Performance improvement and wavelength reuse in millimeter-wave radio-over-fiber links incorporating all-fiber optical interleaver

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Abstract

Simultaneous downlink performance improvement and uplink wavelength reuse in a full-duplex millimeter-wave (MMW) radio-over-fiber (RoF) system by using a simple and cost-effective all-fiber optical interleaver are proposed and demonstrated. The MMW RoF downlink performance improvement is based on suppressing optical carrier-to-sideband ratio (OCSR), with which the mechanism is confirmed by theoretic analysis and derived experimental results. Measured results show that, by suppressing OCSR using a fabricated all-fiber optical interleaver, the downlink optical receiver sensitivity is improved about 2.1 dB. The downlink data rate is 1.25 Gbit/s and the carrier frequency is 58.1 GHz; the link consists of 6 km optical single-mode fiber and 1 m wireless connection. On the other hand, with the interleaver suppressing downlink OCSR, simultaneously an optical carrier is recovered from the RoF downlink and is reused for RoF uplink transmission. The uplink is operated at 62.9 GHz and the data rate is the same 1.25 Gbit/s. With the recovered optical carrier, a laser-free remote access point is achieved. The principle, structure, and fabrication of an all-fiber optical interleaver are also presented in this paper.

Keywords: Optical communications; Analogue optical fiber systems; All-fiber optical interleaver; Optical carrier-to-sideband ratio; Optical wavelength reuse; Radio-over-fiber

1. Introduction

Millimeter waves become more and more attractive for high-speed wireless communications in recent years. Employing frequencies in millimeter-wave (MMW) bands can avoid congestions at lower frequencies around 2.4 GHz, 5.8 GHz, and so on. Examples exploring MMW frequencies include: IEEE 802.16 – 10–66 GHz [1]; local multipoint distribution systems (LMDS) – around 30 GHz [2]; and wireless personal area network (WPAN, IEEE 802.15.3c) – 57–64 GHz [3]. However, the air propagation attenuation rate at MMW frequencies is relatively high and then the wireless connection distance of millimeter waves is relatively short. One solution is to modulate millimeter waves on optical carriers and then distribute along optical fiber by radio-over-fiber (RoF). Since optical fiber has ultra-low attenuation rate at usual optical carriers around 1550 nm, the distribution distance of millimeter waves can be greatly extended. Additionally, with RoF transmission, the operation of millimeter waves can be...
centralized at center office, the system structure can be simplified, and the system cost can be saved [4].

As so far optical direct modulation is generally limited below 30 GHz, external optical modulations incorporating Electro-Absorption modulator (EAM) or Mach–Zehnder modulator (MZM) is generally implemented for MMW RoF transmission. However, the linear operation region of an EAM or MZM operating at MMW frequencies is relatively small, then in order to minimize optical high-order harmonics, optical small-signal modulation is a necessary. This is particularly important for systems sensitive to nonlinear high-order harmonics, such as links incorporating dense-wavelength division multiplexing (DWDM) [5], subscriber-carrier multiplexing (SCM), or orthogonal frequency division multiplexing (OFDM). In another hand, optical small-signal modulation needs to be used due to unavailability of high-gain amplifiers for MMW signals.

In optical small-signal modulation, the optical carrier-to-sideband ratio (OCSR) can be more than 20 dB, i.e., compared to optical carrier, the modulation generated optical sideband(s) is(are) very weak. Then in photodetection most of the received optical power is converted to direct current (DC) while a quite small portion is converted to MMW signals. This leads to quite low transmission efficiency of millimeter waves. Moreover, since information is carried by optical sideband(s), in MMW RoF link with optical small-signal modulation, a relatively strong optical receiver power is required to achieve certain signal-to-noise ratio (SNR). The consequent relatively strong DC, which is mainly generated from the optical carrier, may damage the photodector (PD) as a PD operating at MMW frequencies generally has a very small active area to limit the capacity. In addition, higher optical receiver power results in smaller link budget and shorter fiber connection distance. Also, nonlinearity problems associated with optical fiber under high optical power, like four-wave mixing in DWDM systems, may arise and lead to additional performance deterioration.

