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Rasha K. Al-Dabbagh, Hamed S. Al-Raweshidy, "64-GHz millimeter-wave photonic generation with a feasible radio over fiber system," *Opt. Eng*. **56**(2), 026117 (2017), doi: 10.1117/1.OE.56.2.026117.

64-GHz millimeter-wave photonic generation with a feasible radio over fiber system

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Abstract. A full-duplex radio over fiber (RoF) link with the generation of a 64-GHz millimeter wave (mm-wave) is investigated. This system is proposed as a solution to cope with the demands of a multi-Gb/s data transmission in the fifth generation (5G) and beyond for small cell networks. Cost reduction and performance improvement are achieved by simplifying the mm-wave generation method with an RoF technique. High-frequency radio signals are considered challenging in the electrical generation domain; therefore, our photonic generation method is introduced and examined. RoF design is proposed for mm-wave generation using both phase modulation and the effect of stimulated Brillouin scattering in the optical fiber for the first time. RoF system with transmission rates of 5 Gb/s is successfully achieved. In our scheme, one laser source is utilized and a fiber Bragg grating is used for wavelength reuse for the uplink connection. Stable mm-wave RoF link is successfully achieved in up to a 100-km fiber link length with high quality carrier. Simulation results show a reduction in fiber nonlinearity effects and the mm-wave signal has low noise equal to −75 dBm. This study ensures a practical mm-wave RoF link, and it could be appropriate for small cell 5G networks by reducing the installation cost. [DOI: 10.1117/1.OE.56.2.026117]

Keywords: millimeter wave; phase modulation; photonic generation; radio over fiber; stimulated Brillouin scattering; 5G network.

Paper 161293 received Aug. 18, 2016; accepted for publication Jan. 30, 2017; published online Feb. 17, 2017.

1 Introduction

A radio over fiber (RoF) system has recently been developed to optically distribute radio signals over longer distances. Due to the rapid revolution in wireless and mobile technology, RoF is becoming a potential option to cope with high capacity demands of this fast growth communication area for the new broadband services.[1] RoF technology also has the ability to provide simple antenna front ends and improve the wireless access coverage.[2] The overcrowded microwave band and the lack of global bandwidth for wireless communication have encouraged the improvement and the implementation of mm-wave spectrum for 5G communication networks. Applying mm-wave frequencies simplifies the design of practical wireless mm-wave communications, which can offer suitable terminal mobility and high capacity channels.[3–8] Millimeter-wave (mm-wave) with an RoF system is one of the promising candidates to deliver high-speed radio transmission with seamless convergence between optical and radio signals. In addition, RoF technology could directly convert an optical signal to a high frequency radio signal with a photonic direct up-conversion scheme. To keep the remote cells simple, cost effective, and energy efficient, the photonic generation of the mm-wave signal from the RoF link is considered important. This additionally guarantees low-latency transmission for the wireless mm-wave signals so it could offer a satisfying solution with good flexibility for a mobile and broadband access network.[5,9] Figure 1 presents a converged RoF system for realizing high-capacity heterogeneous mobile networks.

By utilizing this system, mm-wave wireless signals will be transmitted from the central station (CS) directly to the remote radio heads (RRHs), so the RRHs are simplified to deal with only the process of conversion and amplification. This means the signal processing could be pooled in a cloud at central stations. The radio access units (RAUs) of the mm-wave RoF link are becoming simpler as well. With this configuration, it is possible to obtain a flexible cloud-based radio access network solution for upcoming high-speed networks. This system can be useful in different applications, such as last-mile broadband access networks and resilient access networks. The performance of free-space optical communications also depends on the weather as is well known, but it still can be an alternative solution for short-range fiber cables. The combination of fiber and mm-wave links can be very vital due to its large bandwidths, high capacity, and robust feature.[10–12] Ultimately, to obtain a higher data rate in 5G wireless networks, it is very important to fulfill the requirement of transmission latency and jitter. This requirement will restrict the length of the fiber link to a few kilometers.[13,14]

An RoF system operating at mm-wave frequency bands, which are license-free bands, such as 57 to 64 GHz, 71 to 76 GHz, and 81 to 86 GHz, has been considered a promising candidate to meet the required capacities for wireless backhauling of future mobile network standards. The capacity of these mm-wave bands exceeds the capacity of microwave bands and they also offer a simplification of base stations over the deployment of RAUs by reusing the passive optical network.[9] In a mm-wave RoF system, the optical fiber is used to transmit mm-wave carriers that are generated,

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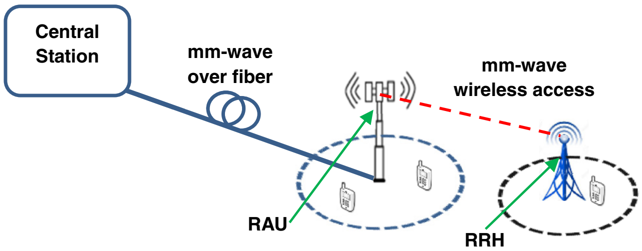

Fig. 1 A converged RoF system for heterogeneous networks.

modulated with data, and up-converted in a central station to the base stations that are distributed through the fiber network. Then base stations transmit the mm-wave signal to the end user. Due to high atmospheric attenuation at mm-wave bands, the operational coverage of base stations is reduced to small cells. This increases the number of base station requirements to allocate coverage to the entire geographic area. Simple and efficient signals distribution to the remote base stations will be verified by using low-cost optical mm-wave generation method with photonic frequency up-conversion schemes and effective modulation at the central station.[15–18] Recently, several investigations have studied the transmission of mm-wave over converged RoF systems.[5,8,9,15,16,19,20] The unlicensed 60-GHz frequency region has global interest and could offer multi-Gb/s data rates, which support the growing capacity demands. Integrating mm-wave in a 60 GHz frequency wireless system with a fiber distribution network would facilitate the delivery of the high data rate wireless signals to a large number of wireless access points with radio coverage optimization. Analog RoF mm-wave signal transmission has the potential to reduce the complexity and cost of the remote antenna site hardware. It enables centralized control and management of the wireless signals. Due to that, only optical to electrical conversion and radio frequency amplification is required. This is considered one of the important benefits for fiber distributed mm-wave wireless systems, which essentially need the deployment of a large number of antenna units.

