sidebands. We present the result of phase noise measurements, which shows that although BS was used as the amplification process, the phase noise is astonishingly small. With the results of a numerical simulation, we are able to determine the optimum parameters for our technique. We show that the optimum fiber length mainly depends on the sideband power. Thus, it will be possible to adapt the power to a given fiber length. The numerical results are verified in experiments.

The paper is organized as follows. In Section II, we will review the idea behind the mm-wave generation with BS and the theory of harmonic generation with an MZM. Section III deals with the fundamentals of BS in optical fibers, and Section IV compares the results of our simulation and experimental results. In Section V, we will discuss the potential of our idea and possible changes and improvements. The paper closes with a conclusion.

II. Harmonic Generation

We have already discussed the experimental setup for the generation of mm-waves with BS in optical fibers in detail elsewhere [25]. Here, we will only review the most important aspects that are necessary to understand the idea behind it.

The basic components of our experimental setup are shown in Fig. 1. A signal laser generates a CW with a small linewidth. The following MZM is driven by an electrical generator working with a fixed frequency; in our case, 10 GHz. The voltage that is applied on the MZM is high enough so that the signal laser wave is modulated nonlinearly with the frequency of the electrical generator. Therefore, in the optical output spectrum of the MZM (point a in the figure), a frequency comb with a separation of 10 GHz between the different lines can be found, as shown in inset (a) in Fig. 1. The frequency comb is launched into a standard single-mode fiber (SSMF) with a length of around 50 km. The pump source generates a combined output signal of two pump lasers. This pump signal is coupled into the fiber from the other side (point b). The wavelength of each pump laser is adjusted in a manner that it is around 11 GHz higher than one of the frequencies in the comb, as shown in inset (b) in Fig. 1.

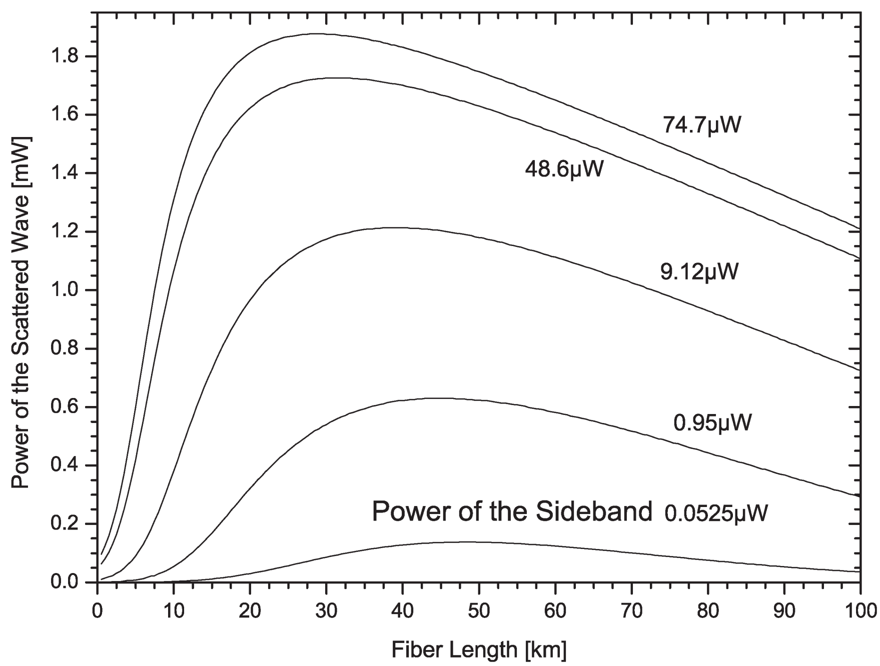

Fig. 2. Measured and simulated normalized amplitude of the sidebands behind the MZM depending on the normalized amplitude voltage.

The power of each pump laser is much lower than the power required to generate stimulated BS from the noise in the fiber. Therefore, only the two chosen frequencies of the comb are amplified by BS due to the counterpropagating pump waves. At the same time, all other frequency components present in the comb are attenuated by the fiber attenuation. Hence, the setup works like a double bandpass filter. Due to this, at the output of the circulator (point c), only two frequency components can be found [inset (c) in Fig. 1]. These two components are superimposed on a p-i-n photodiode. The output current of the p-i-n follows the fading frequency between the two components (point d). If the first two sidebands are chosen for amplification, the fading frequency is 20 GHz, with the second sidebands, it is 40 GHz, and so on [inset (d) in Fig. 1].