An effective method to improve performance of MMW RoF links with optical small-signal modulation is to suppress the optical carrier-to-sideband ratio [6]. Refs. [6–8] demonstrated improvement on optical receiver sensitivity and third-order spur-free dynamic range (SFDR) with this approach. The mechanism behind is straightforward: with suppressed OCSR, more portion of optical power is converted to MMW signal thus the intrinsic gain of the RoF link is increased [9]. A number of schemes suppressing OCSR have been proposed and demonstrated. In summary, most of the demonstrated schemes are based on optical filtering with: nonlinear Brillouin scattering/filtering [10,11]; optical waveguide filter [7]; Fabry–Perot (FP) filter [12]; or fiber Bragg grating [6,8,13], and so on. Recently, the authors proposed to employ an all-fiber optical interleaver to suppress OCSR with advantages of very simple structure, ultra-low cost, and easy connection [14]. In addition, by using the same all-fiber optical interleaver, simultaneously an optical carrier can be recovered from a MMW RoF downlink and reused for RoF uplink. Hence a laser-free optical access point can be realized and the cost, installation, maintenance, and power consuming associated with a laser can be saved. This is very helpful to a MMW RoF system that needs a great number of optical access points for full radio coverage.

In this paper, we demonstrate full-duplex MMW RoF transmission with performance improvement in optical downlink and wavelength reuse in optical uplink, by using a specially designed and fabricated all-fiber optical interleaver. Theoretic analysis is presented to describe the mechanism of performance improvement by suppressing OCSR. The structure, principle, and fabrication of an all-fiber optical interleaver is also introduced. The downlink is operated at 58.1 GHz and the uplink is at 62.9 GHz. Both links have a data rate of 1.25 Gbit/s. Measured results show that, by suppressing OCSR the downlink optical receiver sensitivity is improved about 2.1 dB. And with the reused optical wavelength, the uplink RoF transmission on 5.2 km single-mode fiber followed by 1 m wireless connection can achieve a bit-error rate (BER) of $10^{-6}$ at a receiver optical power of $-9.7$ dBm. Discussion shows that the residual downlink optical sidebands in the recovered optical carrier has negligible effect on the experiment RoF uplink performance.

The organization of the rest of this paper is as following: in Section 2, theoretic analysis of performance improvement on SNR by suppressing OCSR in MMW RoF links is presented. In Section 3, we introduce all-fiber optical interleaver, and demonstrate improvement of optical receiver sensitivity and wavelength reuse by using an all-fiber optical interleaver. Finally, we conclude the paper in Section 4.

2. Theory of improvement on SNR by suppressing OCSR in RoF links

Fig. 1 shows a general model of a MMW RoF link. At optical transmitter (OTX), an optical carrier is modulated by a MMW signal at frequency of $f_m$ and then is coupled into an optical amplifier (OA). After fiber delivery, a MMW signal is generated at an optical receiver (ORX). The input average optical signal power of OA, optical gain, fiber transmission optical loss, and average optical signal power of OA; $P_\text{in}$: average input optical signal power of OA; $P_r$: average optical signal receiver power; $G$: optical gain; $L$: fiber transmission loss; $f_m$: modulation RF frequency.
receiver power are represented by $P_m$, $G$, $L$, and $P_r$, respectively.

Optical double-sideband modulation (ODSB) or optical single-sideband modulation (OSSB) can be implemented at an OTX to superimpose a MMW signal on an optical carrier [15,16]. Fig. 2 shows optical spectra of ODSB and OSSB. Optical small-signal modulation is assumed hence optical high-order harmonics are ignored in the diagram. Optical carrier-to-sideband ratio is defined the ratio between the average optical power associated with the optical carrier ($P_c$) and the sideband power of OSSB or either sideband of ODSB ($P_s$, i.e., $OCSR = P_c/P_s$). Then small-signal ODSB generated optical signal is given by

$$E_M = \sqrt{OCSR \cdot P_c e^{j\omega_m t}} + \sqrt{P_s e^{j(\omega_o + \omega_m)t}}$$

$$+ \sqrt{P_s e^{j(\omega_o - \omega_m)t}},$$

(1)

where $\omega_o$ and $\omega_m$ are angular frequencies of optical carrier and modulation RF subcarrier, respectively. Compared with a general description of small-signal ODSB output, OCSR in Eq. (1) is a function of modulator chirp [17]. In addition, modulator chirp gives a phase bias in all three terms of Eq. (1), however, for simplicity chirp is not explicitly included in the equation.