Optical generation techniques of mm-waves have been presented in widely different methods. Some approaches are based on dual mode or wavelength lasers, injection phase locking, mode locked lasers, optical external modulation, and optical heterodyning techniques. The other optical generation methods are based on nonlinear properties, such as four-wave mixing and stimulated Brillouin scattering (SBS).[21] Nonlinear effects in optical fiber can limit the capacity of transferring information. Due to this, some research has presented schemes to cancel the Kerr-induced distortion in optical fibers based on wavelength division multiplexing systems that are generated by frequency combs, which are considered easier to use in digital electronics as the nonlinear distortions are more deterministic.[22]

In the literature, some studies are focused on the demonstration of low-cost laser types like a doped fiber external cavity laser to generate mm-wave signals for use in RoF systems and sensors.[23] But there is still a challenge in implementing such lasers in RoF networks because of the large size and high cost of the optical components and devices. Other research has proposed a simple setup using a directly modulated dual-mode laser with third-order intermodulation distortion.[24] They have tried to increase the transmission capacity and optimize the optical received power but still face induced nonlinear modulation distortion that is included in a dual-mode laser. In recent research, the need for multi-Gb/s data transmission in 5G communications is shown so they have proposed a photonic-based method for generating mm-waves applicable in the fronthaul in the 60-GHz frequency band RoF system for transmission of orthogonal frequency division multiplexing. But their method is based on a dual wavelength fiber laser and still has a large size and complex structure.[25]

In our recent research,[26] we proposed and demonstrated novel mm-wave generation models based on SBS nonlinearity effect in the optical fiber. These generation models are based on the Brillouin fiber laser properties and the effect of SBS in the fiber link with the characterization of phase modulation. The generation of mm-wave with different frequencies is done for the first time with a very simple optical communications setup, as proven in our previous demonstration.[26] The generation of mm-waves by applying the proposed methods can reduce the system cost, as well as having the possibility to generate mm-wave carriers with low signal noise and very high stability. This could improve mm-wave RoF technology to meet 5G networks requirements.

In this paper, our RoF link based on a photonic generated mm-wave is proposed for the first time. This new setup differs from the previous related research by taking into consideration the generation and transmission performance of mm-wave. The mm-wave signal is generated using a phase modulator and it has been investigated with the benefits of SBS in the fiber. Exploiting a single laser source with direct data modulation will reduce the cost and complexity of the system. On the other hand, the use of a fiber Bragg grating (FBG) for wavelength reuse has increased the stability of the mm-wave over RoF link and reduced the nonlinearity properties as well. In our setup, there is no need to apply expensive components to generate mm-waves like some previous techniques that used costly apparatus to reduce complexity. Due to that, this research proposes a simple setup which has the potential to support the implementation of mm-waves in wireless systems that are integrated with an optical fiber link in 5G networks.

2 System Principle and Architecture

In this section, the operating principle of the proposed full-duplex RoF link with the photonic generation method of mm-waves is presented and the evaluation of the system performance is discussed. Figure 2 explains a block diagram of the proposed system design. The full-duplex mm-wave RoF network consists of two main parts: the central station and the RAU. The central station consists of a directly modulated laser, which is driven by data signals, a phase modulator, which is driven by RF sinusoidal signals of the local oscillator, and the uplink receiver. A phase modulator can be stably operated without an electrical DC bias control circuit. Besides, a phase modulator has a small insertion loss; therefore, the RoF system using the phase modulator has a larger margin. So, the phase modulator is driven by the appropriate radio frequency signal and this will lead to obtaining small modulation depth. Therefore, the reuse of the remaining optical carrier can realize the cost-effective operation. The optical signals are then launched into the standard single-mode fiber (SMF) and propagated to the RAU.

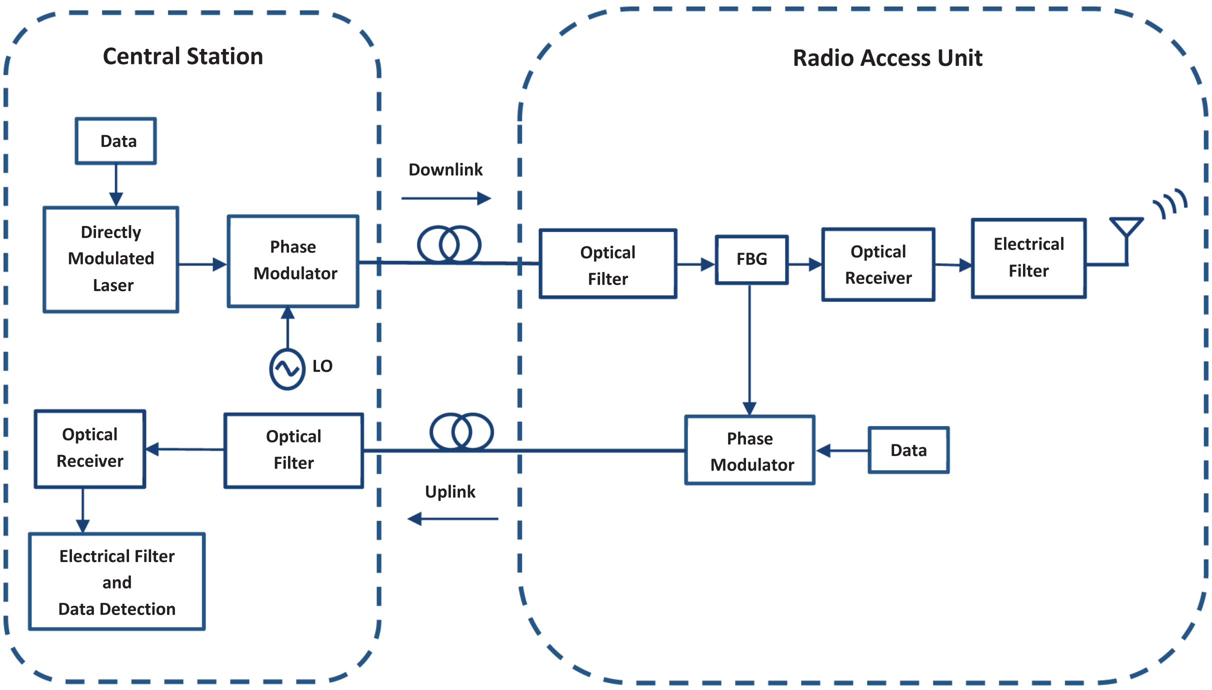

Fig. 2 A block diagram of a full-duplex RoF with mm-wave photonic generation.