The RF signal from the electrical generator that drives the MZM with the frequency $\omega = 2\pi f$ can be written as [30]

$$V_m(t) = V_\pi(1+\ \epsilon) + \alpha V_\pi \cos(\omega t) \tag{1}$$

with ϵ as the bias voltage and α as the drive voltage amplitude both normalized to V_π. The factor V_π is the bias voltage that is required to produce a phase shift of π between the two arms of the generator. The output field of the MZM under the above condition can be expanded in a Bessel function as [30]

$$\begin{aligned} E_{\text{out}}(t) &= \frac{1}{2} J_0\left(\alpha\frac{\pi}{2}\right)\cos\left(\frac{\pi}{2}(1+\epsilon)\right)\cos(\omega_0 t) \\ &\quad + \sum_{n=1}^{\infty} J_n\left(\alpha\frac{\pi}{2}\right)\cos\left(\frac{\pi}{2}(n+1+\epsilon)\right) \\ &\quad \times \left(\cos\left((\omega_0 \pm n\omega)t\right)\right) \end{aligned} \tag{2}$$

where J_n is the nth Bessel function of the first kind, and ω_0 is the optical carrier generated by the CW laser. According to (2), the output spectrum of the modulator has an unlimited number of sidebands around the optical carrier separated by the RF signal of the electrical generator. If the normalized bias voltage ϵ is zero, the carrier as well as all even-order sidebands will be suppressed. If, at the same time, the drive voltage amplitude α is small only the first two sidebands will be strong in the output spectrum. With a reasonable control of α and ϵ, all the other sidebands can be suppressed significantly. In this operation, the two strong sidebands can be superimposed on a photodiode to produce a frequency of $2f$.

In our setup, we rely on a different operation of the MZM. If the drive voltage amplitude α applied to the modulator is high and $\epsilon \neq 0$, many sidebands with significant amplitude are present in the output spectrum, as can be seen in Fig. 2 for the first three sidebands. Hence, the relative amplitude of the different sidebands $J_n(\alpha(\pi/2))$ can be controlled with the parameters α and ϵ. In inset (a) in Fig. 1, all odd order sidebands are suppressed and only the even-order sidebands up to the eighth order are visible, which corresponds to a frequency difference of 160 GHz. In our setup, two of these sidebands are amplified by BS, whereas all others are attenuated due to the propagation in the fiber. The phases of any two sidebands are correlated, as can be seen from (2), and hence, the phase noise at the photodiode is suppressed if the amplification process remains the phase correlation between the sidebands.

In principle, all other optical sources producing a comb with the required frequency separation such as a frequency modulated [31] or a pulsed laser [21] are suitable for our technique as well. If the nth-order sidebands of the comb are chosen, the superposition on the photodiode produces an output frequency of $2nf$.

III. Brillouin Scattering

BS is the nonlinear effect with the smallest threshold. Due to the fact that efficient scattering can be reached already with rather low power laser diodes, it is very attractive for optical telecommunications. A constraint of BS, which is exploited here, is its low bandwidth. BS is a result of an interaction between an incident light field and the material. Density fluctuations of the material result in a refractive-index modulation, which causes a scattering of the incident wave. The refractive-index modulation moves away from the incident lightwave with a relative velocity to it. Hence, due to the Doppler effect, the scattered wave (Stokes wave) has a lower frequency than the incident wave. The frequency shift between pump and backscattered wave depends on the pump wavelength, the fiber type [33], the dopant concentration [34], as well as on surrounding conditions such as temperature and strain [26], [35]. For SSMFs at a temperature of 20 °C, this frequency shift is around 11 GHz if the pump wavelength is 1550 nm. If the origin of the density modulation is the incident lightwave by itself, the effect is called stimulated and a large part of the power is transferred to the scattered wave [26]. If other nonlinear effects are neglected, the amplitudes of the pump and Stokes waves can be described by the coupled differential equation system given as

$$\frac{dE_\mathrm{P}}{dz} = -\frac{g_\mathrm{B}}{2A_\mathrm{eff}}[\Delta k_1 + j\Delta k_2]E_\mathrm{P}P_\mathrm{S} - \frac{\alpha}{2}E_\mathrm{P} \tag{3}$$

$$\frac{dE_\mathrm{S}}{dz} = -\frac{g_\mathrm{B}}{2A_\mathrm{eff}}[\Delta k_1 - j\Delta k_2]E_\mathrm{S}P_\mathrm{P} + \frac{\alpha}{2}E_\mathrm{S} \tag{4}$$

with P_S and P_P as the powers of the scattered and the pump wave, α as the attenuation in the fiber, A_eff as the effective area, and g_B as the Brillouin gain. The variables Δk_1 and Δk_2 are phase mismatch terms that can be described by