After optical amplification and fiber delivery, the average optical signal power at an optical receiver is $P_r = (2 + OCSR)P_c/G/L$, and the optical signal received is given by

$$E_R = \sqrt{\frac{OCSR}{2 + OCSR}} \cdot P_c e^{j\omega_m t} + \sqrt{\frac{P_r}{2 + OCSR}} e^{j(\omega_o + \omega_m)t}$$

$$+ \sqrt{\frac{P_r}{2 + OCSR}} e^{j(\omega_o - \omega_m)t},$$

(2)

In above fiber dispersion is not included as it does not change OCSR. By square-law detection of a photodetector, MMW signal at $f_m$ is generated. The signal-to-noise ratio at the output of the photodetector is given by

$$SNR_D \sim \frac{P_r^2}{N} \cdot \frac{OCSR}{2 + OCSR},$$

(3)

where $N$ is noise power including thermal noise $n_{th}$, shot noise $n_s$, relative-intensity noise (RIN) $n_{RIN}$, and noise due to amplified spontaneous emission (ASE) from Erbium-doped fiber amplifier (EDFA) $n_{ase}$.

At a given temperature, $n_{th}$ keeps unchange. Shot noise $n_s$ is proportional to the DC photocurrent and RIN noise $n_{RIN}$ is proportional to the square of DC photocurrent; hence at condition with same received average optical signal power $P_r$, power of these two noises do not change with OCSR. Noise $n_{ase}$ includes noise due to beat between optical signal spectral components and optical amplified spontaneous emissions, and noise due to self-beat of optical amplified spontaneous emissions [18]. The power spectrum densities of both noises introduced by ASE are functions of $G$ and OA input power $P_m$. With same $P_r$ and fiber loss $L$, $G$ and $P_m$ keep unchange with OCSR, therefore $n_{ase}$ keeps unchange with OCSR. Then for ODSB, with same $P_r$, SNR is only proportional to $OCSR/(2 + OCSR)^2$. Mathematically, it is easy to find with same $P_r$, maximum SNR can be achieved at an OCSR of 2 (3 dB) for ODSB.

Similarly, for OSSB, at the output of a photodetector, the SNR is given by

$$SNR_S \sim \frac{P_r^2}{N} \cdot \frac{OCSR}{(1 + OCSR)^2}.$$  

(4)

And at condition keeping optical signal receiver power $P_r$ unchange, maximum SNR can be achieved at an OCSR of 1 (0 dB).

By setting OCSR of 2 and 1 as reference for ODSB and OSSB, respectively, SNR given by Eqs. (3) and (4) is normalized and plotted in Fig. 3. We can see for OSSB with OCSR more than 20 dB, the normalized SNR is less than 0.1; for ODSB it is smaller than 0.05. While with smaller OCSR, SNR can be greatly increased. The condition is keeping optical signal receiver power $P_r$ unchange with OCSR.

In above the optical receiver power keeps unchange then with smaller OCSR higher SNR can be achieved. This indicates at a given SNR, lower optical receiver power is...
required with higher OCSR. Then the optical receiver sensitivity can be improved by suppressing OCSR for both ODSB and OSSB.

In [6], Lim et al. measured optical receiver sensitivity as function of OCSR for RoF transmission with OSSB. From the measured results given by Figs. 5 and 8 of [6], normalized SNR as function of OCSR is derived and also plotted in Fig. 3. As shown in Fig. 3, the derived results with both data rates of 155 Mb/s and 51.8 Mb/s fit very well with the theoretical curve. Thereby the model presented in this paper is confirmed.

3. Suppressing OCSR and reusing wavelength by an all-fiber optical interleaver

In Section 2 we show theoretically with lower OCSR higher SNR can be achieved in a RoF link. In this section we propose and demonstrate improving optical receiver sensitivity by suppressing OCSR with an all-fiber optical interleaver. In addition, with the same interleaver, we propose and demonstrate recovering an optical carrier for RoF uplink transmission simultaneously.