After the transmission of the optical carrier along the fiber, the optical signal is filtered and amplified in the RAU. An FBG is used to reuse the optical carrier for the uplink signal. The other part of the optical carrier, which passes through the FBG, will be then coherently detected by the optical receiver to produce the required mm-wave signal. Detection methods (i.e., coherent or incoherent methods) can be applied. Although the incoherent detection is simple, its performance is not in the same quality as that of the coherent method to have a stable mm-wave carrier, which is essential in this RoF system. An optical modulation technology based on a phase modulator could generate such a high-quality mm-wave over fiber. After that, an antenna is operated to transmit and receive the mm-wave wireless signal to and from the user terminal. In the uplink direction, after the detection process, the signal is modulated on the optical carrier and then transmitted back to the CS through the optical fiber.

In this research, we proposed a mm-wave generation model based on SBS with RoF. Brillouin scattering happens in the fiber due to the process of interaction between light with propagating density waves or acoustic phonons. This process exists in each fiber because of microscopic defects and thermal fluctuations. The SBS effect is an important consideration among the other fiber nonlinear effects. The SBS threshold power (P_{th}) is indicated from the point where SBS becomes a limiting factor. The use of a laser source with narrow linewidths makes SBS have a low threshold power in the schemes. When the linewidth of the laser source is smaller than the Brillouin bandwidth, P_{th} can be assessed with Eq. (1):

$$P_{\text{th}} = 21\frac{kA_{\text{eff}}}{gL_{\text{eff}}}\left(1+\frac{v_{\text{s}}}{v_{\text{b}}}\right), \tag{1}$$

where k is the polarization factor (equals to number 2, depending on the wave polarization state), A_{eff} is the fiber effective area (equals to 80 μm^2), g is the Brillouin gain (46×10^{12} m/W), v_{s} is the linewidth of the laser source (we have examined 3 values 1, 10, and 100 MHz), and v_{b} is the SBS interaction bandwidth (31.7 MHz for 1550 nm laser wavelength). L_{eff} is the interaction effective length, which can be defined and calculated as

$$L_{\text{eff}} = \frac{1-\exp(-\propto L)}{\propto}, \tag{2}$$

where α is the attenuation coefficient (0.2 dB/km) and L is the length of the fiber (varied from 5 to 100 km).[27]

This nonlinear effect will produce mm-wave signals by the heterodyning with the laser source signals. The optical heterodyning technique is generating mm-waves that depend on the principle of combining two optical signals in a photodiode (PD). This can produce an electrical signal having a frequency equal to the frequency difference between the two optical signals.

In an alternate technique, the SBS nonlinear effect is utilized to produce mm-waves by the heterodyning method with phase-modulated signals. In theory, the optical field envelope of the phase modulator output is denoted by Eq. (3):

$$E(t) = \exp[j\beta\cos(\omega_{\text{m}}t)] = \sum_{n=-\infty}^{\infty} j^n J_n(\beta)\exp(jn\omega_{\text{m}}t)$$
$$= \sum_{n=-\infty}^{\infty}\Gamma_n, \tag{3}$$

where $E(t)$ is the optical carrier amplitude, β is the modulation index, ω_{m} is the angular frequency of the modulating microwave signal, and $J_n(\beta)$ is the Bessel function of the first kind of order n.[26]

This transmission of analog mobile signals on mm-wave RoF systems offers many advantages compared to other solutions. Scalability and latency reduction are two of the main issues that can be solved with mm-waves over fiber systems. Mm-wave transmission over fiber offers enormous bandwidth up to THz. A large optical bandwidth implements a huge increase in signal processing speed. Furthermore, optical fiber has low loss transmission, which is very useful in distributing wireless data transmission. This makes mm-waves with RoF technology a viable solution. The system cost is reduced because the complex and expensive equipment is set at the CS, while simpler, smaller, and lighter remote antenna units are located at the base stations.[28] This contributes to make the processes of installation and maintenance very easy. In addition, a good amount of power could be saved in due to the improved and simplified RAU. In 5G networks, this system can be integrated with optical access networks to use the benefits of installed fiber. The centralization of the network management is suitable for the analog waves of mobile communication because all the computing processes are placed in the central stations. This means system complexity can also be simplified with the network arrangement. The use of an SBS fiber laser in these systems can enable dispersion tolerant signal transport while also supporting the optical encoding and wireless transmission of high-data rate signals.[15]

3 Simulation Setup and Results

The proposed architecture is built by using Optisystem simulation to analyze and calculate the results of the system. Simulation results for our scheme are represented and explained using this advanced optical simulation package with the ability to virtually design, test, and optimize the optical link properties in the physical layer of a broad spectrum of optical networks. This research investigates a full-duplex RoF link based on a simple photonic generation method of mm-waves, which is proposed for the first time. The configuration of the mm-waves generating methods is schematically shown in Fig. 3, in which simulation optical spectrum results are presented.

Applying this mm-wave with RoF technology is suggested in this work for the next-generation communication