$$\Delta k_1 = \frac{\frac{\alpha_\mathrm{a}}{2}}{\left(\frac{\alpha_\mathrm{a}}{2}\right)^2 + (\Delta k)^2} \tag{5}$$

and

$$\Delta k_2 = \frac{\Delta k}{\left(\frac{\alpha_\mathrm{a}}{2}\right)^2 + (\Delta k)^2} \tag{6}$$

whereas $\Delta k \approx 1/v_\mathrm{a}(\omega_\mathrm{S} - \bar{\omega}_\mathrm{S})$. In these equations, α_a is the attenuation, v_a is the velocity of the acoustic wave, and $\omega_\mathrm{S} - \bar{\omega}_\mathrm{S}$ is the detuning of the signal frequency from the maximum of the Brillouin gain. The phase of the amplified Stokes wave is determined by the term associated with the complex number j in (4). Therefore, if $\Delta k_2 = 0$, then the phase of the amplified sideband remains the same during the amplification process. According to (6), this is the case if the frequency detuning is zero.

We measured the Brillouin gain of our fiber with a length of $L = 50.434$ km as $g_\mathrm{B} \approx 1.2 \times 10^{-11}$ m/W. Due to the fiber length, this gain can be assumed as polarization averaged. According to (4), as long as the product of gain and pump power is higher than the fiber attenuation, the scattered wave grows exponentially with negative z. Therefore, the Stokes wave is generated in the backward direction. At the same time, the amplitude of the pump wave is decreased along z (4) due to the fiber attenuation and because it loses power to the Stokes wave. If the pump power becomes too low, the growing of the Stokes wave will come to an end and the backscattered wave will decrease if it propagates further in the fiber.

If the pump power is high enough, the backscattered wave can be generated from the noise floor in the fiber. Commonly, the input pump power (P_{0i}, with $i = 1, 2$ for the two pump waves) that is required to generate a Stokes wave from the noise with equal power is the threshold of stimulated BS. If the depletion of the pump wave due to the scattering process is neglected, this pump power will be [32]

$$P_{0i\,\max} = 21\frac{A_\mathrm{eff}}{g_\mathrm{B}L_\mathrm{eff}} \tag{7}$$

with $L_\mathrm{eff} = (1e^{-\alpha z})/\alpha$ as its effective length. For our experimental setup ($A_\mathrm{eff} = 86\ \mu\mathrm{m}^2$, $g_\mathrm{B} = 1.2 \times 10^{-11}$ m/W, $\alpha = 0.217$ dB/km, $L = 50.434$ km), the threshold can be calculated as $P_{0i\,\max} \approx 9.1$ dBm. This pump power defines the upper limit for our application. If the power is higher, the Stokes wave is generated from the noise in the fiber and the phases between the two backscattered waves are stochastic.

For our method, the pump power must be lower than the threshold for stimulated BS, but high enough that the power of the backscattered wave will increase during propagation in the fiber. If the depletion of the pump due to the Brillouin process is neglected, the pump power will only depend on the attenuation in the fiber. The intensity of the pump wave $i = 1, 2$ at the position L in the fiber is then

$$I_{\mathrm{P}i}(L) = I_{\mathrm{P}i}(0)\int_0^L e^{-\alpha z}\,dz = I_{\mathrm{P}i}(0)L_\mathrm{eff} \tag{8}$$

where $I_{\mathrm{P}i}(0)$ is the pump intensity at the fiber input. With (8) and $I_{\mathrm{P}i}(0) = P_{0i}/A_\mathrm{eff}$, it follows for the intensity of the scattered wave $i = 1, 2$ at the fiber input from (4)

$$I_{\mathrm{S}i}(0) = I_\mathrm{S}(L)e^{\frac{g_\mathrm{B}P_{0i}L_\mathrm{eff}}{A_\mathrm{eff}} - \alpha L}. \tag{9}$$

The scattered wave increases if the gain due to the Brillouin process is higher than the attenuation in the fiber. Hence, it follows that

$$\frac{g_\mathrm{B}P_{0i}L_\mathrm{eff}}{A_\mathrm{eff}} \gg \alpha L. \tag{10}$$

The minimum required pump power at the fiber input is therefore

$$P_{0i\,\min} = \frac{\alpha A_\mathrm{eff}L}{g_\mathrm{B}L_\mathrm{eff}}. \tag{11}$$

With our values, the minimum pump power can be calculated as $P_{0i\,\min} \approx 0$ dBm. According to this deliberation, the pump power for our experimental setup lies in the range from 0 to 9 dBm.