3.1. Scheme suppressing OCSR and recovering optical carrier using optical interleaver

Optical interleaver is usually used in dense-wavelength division multiplexing (DWDM) system to de-multiplex optical wavelengths. A 2×2 optical interleaver is shown in Fig. 4a. Due to the complementary frequency responses at the two interleaver output ports, a group of multiplexed wavelengths \( \lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_{n-1}, \lambda_n \) at one of the interleaver input ports can be separated to group \( \lambda_1, \lambda_3, \ldots, \lambda_{n-1} \) and group \( \lambda_2, \lambda_4, \ldots, \lambda_n \). With this property, an interleaver with a free spectral range (FSR) of \( 2f_m \) can separate optical carrier at \( f_m \) and sideband(s) at \( f_o \pm f_m \). However, usually an interleaver product has a limited suppression ratio. Therefore, as shown at the upper output port of an optical interleaver in Fig. 4b, the optical carrier is suppressed but not totally removed. Hence, at the upper output port, the OCSR is suppressed. While at the other output port (the lower one in Fig. 4b), the small-signal modulation generated optical sidebands are suppressed and can be ignored when compared to the much stronger optical carrier, i.e., an optical carrier is recovered.

The above scheme simultaneously suppress OCSR and recover an optical carrier with a single optical interleaver. This scheme can be used in RoF link with small-signal OSSB or ODSB modulation.

3.2. All-fiber optical interleaver

In our experiment with above proposed scheme, an all-fiber optical interleaver is used to suppress OCSR and recover optical carrier. The all-fiber optical interleaver is Fourier Filter Flat-Top (F3T) type. Compared to other technologies, this type of interleaver has several advantageous properties such as all-fiber implementation, low insertion loss, an uniform response over a wide wavelength range, low chromatic dispersion, and minimal polarization-dependence effects [19]. An F3T interleaver is basically a generalized unbalanced Mach–Zehnder interferometer as shown in Fig. 5. It consists of three cascaded couplers linked by two differential delays. Denote the phase delay as \( \phi = \Delta L \pi n \lambda_c \) that corresponds to half of \( \Delta L \), where \( \Delta L \) is the physical length of the differential delay, \( \lambda_c \) is the wavelength of the lightwave propagating in vacuum and \( n \) is the refractive index of the optical fiber. The normalized electric fields transfer function from the two inputs \( E_1 \) and \( E_2 \) to the two outputs \( E_3 \) and \( E_4 \) can be expressed by the following matrix transfer function [19]

\[
\begin{bmatrix}
E_3 \\
E_4
\end{bmatrix} =
\begin{bmatrix}
c_3 & j s_3 \\
 j s_3 & c_3
\end{bmatrix}
\begin{bmatrix}
e^{-2 j \phi} & 0 \\
0 & e^{2 j \phi}
\end{bmatrix}
\begin{bmatrix}
c_2 & j s_2 \\
 j s_2 & c_2
\end{bmatrix}
\begin{bmatrix}
e^{j \phi} & 0 \\
0 & e^{j \phi}
\end{bmatrix}
\begin{bmatrix}
c_1 & j s_1 \\
 j s_1 & c_1
\end{bmatrix}
E_1
\begin{bmatrix}
E_1 \\
E_2
\end{bmatrix},
\]

Fig. 4. Scheme suppressing optical carrier-to-sideband ratio and recovering optical carrier using optical interleaver: (a) principle of optical interleaver de-multiplexing optical wavelengths; (b) suppress OCSR and recover optical carrier using optical interleaver. FSR: free spectral range.

Fig. 5. Structure of an F3T type all-fiber optical interleaver.
where \( c_i = \sqrt{k_i} \) and \( s_i = \sqrt{1 - k_i} \) with \( k_i \) as the bar-state intensity coupling ratio of the \( i \)th directional coupler. The FSR of the interleaver can be expressed as

\[
\text{FSR} = \frac{C}{\Delta L n},
\]

(6)

where \( C \) is the lightwave speed in vacuum.