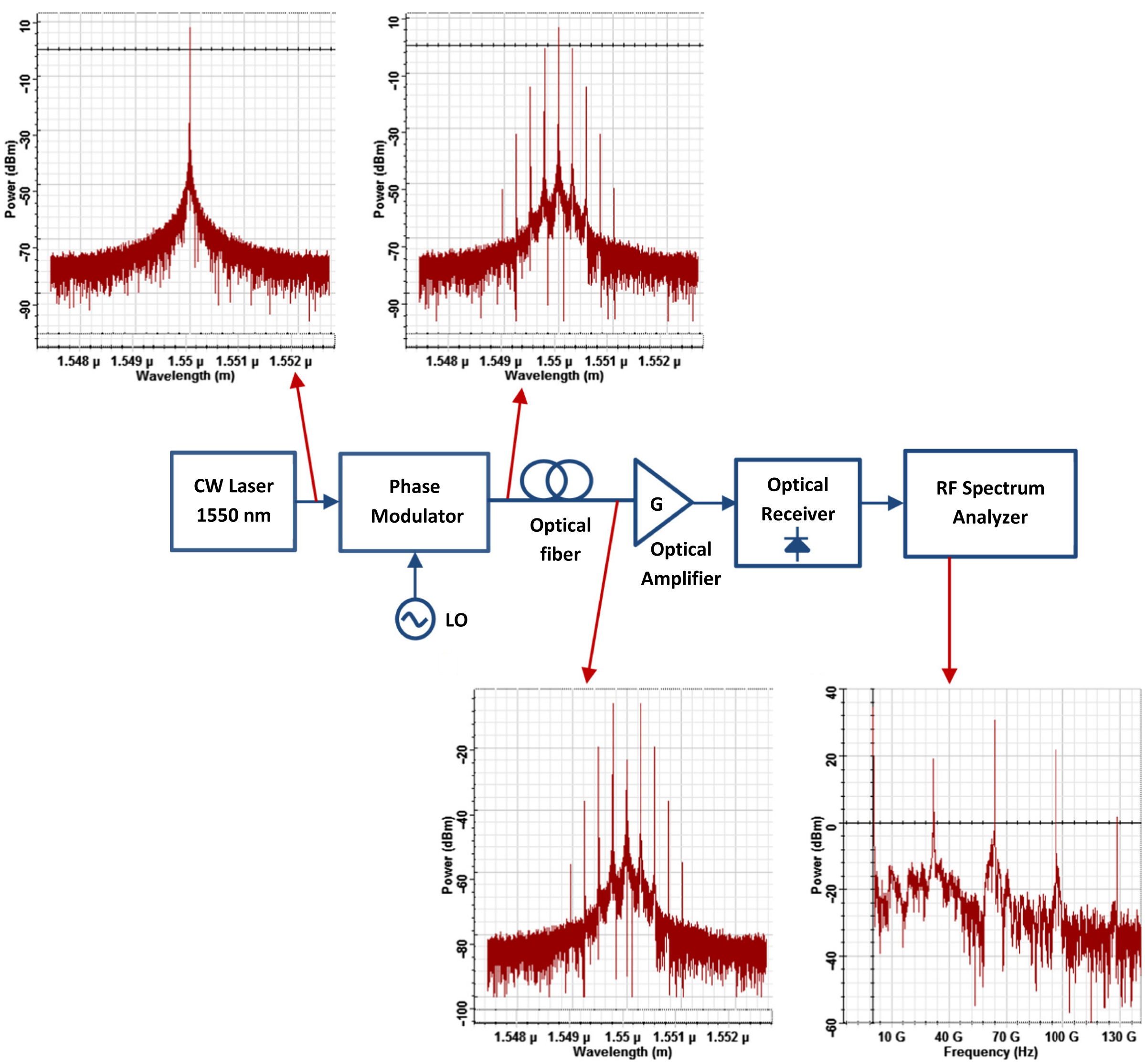

Fig. 3 The experimental setup of mm-wave generation method with simulation results.

systems. For this reason, two main issues are taken into consideration, the frequency fluctuation and spurious sidebands suppression ratio. Latest research shows that the easiest way for mm-wave generation is the use of two laser sources.[5] Mm-waves fluctuate around a central frequency because of the phase mismatch between two diode lasers and the relative frequency instability. This adds the residual frequency offset and increases the single sideband phase noise. In our research, we avoid this situation by using a single laser source as a pump wave source. In some research, suppression methods are presented to cancel undesired optical sidebands and generate mm-waves. In this case, the suppression ratio limits the influence of the whole mm-wave generation system. The analysis of the latest research showed that the suppression ratio of the optical side band can go above 37 dB and the suppression ratio of the RF sideband exceeds 31 dB.[29]

Optical power fluctuates due to the SBS effects and this will degrade the Q factor and the bit error rate (BER) of the optical communication system. This will limit the performance of the optical transmission system, thus the laser input power to the fiber should be kept less than the Brillouin threshold. The maximum power transmitted through the fiber can be obviously affected by this and this will limit the efficiency of fiber lasers. Figure 4 shows our simulation result when we varied the input power versus Q factor. This graph shows that the Q factor degrades sharply when the optical power increased to more than 8 dBm. This means that the Brillouin threshold for our setup is around 8 dBm and the degradation of the Q factor begins after reaching this value.

The use of a directly modulated laser has the option of increasing the linewidth of the laser source, but it can increase the dispersion penalty as well. To avoid this, it should modify the linewidth of the laser and this will decrease the SBS threshold power without increasing the dispersion penalty that is related to the direct modulated laser. Figure 5 shows the relationship between SBS threshold power and fiber length for three different linewidths, which is calculated by Eq. (1) due to our simulation parameters. The SBS threshold decreases with the increase of effective fiber length but it has higher values when applying higher laser linewidth.

The system performance of our proposed approach, as shown in Fig. 3, is simply optimizing the generation of stable mm-waves. In our set up, a narrowband linewidth laser source (1 MHz linewidth) is used with 8-dBm power at a wavelength of 1550 nm. The continuous wave (CW) laser enters into the phase modulator and the modulated signals are propagated through the optical fiber. Due to the appropriate laser power, first-order side bands (FOBS) are generated regarding the SBS effect in the fiber, where the Brillouin linewidth is set to 31.7 MHz with frequency shift equals 11 GHz.

The effect of SBS is involved in the optiwave simulation. The simulation of SBS used here is based on nonlinear Schrödinger equations, which are solved in the simulator program by the use of the symmetrized noniterative split-step Fourier method. In our set up, the step size is selected to be variable so it changes depending on the value of the maximum nonlinear phase shift and the calculation process in this case is more flexible and faster. If the step size is fixed, it will be calculated only once when the simulation starts. Due to that, we have used a variable step size and the optical fiber numerical parameters are set up as follows: the number of iterations is 50, the number of steps is 200, and step accuracy is 0.001.

The spectrum analyzer results from the simulation are shown in Fig. 3 for both the generated signals at the output of the laser source and the effect of the FOBS on phase-modulated signals. By applying this setup, the achievement of high quality mm-waves at different frequencies is possible. The simulation result also shows that the generation of mm-wave carriers has low noise on a signal at a high frequency up to 96 GHz with good peak power.