A disadvantage of BS is the very high amplified spontaneous emission noise, which can be about 20 dB higher than that of an ideal amplifier [27]. This limits the applicability of BS for signal boosting in lightwave systems [28]. However, for higher signal levels—as in our case—the amplified spontaneous

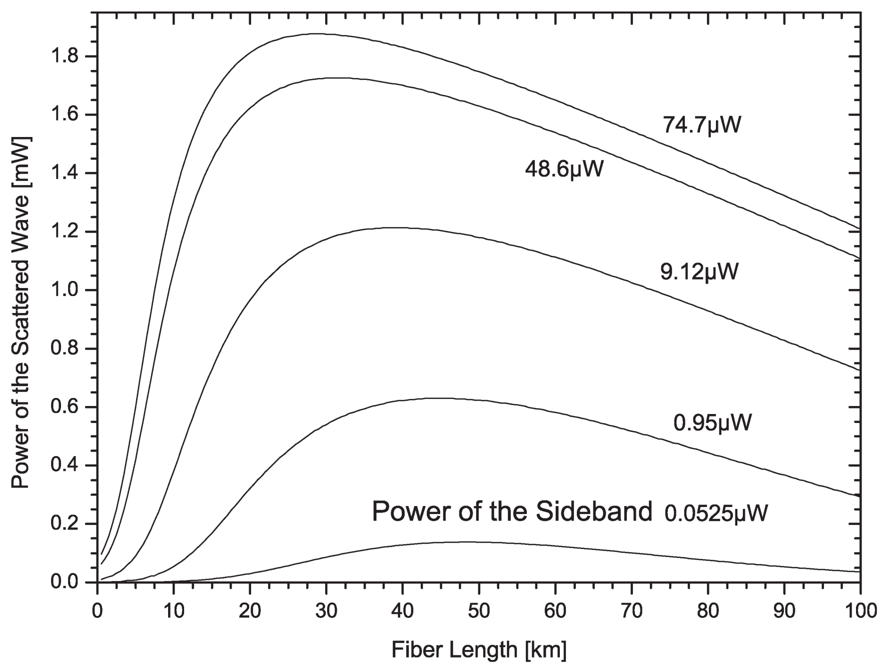

Fig. 3. Simulated power of the scattered wave depending on the fiber length for different powers of the sideband at the beginning of the scattering process. For the simulation, the following parameters were used: pump power $P_0 = 4.2$ mW; $g_\mathrm{B} = 1.2 \times 10^{-11}$ m/W; $A_\mathrm{eff} = 86\ \mu\mathrm{m}^2$; and $\alpha = 0.217$ dB/km.

emission noise can be reduced significantly if the BS is in the saturated regime [29].

For quasi-monochromatic pump waves, the spectrum of the Brillouin gain is very narrow. For our SSMF, the spectral distribution can be approximated by a superposition of a Gaussian and Lorentzian function, it depends on the temperature and strain of the fiber and on the pump power. For the full-width at half-maximum (FWHM), we measured around 36 MHz at room temperature for a signal power of -3 dBm and a pump power of 4.77 dBm. Hence, this is the smallest achievable resolution or, in other words, the minimum frequency that can be generated with our method is higher than 36 MHz. The maximum frequency depends on the frequency comb generation method and the bandwidth of the photodetector; so with current photodetectors, frequencies as high as 330 GHz [36] are possible.

On the other hand, for pure BS, the 36-MHz frequency determines the maximum bandwidth that a modulated sideband can have. However, with an additional modulation of the pump lasers, the bandwidth of the Brillouin gain can be enhanced significantly [37]. Thus, for broadband applications, the bandwidth of BS can be adapted to the application with a modulation of the pump lasers.

IV. RESULTS

Equations (7) and (11) were derived under the simplification that the pump depletion can be neglected. If the Stokes wave is amplified remarkably, this simplification is no longer applicable, because the power that was won by the Stokes was lost by the pump wave. Therefore, for exact predictions the differential equation system (3) and (4) must be solved numerically. Since both sidebands behave in the same manner and there is no interaction between them, the investigation of just one sideband is sufficient.

The results of our numerical simulation are shown in Fig. 3. The trace indicated by "48.6 μW," for instance, can be read as follows: If into the output of a fiber with a length of 70 km a signal with a power of 48.6 μW is injected, the BS leads—under the given parameters—to a backscattered wave with a power of 1.4364 mW at the fiber input, whereas, if the fiber length is only 30 km, the power at the fiber input is higher, namely 1.73 mW. According to this, there is an optimum fiber length, and this optimum length depends on the power of the injected signal. For higher signal powers, the optimum fiber length is shorter than for smaller ones. The optimum fiber length for a signal with a power of 74.7 μW is, according to Fig. 3, $L_\mathrm{opt} \approx 29$ km. Whereas, if the power of the sideband is only 0.05 μW, the optimum length is $L_\mathrm{opt} \approx 48.5$ km. The optimum length does not only depend on the signal power but on the pump power as well. However, as can be seen in Fig. 4, the effect is much less dramatic. For pump powers in the working range of our setup, the optimum length changes only around a few kilometers.