To design an interleaver with an FSR two times of the dedicated 60-GHz frequencies (MMW frequencies used in our experiment), the length difference \( \Delta L \) of the interleaver can be obtained from Eq. (6) as 1.7 mm. For an F\(^3\)T interleaver, the left design is to choose appropriate parameters \( c_i \) and \( s_i \) such that the insertion loss is as low as possible, and the channel isolation as high as possible. Based on the design approach in [19], an F\(^3\)T interleaver can be designed analytically to meet certain performance parameters.

For the fabrication of such F\(^3\)T interleaver, the technique in [19] is applied. With this method, one coupler is fabricated as usual using a coupling machine. Then, another coupler is fabricated consecutively using a broadband light emitting diode (LED) as light source and an optical spectrum analyzer (OSA) for spectral response monitoring. During the fabrication of the second coupler, an interference pattern can be observed from the OSA. The coupling ratio of the second coupler can be induced from the isolation of the interference pattern. For example, a Mach–Zehnder interferometer having two 3-dB couplers can be fabricated when observe the interference pattern reaches the maximal isolation during the fabrication. After fabrication of the fiber couplers, the required length difference between the two arms is achieved by stretching one of the fibers between the two couplers through thermal heating. With this method, an F\(^3\)T interleaver was successfully fabricated.

The FSR of the F\(^3\)T interleaver inversely depends on the length difference \( \Delta L \) of the interleaver. With the above fabrication technique, a length difference of 4 cm for the lower limit is realizable. Correspondingly, the lower limit of FSR is 5 GHz and the limited operation RF frequency is 2.5 GHz.

The 2 × 2 all-fiber optical interleaver fabricated has an FSR of 120 GHz, (two times of the operation 60-GHz band frequencies), corresponding to 0.963 nm at a target optical carrier wavelength of 1551.21 nm. The spectral response of the device at the upper output port is measured using a broad optical source, and is normalized to the input port. As shown in the picture. As shown in Fig. 7, OCSR at the upper output port of the interleaver is suppressed, while at the lower output port an optical carrier centered at \( f_0 \) is recovered. The OCSR-suppressed downlink signal is then photodetected and a MMW subcarrier at frequency \( f_m \) is radiated out to users after amplification and bandpass filtering. The recovered optical carrier is modulated by MMW uplink signals from users and is transmitted back to center office. After photodetection, amplification, filtering, and frequency down-converting, uplink data can be de-modulated. With this scheme, a laser-free RAP can be achieved.
3.4. Experiment and results

A pair of Ceragon Gigabit Ethernet Radio FibeAir10060 is used for downlink and uplink MMW signals generation and reception. A schematic block diagram of a FibeAir10060 is shown in Fig. 8. It is an integrated product and consists of two link paths. In one path, it receives baseband data via multimode fiber data interface and then modulates baseband data on MMW carrier (at 58.1 GHz or 62.9 GHz) with format of binary-phase-shift keying (BPSK). Finally it radiates out MMW carrier via a directional antenna with a gain of 40 dBi. In the other path, it receives MMW carrier (at 62.9 GHz or 58.1 GHz). The demodulated baseband data is sent out via multimode fiber data interface.

Fig. 9 shows the experiment setup. For downlink transmission, an Anritsu data quality analyzer (MD1230A) is used to generate 1.25-Gbit/s baseband data. The generated baseband data is sent to a Ceragon Gigabit Ethernet Radio FibeAir10060 via a short multimode fiber link. This FibeAir10060 modulates the baseband data on 58.1 GHz carrier and radiates the MMW carrier to air. A horn antenna is used to receive the 58.1 GHz data-bearing carrier. The wireless connection distance is about 1 m. The received 58.1 GHz carrier is connected to a Comotech duplexer, and then is amplified by a Comotech power amplifier. Fig. 10a shows the measured RF spectrum of the data-bearing 58.1 GHz carrier after the power amplifier (point A in Fig. 9). After bandpass filtering, the 58.1 GHz carrier is applied on an EAM operating in 60-GHz band. Fig. 11 shows measured s21 of the EAM with a broad-band photodetector. The two s21 curves correspond to EAM bias voltages of 1.0 V and 2.0 V, respectively. In the experiment, we biased the EAM at 2.0 V. The power of the 58.1 GHz carrier applied on EAM is measured about 10 dBm. This value gives a small optical modulation depth about 0.0354.