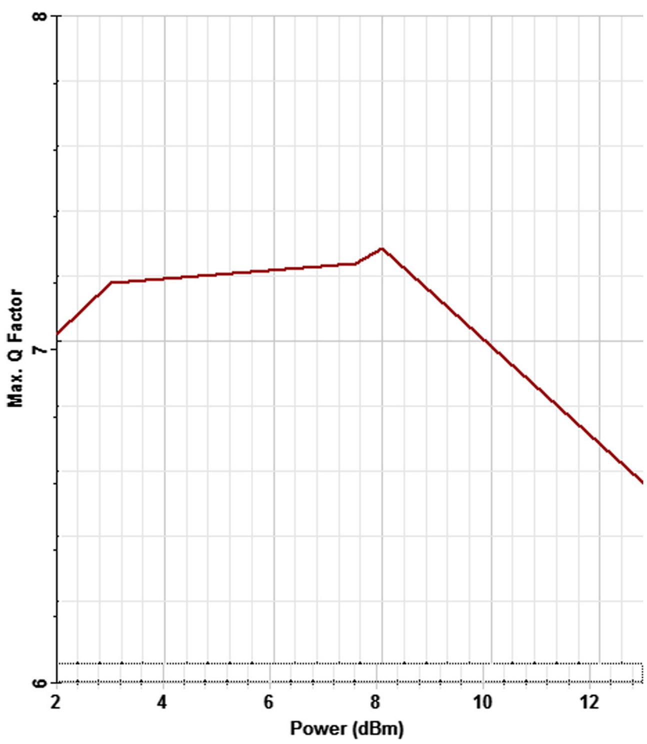

Fig. 4 Optical power transmitted through the fiber versus Q factor.

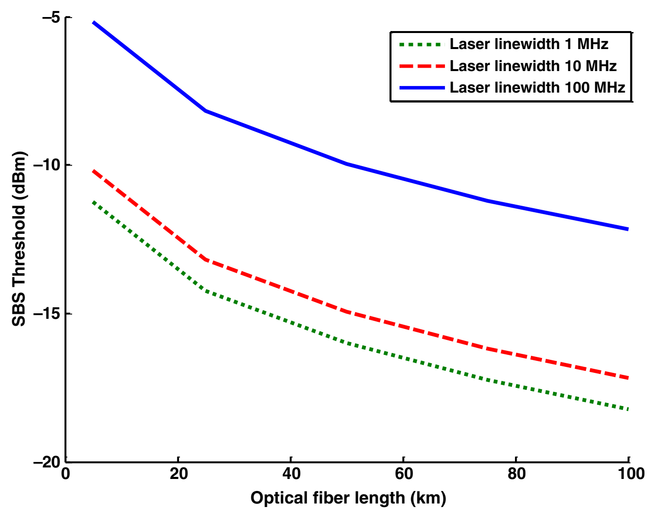

Fig. 5 SBS threshold power versus fiber length with different laser linewidth.

The performance of the generated mm-wave has been investigated with the phase-modulated signals and SBS effect in the optical fiber. Modeling and simulating the mm-wave generation method is based on the nonlinearity effect in the fiber. By exploiting a single-laser source and an FBG for wavelength reuse, a stable mm-wave RoF link is achieved and the quality of the carriers is increased with the reduction of the fiber nonlinearity effects. This research proposed a practical mm-wave RoF link for the applications of small cell 5G networks. The configuration of the full link of mm-wave full-duplex RoF is shown in Fig. 6. The spectrum analyzer results in the simulation for each inset in Figs. 6(a)–6(i) are presented in Fig. 7.

In the central station, a directly modulated CW laser source is used with 8-dBm power at 1550 nm and 1 MHz linewidth. The amount of laser power is set to be more than the Brillouin threshold to consider the effect of SBS in the fiber. The directly modulated laser is driven electrically by the downlink binary data, represented by 5-Gb/s pseudorandom bit sequences.

In this set-up, the directly modulated laser signal enters into the phase modulator, which is driven by an RF sinusoidal signal with a 32-GHz frequency and the phase is 90 deg. Then, the signals are injected to the 100-km SMF having a dispersion of 16.75 ps/nm/km and an attenuation of 0.2 dB/km, as shown in Fig. 6. The effects of the phase modulator are added to the proposed setup to improve mm-wave generation method. Phase-modulated signals are combined with the Brillouin stokes of SBS in the fiber laser. These signals are heterodyning at the photodetector and converted into an electrical signal to generate a 64-GHz mm-wave carrier.

The phase modulator function uses the same principle as a Mach–Zehnder modulator, with the exception that it has a single arm. The phase modulator has a switching voltage V_π and is fed by a laser with an optical power level of P_{in}, so the output optical field of it can be calculated as shown below:[5]

$$E_{\text{p}}(t) = e^{j\frac{\pi V(t)}{2V_\pi}}\sqrt{2P_{\text{in}}}e^{j\omega_c t}, \tag{4}$$

where ω_c is the carrier frequency and $V(t)$ is the electronic modulating signal. This electrical modulating signal imposes a phase modulation on an optical carrier, so the behavior of this model is described by Eq. (5). Supposing the optical input signal is E_{in}, the resulting equation will be

$$E_{\text{out}} = E_{\text{in}}(t).\exp[j.\Delta\varnothing.\text{modulation}(t)], \tag{5}$$

where $E_{\text{out}}(t)$ is the output optical signal, $\Delta\varnothing$ represents the phase deviation, and modulation(t) is the electrical input signal. The normalization of the electrical input signal is between 0 and 1. The phase modulator does not affect the noise bins signals in this case. The spectrum analyzer result at the output of the phase modulator is shown as point (a) in Fig. 7 due to Eq. (5), while point (b) in Fig. 7 represents the optical spectrum of the amplified optical signal after propagating via the fiber and the optical filter. Point (c) shows the output of the optical receiver, which is the mm-wave carrier with data. These results point out that the stimulated Brillouin stokes have affected this generation method by using sufficient Brillouin pump power. As a result, this setup is based on combining the effect of the FOBS with the phase-modulated signal of a fiber link. The generated mm-wave carrier is at frequency of 64 GHz with high quality, as shown in Figs. 8(a) and 8(b). Results show that the generated mm-wave carriers have low noise, which approximately equals −75 dBm. Figure 7(d) shows the eye diagram for the RoF down link, which explains the good performance because the eye diagram still remains open after data is transmitted through a 100-km over fiber.

For the uplink signal, FBG is used to extract half of the blank optical carrier at 1550 nm, as shown by the spectrum in Fig. 7(e). For the RoF uplink, mm-wave wireless uplink data signal is received by the antenna. Then this signal is modulated on the abstracted blank optical carrier at 1550 nm via a phase modulator, as shown in Fig. 7(f).