If we assume a frequency comb having sidebands with an equal power of 48.6 μW, the optimum length for a pump power of $P_0 = 4.2$ mW is $L \approx 32$ km, according to Fig. 3. The power of the amplified sidebands at the fiber input is $P_\mathrm{s} \approx 1.73$ mW, leading to an amplification of 15.5 dB. At the same time, all the other sidebands undergo an attenuation of 7 dB. Therefore, the difference between the gain of the amplified sidebands and the loss of the nonamplified sidebands is 22.5 dB. The gain–loss difference, or the ratio between amplified and attenuated power, is shown in Fig. 5 for our simulation parameters. As it can be seen, already for a fiber length of only 10 km, the two amplified sidebands are 15–20 dB above the rest, if the initial power of all sidebands is the same.

We investigated our simulated predictions in an experimental setup as shown in Fig. 1. The wavelength of the signal laser was 1578.6 nm, with an optical power of 3.31 dBm and a

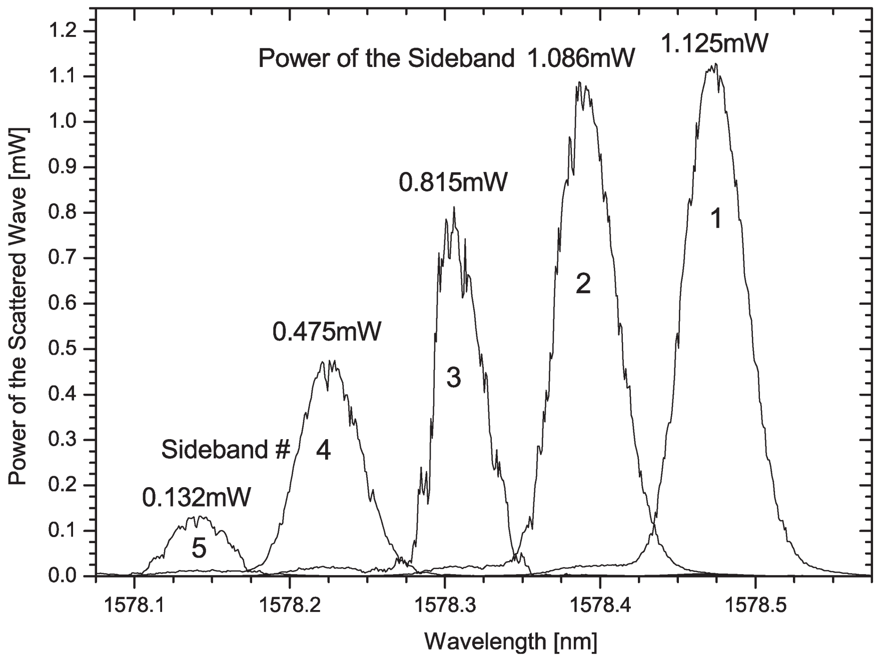

Fig. 4. Simulated power of the scattered wave depending on the fiber length for different pump powers and a fixed sideband power of 48.6 μW. For the simulation, the following parameters were used: $g_{\mathrm{B}} = 1.2 \times 10^{-11}$ m/W; $A_{\mathrm{eff}} = 86\ \mu\mathrm{m}^2$; and $\alpha = 0.217$ dB/km.