The lightwave carrier is from a distributed-feedback (DFB) laser with temperature control. The optical wavelength is 1551.21 nm and the measured laser output power is about 10 dBm. Due to loss introduced by the optical modulator, the output of the EAM is measured about 2.3 dBm. The spectrum of the modulated optical signal is shown in Fig. 12. The OCSR is observed about 38 dB due to optical small-signal modulation.

After an adjustable optical attenuator, the modulated optical downlink signal is coupled into a conventional single-mode fiber with a length of 6 km. With this fiber length, signal fading at 58.1 GHz due to fiber chromatic dispersion can be minimized and then for simplicity OSSB filtering is not applied in this experiment. Choosing this fiber length is based on our another measurement of 58.1 GHz signal power along optical fiber [20]. The x chirp parameter of the EAM used in both experiments can be characterized as 0.8 from the measured results in [20].

At the other end of downlink fiber, the optical signal is coupled into the fabricated all-fiber optical interleaver. As shown in Fig. 13, at the upper output port of the interleav-
er, the optical carrier is about 15 dB stronger than the sidebands, indicating an OCSR suppression of about 23 dB is achieved by using the interleaver. The OCSR suppressed downlink optical signal is then photodetected and a 58.1 GHz data-bearing signal is generated. This signal is amplified by another Comotech amplifier. The RF spectrum of the amplifier output (point B in Fig. 9) is shown in Fig. 10b. After amplification, the signal is bandpass filtered and connected to a duplexer, and is radiated to air by another horn antenna. A Ceragon FibeAir10060 with receiving frequency at 58.1 GHz is used to collect the downlink MMW signal. The wireless distance is about

Fig. 9. Experimental setup of millimeter-wave RoF transmission incorporating all-fiber optical interleaver for performance improvement and wavelength reuse. EAM: electro-absorption modulator; ATT: attenuator; PD: photodetector; AMP: amplifier; BPF: bandpass filter; DUP: duplexer.

Fig. 10. Measured RF spectrum: (a) at the point A; (b) at the point B; (c) at the point C; (d) at the point D, marked in Fig. 9. The spectral resolution is 10 kHz, and all with 1.25 Gbit/s data.
After reception and demodulation, the recovered baseband data is sent back to the data generator Anritsu MD1230A for bit-error rate (BER) measurement. By adjusting the optical attenuator at the downlink optical transmitter, the received optical power varies in a range of $-7$ dBm to $-12$ dBm, and the measured BER is between $10^{-8}$ and $10^{-5}$ as shown in Fig. 14. For comparison, BER of the case without OCSR suppression is also measured and shown in the same figure. It is observed that by suppressing OCSR with the use of the interleaver, an improvement of about 2.1 dB in optical receiver sensitivity is achieved at a given BER of $10^{-6}$.

The measured optical spectrum at the lower output port of the all-fiber optical interleaver is shown in Fig. 15. The recovered optical carrier at 1551.21 nm is more than 60 dB stronger than the residual optical downlink sidebands. As shown in the uplink part in Fig. 9, this optical carrier is coupled into another EAM operating in 60-GHz band and is modulated by an uplink MMW carrier at 62.9 GHz. The uplink MMW carrier is generated by the FibeAir10060 receiving the 58.1 GHz downlink carrier and the uplink data is generated by the same Anritsu MD1230A data generator. The bit rate is the same 1.25 Gbit/s and the carrier modulation format is BPSK. Fig. 10c shows the measured RF spectrum at the output of the amplifier used for boosting the uplink MMW carrier from the FibeAir10060 (point C in Fig. 9). The uplink fiber length is 5.2 km, with which 62.9 GHz signal fading due to fiber chromatic dispersion can be minimized and OSSB filtering is not applied for simplicity. The uplink optical signal is photodetected by another broadband photodetector and a 62.9 GHz data-bearing signal is generated. One more Comotech amplifier is used to amplify the photodetection generated 62.9 GHz signal. The measured RF spectrum at the amplifier output (point D in Fig. 9) is shown in Fig. 10d. After bandpass filtering, the MMW signal is coupled into the downlink duplexer and radiated to air by

Fig. 11. Measured s21 of the experiment downlink EAM with a broadband photodetector.