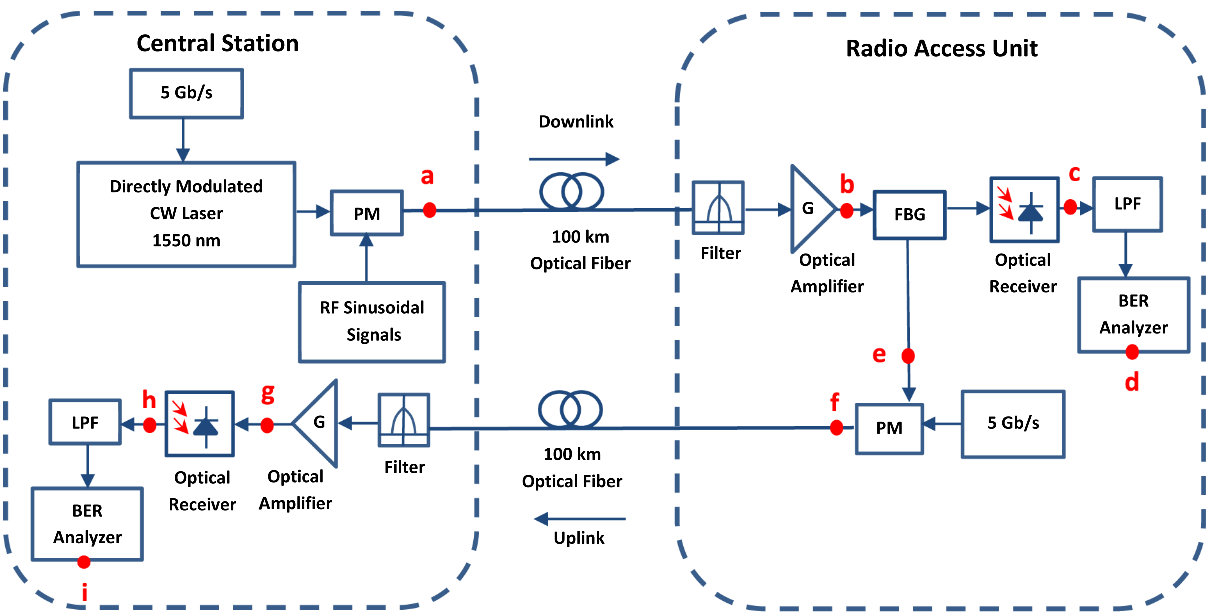

Fig. 6 Experimental structure of the mm-wave full-duplex RoF link.

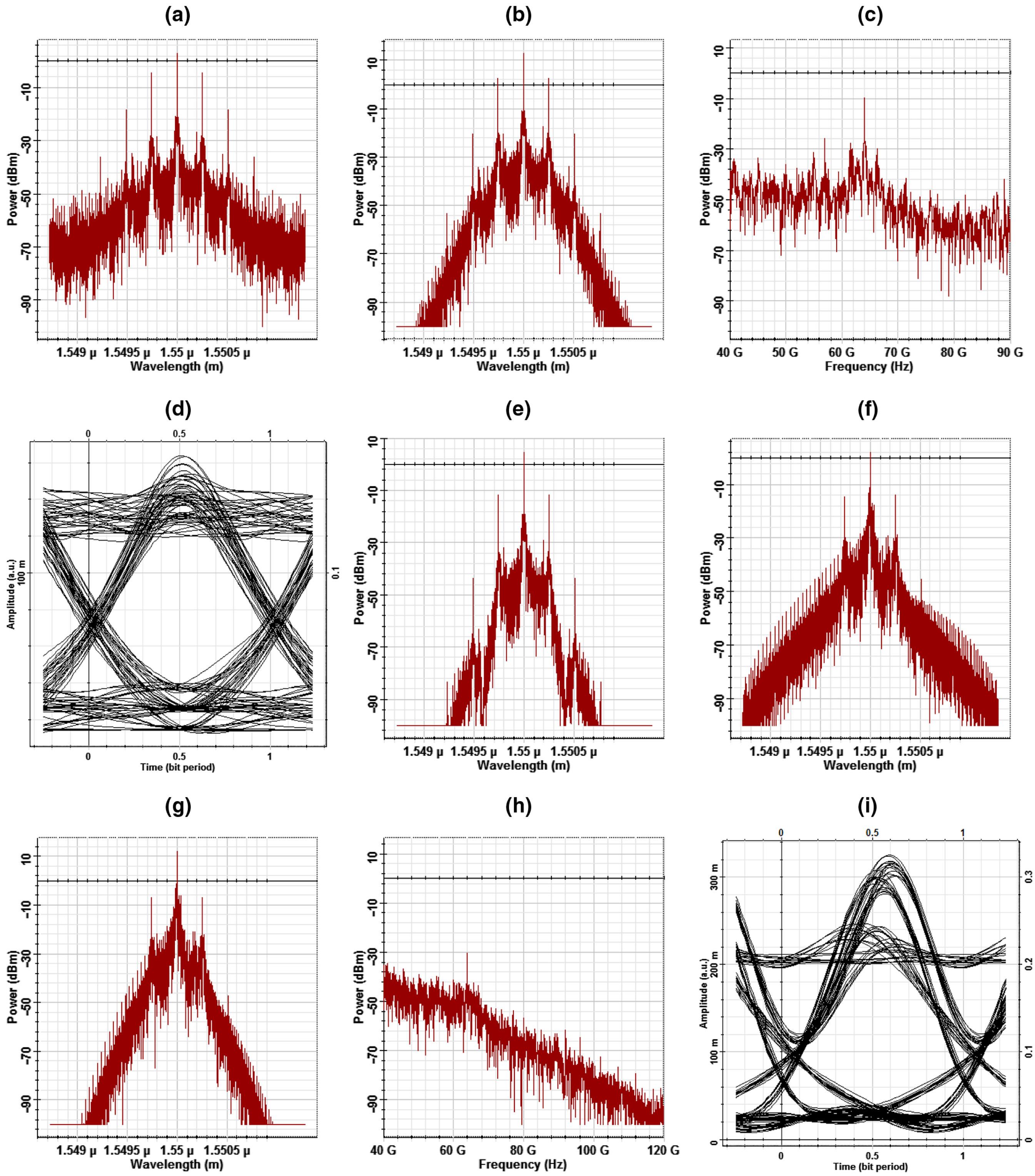

Fig. 7 The analyzer results at the corresponding points in Fig. 6.

This spectrum of the generated optical signal is transmitted back to the CS over SMF. Then the optical signal is amplified, as shown in Fig. 7(g), and is detected by a PD as in Fig. 7(h). The eye diagram performance for the RoF up link is shown in Fig. 7(i), which presents the good performance and the eye still remains open clearly after the uplink data is transmitted through 100-km over fiber with frequency reuse.