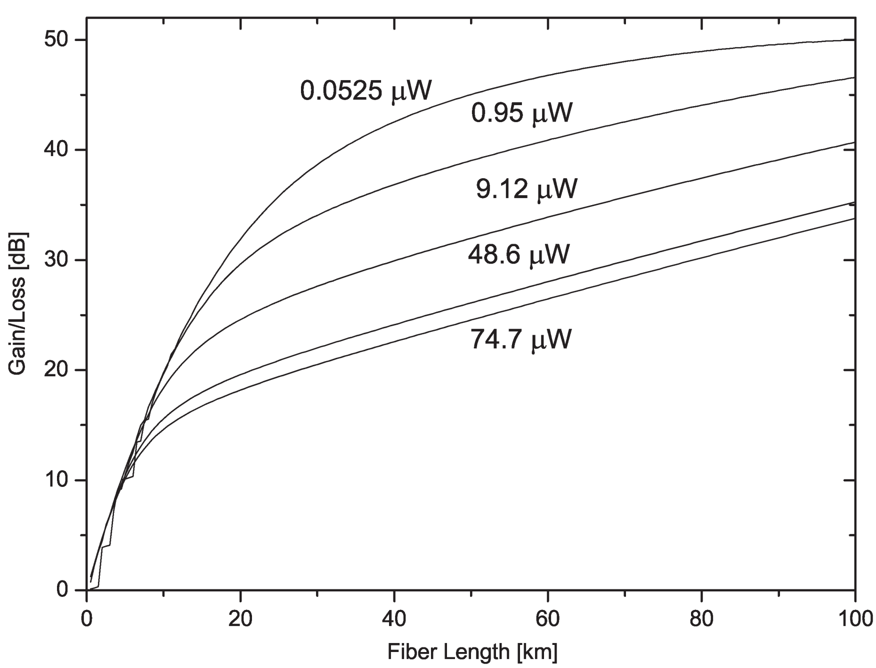

Fig. 5. Ratio between amplified and nonamplified sidebands for different initial sideband powers depending on the fiber length ($P_0 = 4.2$ mW, $g_{\mathrm{B}} = 1.2 \times 10^{-11}$ m/W, $A_{\mathrm{eff}} = 86\ \mu\mathrm{m}^2$, and $\alpha = 0.217$ dB/km).

linewidth of < 1 MHz. The MZM was driven with a fixed frequency of 10 GHz. The length of the SSMF ($A_{\mathrm{eff}} = 86\ \mu\mathrm{m}^2$, $g_{\mathrm{B}} = 1.2 \times 10^{-11}$ m/W, $\alpha = 0.217$ dB/km, $L = 50.434$ km) was not changed during the experiments, and the power of the pump laser was fixed to 6.23 dBm. At point a in the setup, we measured the power of the different sidebands generated by the MZM and changed the wavelength of the pump laser in order to amplify each sideband independently. The superimposed spectra of the five amplified sidebands, measured at point c in the setup, can be seen in Fig. 6.

A comparison between the simulated and the measured results is shown in Table I. As it can be seen, simulation and measurement are in good compliance with each other.

The phase noise and the spectrum of the converted 40-GHz signal at the output of the 50-km fiber are shown in Fig. 7. For this measurement, we used a fiber laser with a narrow bandwidth of less than 1 kHz as a signal laser. We determined the FWHM bandwidth of the converted signal with an electrical spectrum analyzer to be around 300 Hz. However, due to the fact that the resolution of the analyzer is 300 Hz, we assume

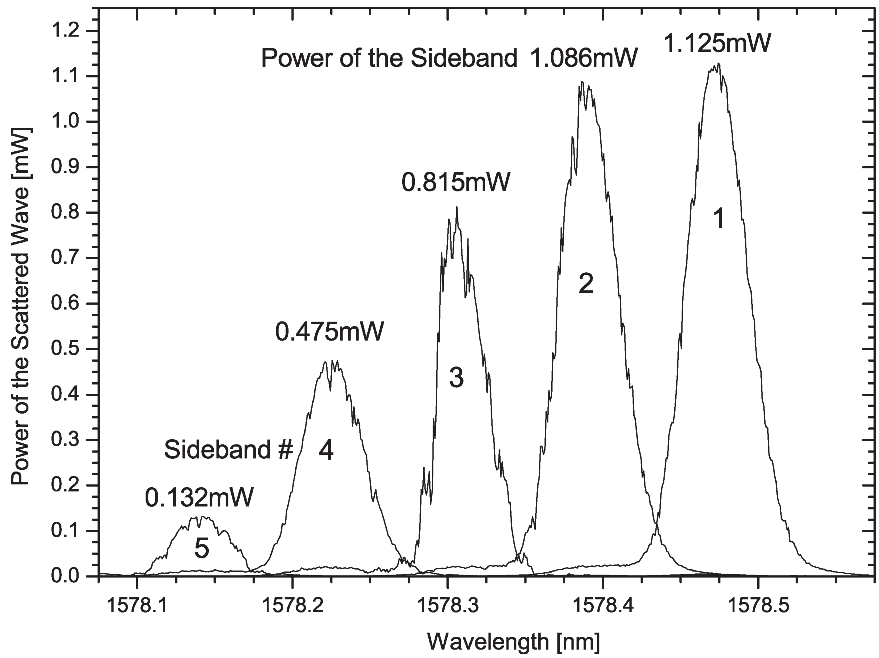

Fig. 6. Superimposed spectra of the sidebands at point c in Fig. 1 amplified by BS for a pump power of 6.23 dBm and a fiber length of 50.434 km. Please note that the resolution of our spectrum analyzer is 0.1 nm, and hence, the shown bandwidths of the spectra are strongly exaggerated.