Fig. 12. Measured optical spectrum at the output of the EAM for 58.1-GHz RoF downlink transmission.

Fig. 13. Measured optical spectrum at the upper output port of the fabricated all-fiber optical interleaver.

Fig. 14. Measured BER of the experiment downlink and uplink, as function of optical receiver power.
using the same downlink horn antenna as shown in Fig. 9. The FibeAir10060 generating 58.1 GHz downlink carrier receives and demodulates the 62.9 GHz data-bearing uplink carrier. The recovered uplink baseband data is sent back to the data generator for BER measurement. By adjusting the attenuator right before the uplink photodetector, the uplink optical receiver power can be varied. The measured uplink BER as function of optical receiver power is plotted in Fig. 14. At an optical receiver power of \(-9.7 \text{ dBm}\) a BER of \(10^{-6}\) is achieved. This confirms the scheme reusing recovered optical wavelength in RoF uplink.

### 3.5. Discussion

In the above scheme reusing optical wavelength, the recovered optical carrier has residual optical sidebands due to limited suppression ratio of the interleaver used. The difference between the central frequencies of the residual optical sidebands and the optical carrier is 58.1 GHz as the downlink optical carrier is modulated at this frequency. The uplink MMW frequency is 62.9 GHz then at the uplink photodetector, the generated RF signal includes uplink signal at 62.9 GHz and 58.1 GHz interference due to residual sidebands. The residual optical sidebands are more than 60 dB weaker than the recovered optical carrier as shown in Fig. 15. While with a small modulation depth of 0.035 and an EAM 

\[ \text{ parameter of 0.8 in the experiment, the uplink optical signal sidebands (62.9 GHz away from the optical carrier) are about 40 dB weaker than the optical carrier. Then the photodetection generated uplink carrier at 62.9 GHz is 20 dB stronger than the 58.1 GHz interference due to residual sidebands. The residual optical sidebands are more than 65 dB at 58.1 GHz, then after bandpass filtering the 58.1 GHz interference is 85 dB lower than the 62.9 GHz uplink signal. The experiment uplink consists of RoF fiber connection and wireless connection. Assume the uplink RoF fiber connection gives a BER of \(10^{-9}\) (a usual requirement of fiber link), then at the output of the bandpass filter after the uplink photodetector, the SNR is about 14 dB (since the modulation format is BPSK). This is to say, the total power of the 58.1 GHz interference and other noises after bandpass filtering is 14 dB lower than the 62.9 GHz carrier. Therefore, compared to other noises, 58.1 GHz interference can be ignored.

With the presence of the residual optical sidebands, shot noise, RIN noise and noise due to ASE increase as the residual optical sidebands introduce additional DC photocurrent and signal-to-spontaneous noise [18]. However, the optical residual sidebands are 60 dB weaker than the optical carrier recovered in this experiment, so the additional noise increased can be ignored.

From the above discussion, the noise figure of the experiment RoF uplink keeps unchanged when the residual optical sidebands present. In addition, as the third-order input interference point and background noise power (thermal noise) do not change with the presence of the optical residual sidebands, then the presence of the residual sidebands has negligible effect on the third-order spur-free dynamic range (SFDR) of the experiment RoF uplink.

### 4. Conclusions

This paper demonstrated improvement on optical receiver sensitivity of MMW RoF downlink and optical wavelength reuse in MMW RoF uplink, by using a fabricated all-fiber optical interleaver. The two operations are simultaneously achieved with this simple and cost-effective single device, and the scheme is feasible for both OSSB and ODSB modulations. The effect of the residual optical sidebands in the recovered optical carrier for RoF uplink transmission is also discussed. In our experiment, the introduced RF interference and the effects on RoF uplink NF and SDFR are negligible. The structure, principle, fabrication, and limitation of an all-fiber optical interleaver for the proposed scheme are also presented in this paper.

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