Figures 9(a) and 9(b) show the eye diagrams of the demodulated downlink and uplink signals after transmission over different lengths of the fiber link. From these eye diagrams, we have noticed that with the increase of the fiber length, the opening of the eyes decreases as well. We have also noticed that the eye lids become thick. This happens because of the degradation and the phase noise decorrelation of the optical tones. After the transmission over a

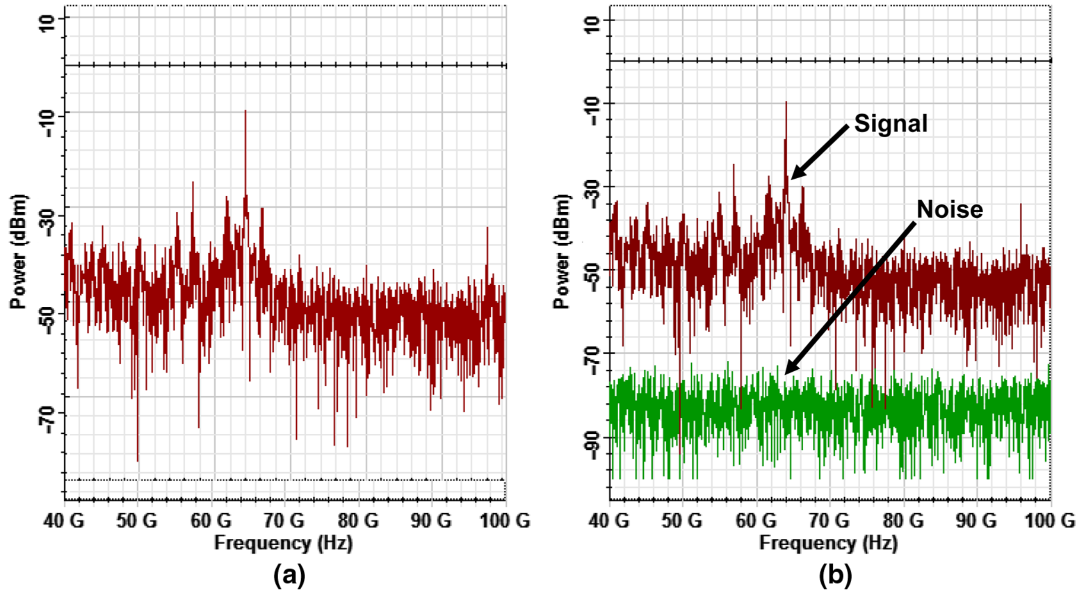

Fig. 8 (a) 64 GHz mm-wave carrier and (b) mm-wave with the noise signal.

100-km SMF, the eyes look clearly open. This indicates that the good performance of both link (down and up) signals can be assured. At this point, the modulation depth should be improved by minimizing the difference between the blank optical carrier and the data-bearing side band by the FBG.

In order to calculate the link performance, we have measured the BERs for two data rates: 5 and 7.5 Gb/s. We have measured for both downlink and uplink data versus the received power along the 100-km fiber link, as illustrated in Figs. 10(a) and 10(b), respectively. It is recognized that

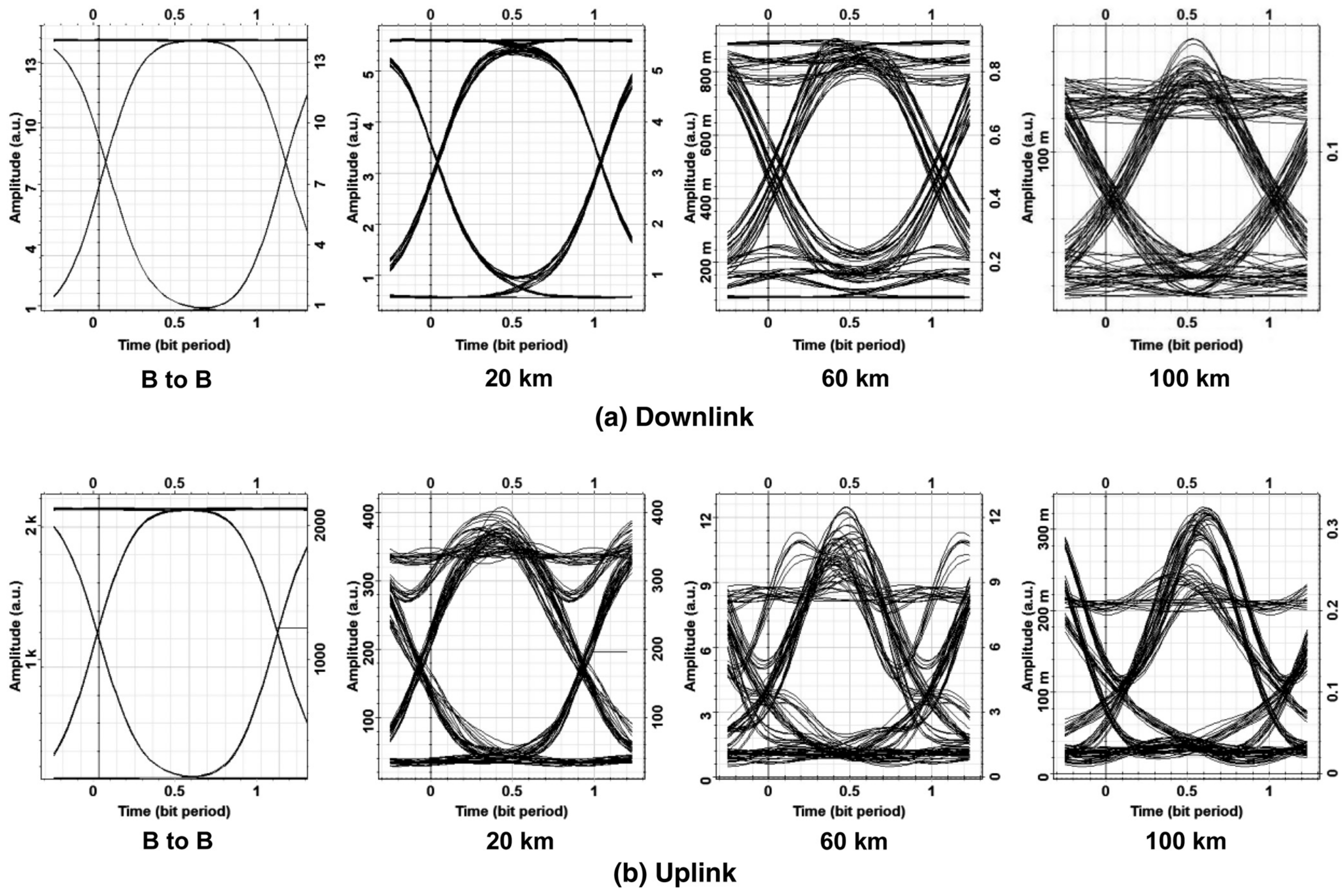

Fig. 9 Eye diagrams with different transmission lengths along SMF for (a) the downlink and (b) the uplink.