TABLE I
SIMULATED AND MEASURED VALUES FOR THE AMPLIFIED SIDEBANDS WITH DIFFERENT POWER. PARAMETERS FOR THE SIMULATION AND THE EXPERIMENT ARE GIVEN IN THE TEXT. POINTS a AND c ARE RELATED TO FIG. 1. PLEASE NOTE THAT THE SIMULATED RESULTS WERE REDUCED BY 1.6 dB IN ORDER TO INCORPORATE THE ADDITIONAL ATTENUATION OF THE CIRCULATOR

Sideband #	Power at a [μW]	Power at c Simulated [mW]	Power at c Measured [mW]
1	74.7	1.21	1.12
2	48.6	1.12	1.1
3	9.12	0.82	0.81
4	0.92	0.43	0.47
5	0.0525	0.1	0.13

that the actual bandwidth of the signal is smaller. Although BS was used for the amplification of the sidebands, the phase noise is remarkably small. Without any optimization of the setup in respect to noise characteristics, we achieved a phase noise of less than −90 dBc/Hz for a frequency separation above 10 kHz from the carrier. Thus, we assume that, for instance, with a smaller fiber length, the phase noise can be further decreased.

V. DISCUSSION

The special advantage of our method is its simplicity; the whole experimental setup only uses standard elements of optical telecommunications. The main idea is the amplification and following heterodyne superposition of two sidebands generated from one source. Due to the fact that both sidebands come from the same source, they show a phase correlation minimizing the effect of phase noise in the photodiode. The generation of sidebands is not necessarily restricted to an MZM. The MZM can be saved if the signal laser is directly modulated with the electrical generator. In the case of frequency modulation, the laser directly generates sidebands of the modulation signal [31] that can be amplified by BS. Another possibility is the incorporation of a broadband signal laser with sidebands in its output spectrum, for instance, a pulsed laser [21] or a Fabry–Pérot laser. Nonlinear optical effects such as four-wave mixing can also be used for the generation of a frequency comb [38].

The exploitation of a so-called supercontinuum [39] generated from short pulses by nonlinear physical processes is also very interesting. Such a supercontinuum can span over an octave [40]. Thus, with many different pump lasers amplifying parts of the supercontinuum, a large number of mm-wave carriers with different frequencies can be produced from only one source.

The setup as shown in Fig. 1 can be used for the generation of mm-waves in the control station. In this case, a fiber for the distribution of the generated waves from the control to the base station can be connected at point c. Due to the fact that both sidebands were amplified by BS, the power of the sidebands is sufficient to propagate over large distances in optical fibers without the need of additional amplification. Another possible setup can use the fiber in which the BS amplifies the sidebands for the propagation between control and base station as well. In this case, the pump lasers are located in the base station. Due to the fact that the optimum length of the fiber is mostly determined by the power of the sidebands—as can be seen in Fig. 3—it will be possible to adapt the sideband power to the given fiber length.

The pump lasers interact independently of each other with the respective sideband. Therefore, not only one mm-wave carrier can be generated in the optical fiber. As long as the separation is not smaller than the resolution of BS, in principle, in the whole transparency range of the fiber, mm-waves can be

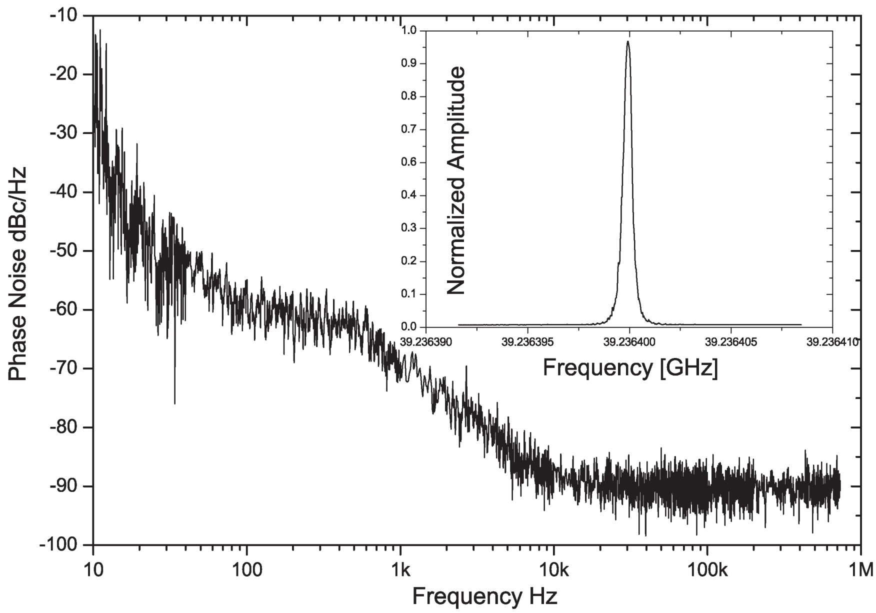

Fig. 7. Phase noise and spectrum (inset) of the converted 40-GHz signal.

produced. Due to this, the control station can inject a frequency comb into a fiber. Every base station connected to this fiber can generate its own mm-wave independently by amplification of just two of these frequencies out of the comb.

The frequency of the mm-wave depends on the RF of the electrical generator and on the sidebands that were chosen for amplification. The generated mm-wave has the frequency

$$f_{\mathrm{mm}} = 2nf \tag{12}$$

with n as the number of the sideband used and f as the RF of the electrical generator. With $f = 10$ GHz, mm-waves with frequencies of 20, 40, 60, 80, ... GHz are possible. If the frequency of the generator is $f = 5$ GHz, output frequencies of 10, 20, 30, ... GHz can be produced, and so on. Hence, with a common control of the RF and the pump lasers wavelengths, the setup can be tuned to produce frequencies in the range from a few tenths of megahertz up to the limit set by the photodetector used.

A modulation of the mm-wave with a baseband signal can be performed with an additional modulator (MZM) inserted behind one of the pump lasers, for instance. Much easier is the direct modulation of the signal laser or one of the pump lasers. If the control current of a laser is changed, it alters its output wavelength. So if, for instance, the control current of one of the pump lasers is altered, depending on the baseband signal, its wavelength shift in comparison to one of the sidebands fulfills the condition for BS if the control current is high. Whereas, if it is low, the condition is not fulfilled. Hence, if the control current is high, the sideband will be amplified, leading to a mm-wave signal due to the superposition with the other sideband. If the control current is low, only one sideband is present at the photodiode, and, hence, no mm-wave signal is generated. Another possibility is the modulation of the electrical generator. If it is frequency modulated, depending on the baseband signal, the frequency comb generated by the MZM will be shifted. If the sidebands slip out of the bandwidth of BS, they will no longer be amplified, which leads again to an intensity modulation of the mm-wave. A frequency modulation can be done by a common control of RF and pump wavelengths. In wireless communications, higher order modulation formats like quadrature amplitude modulation (QAM), m-ary phase-shift keying (M-PSK), and others are of special interest because of their spectral efficiency. To what extent our mm-wave generation technique is suitable for such modulation techniques will be investigated in future research activities.

The proposed method was discussed from the viewpoint of a downlink system. However, an uplink is possible as well if alongside with the two modulated wavelengths for the downlink (λ_1, λ_2) two additional wavelengths (λ_3, λ_4) are delivered from the control to the base station. The frequency difference between the two additional wavelengths corresponds to the uplink frequency of the wireless system. A filter in the base station separates λ_1 and λ_2 from λ_3 and λ_4. An additional photodiode generates the uplink frequency from λ_3 and λ_4. This frequency is mixed with the received signal in an oscillator producing the baseband signal. The baseband signal is then used to modulate a laser diode or an additional modulator. A modulated optical signal with the wavelength λ_5 can then be sent back to the control station over the same fiber.

VI. Conclusion

We have investigated a new and simple method for the tunable generation of mm-waves for radio-over-fiber systems in theory and experiment. The method relies on the separate amplification and heterodyne detection of two sidebands out of a frequency comb. All the other sidebands are attenuated due to the fiber attenuation. Already for a fiber length of only 10 km, the ratio between amplified and nonamplified sidebands is between 15 and 20 dB. A tuning of the generated frequency can be done in a very simple way by the alteration of the generator frequency and the pump wavelengths.

The phase correlation between the sidebands will be maintained during the amplification process. Thus, we measured a very low phase noise. The optimum length of the fiber required for the amplification depends on the power of the sidebands. Hence, it will be possible to adapt the sideband power to a given fiber length. The Brillouin gain bandwidth can be extended to a 3-dB bandwidth of 1.5 GHz and 10-dB bandwidth of 2 GHz by controlling the spectrum shape of the pump wave using binary phase-shift keying modulation with an arbitrary pulse pattern [37], [41]. Therefore, wideband and high-speed applications might be possible. The increase of the Brillouin bandwidth and the investigation of the robustness of our mm-wave generation technique in respect to a modulation, especially to higher order modulation formats, will be addressed in future research activities.

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