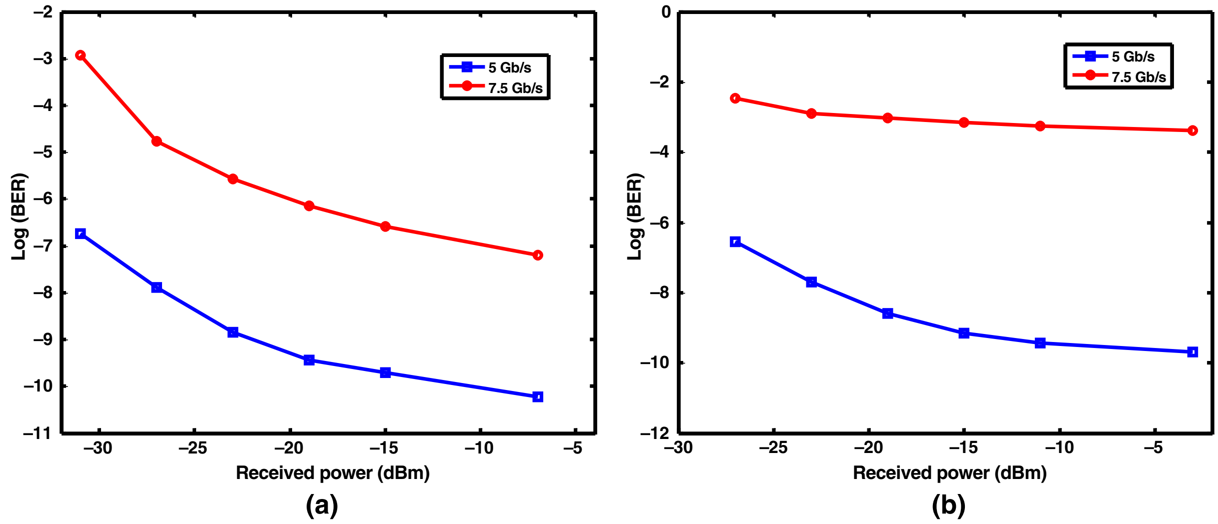

Fig. 10 BER versus received power: (a) for the downlink and (b) for the uplink.

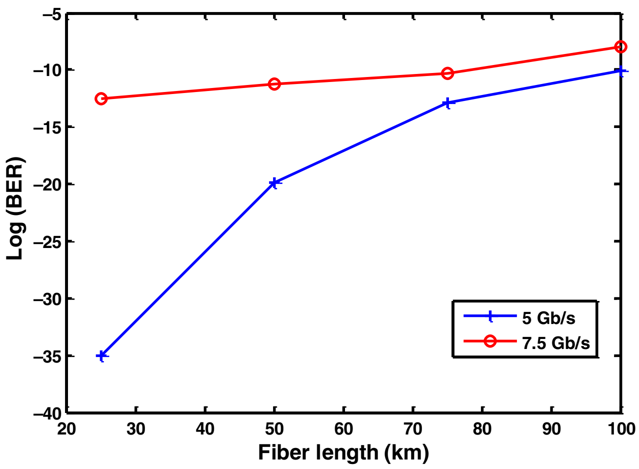

Fig. 11 BER versus fiber length for the downlink.

as the pump power from the laser source goes above the threshold amount of SBS, the BER in the receiver increases. The reason behind this is the previous onset of the scattering threshold at the long fiber link. This comparison shows that for a data rate of 5 Gb/s, we have obtained the perfect BER performance ($\text{BER} < 10^{-9}$) for both downstream and upstream over the 100-km SMF transmission. While in the case of a data rate of 7.5 Gb/s, the performance of BER seems poor over the long fiber link.

Figure 11 shows the BER performance for the downlink along different fiber lengths. The tests were carried out with two rates, 5 Gb/s and 7.5 Gb/s, along fiber links from 25 km to 100 km. Nonlinear effects and the attenuation with dispersion were determined by common industry values (i.e., dispersion of 16.75 ps/nm/km and an attenuation of 0.2 dB/km) to simulate the real environment as closely as possible. Results show the effect of increasing the fiber length on the amount of the received signal power. That means losses increase when using a longer fiber. So, for a short fiber link, the data rate should be higher. The important point in the design of a mm-wave RoF link is specifying the maximum fiber length that can achieve a higher data rate with a good system performance.

4 Conclusion

In this study, we have proposed and demonstrated the simulation of a full-duplex RoF link based on novel photonic generation method of mm-wave to realize wireless access. In our scheme, we have investigated the transmission performance of mm-waves generated using a phase modulation technique with the study of the characteristics of the SBS effect in the optical fiber. A single laser source is used with an FBG for wavelength reuse for the uplink connection. This not only increases the stability and the quality of the applied 64-GHz carrier frequency mm-wave RoF link up to 100 km, but the fiber nonlinearity effects are also reduced with low noise in the mm-wave signal less than −75 dBm. In our setup, the RAU structure is simplified to achieve cost reduction of the system. RAU does not need any laser source because of the uplink optical carrier that is extracted by using FBG from the downlink. The transmission performance of the full-duplex mm-wave RoF link is investigated theoretically and verified by simulation.

The simulation results show that our proposed full-duplex link with the data rate of 5 Gb/s for each of the downlink and the uplink signals can reach a transmission distance up to 100 km over the SMF successfully with good agreement with optical communication standards. Based on the obtained results, this research is proposed as a promising choice for future small cell networks with a simple setup. The proposed work may have the potential to support the implementation of mm-waves in wireless systems that are integrated with optical fiber links in 5G networks.

Acknowledgments

Rasha K. Al-Dabbagh would like to acknowledge the Iraqi Ministry of Higher Education and Scientific Research for funding the scholarship of her PhD study at Brunel University London.

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