Generation and transmission of multiband and multi-gigabit 60-GHz MMW signals in an RoF system with frequency quintupling technique

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Abstract: We propose and experimentally demonstrate a cost-effective radio-over-fiber (RoF) system to simultaneously generate and transmit multiband and multi-gigabit 60-GHz millimeter wave (MMW) signals using frequency quintupling technique. Multiband signals at 56-GHz and 60-GHz are realized with two cascaded single-drive Mach-Zehnder modulators (MZMs), where phase control is not required. Furthermore, only low-frequency (≤12GHz) optical and electrical devices are used in the central station (CS), which enable a cost-effective system. At the user-terminal, two-stage down-conversions are employed by envelope detection (ED) and intermediate frequency (IF) mixing, eliminating expensive high-speed synthesizer and critical phase control components. Error-free performances are achieved for the multiband MMW signals after 50-km single-mode fiber (SMF) and 10-ft wireless link transmissions.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.4080) Modulation; (060.5625) Radio frequency photonics.

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1. Introduction

The ever-increasing video-based interactive and multimedia services are requiring large bandwidths and high data rates in wireless access networks. 60-GHz wireless technology has gained much attention for its wide bandwidth availability over the 7-GHz unlicensed millimeter-wave (MMW) band [1–6]. In addition, the 60-GHz MMW has been considered globally as a candidate for next-generation very high throughput (VHT) wireless personal area networks (WPANs) and wireless local access networks (WLANs). Recently, several industrializations and standardizations have been carried out, such as IEEE 802.15.3c [7], 802.11ad [8], ECMA [9], and Wireless-HD [10], to promote the global use of multi-gigabit 60-GHz wireless technology. However, due to high atmospheric loss of the 60-GHz MMW signal, the convergence range is limited to tens of meters [1]. Thanks to the huge bandwidth and low transmission loss provided by optical fibers, radio-over-fiber (RoF) technology is considered to be a promising solution to increase capacity and mobility as well as to reduce overall cost in wireless access networks [2]. Among them, multiband signal transmission is an attractive choice. Recently, in Ref [11–14], several demonstrations were carried on to realize multiband-signal transmissions based on RoF technology. However, all of the schemes produced widely-separated bands (baseband, microwave and millimeter wave) to carry single service [11,12] or multi-services [13,14], none of them realized multiband signal within 60-GHz band.

According to the recent standardization [10], the 60-GHz license-free band is divided into several sub-bands: 58.32 GHz, 60.48 GHz, 62.64 GHz and 64.8 GHz, thus it is of interest to support multiband MMW-signal transmission in future 60-GHz RoF systems. In Ref [15], we proposed a scheme to realize 60-GHz and 64-GHz multiband signals, however, high-frequency components were required in both central station (CS) and user-terminal, which increased the system cost. Furthermore, the generated 60-GHz and 64-GHz signals were affected by the beating noise of 62-GHz signal. Recently, we reported a 60-GHz RoF system based on frequency quintupling technique [16]. However, only preliminary results are provided on single-band MMW-signal transmission. In this work, we experimentally demonstrate a multiband and multi-gigabit 60-GHz wireless over fiber system with a cost-effective structure, detailed principle and theoretical analysis are also included. In the CS, 1-Gb/s on-off-keying (OOK) signals at 56-GHz and 60-GHz MMW are generated using two cascaded single-drive Mach-Zehnder modulators (MZMs), and only low-frequency (≤12GHz) synthesizers and low-speed devices are used. After 50-km single-mode fiber (SMF) transmission, at the base station (BS), the RoF signal is detected by a high-speed photo-detector (PD) and broadcast to end users through a 60-GHz antenna. After 10-ft air-link transmission, a novel user-terminal is realized using two-stage down-conversion architecture, where another antenna is used to receive the wireless signals. The two-stage down-conversions are implemented through envelope detection (ED) and intermediate frequency (IF) mixing, eliminating high-speed local oscillator (LO) and critical phase control components, which are indispensible for traditional MMW down-conversion. Furthermore, in order to improve transmission performance, single side band (SSB) modulation is employed to reduce chromatic dispersion (CD) and fading effects accumulated through fiber transmission.

2. Architecture and principle of the proposed 60-GHz multiband RoF system

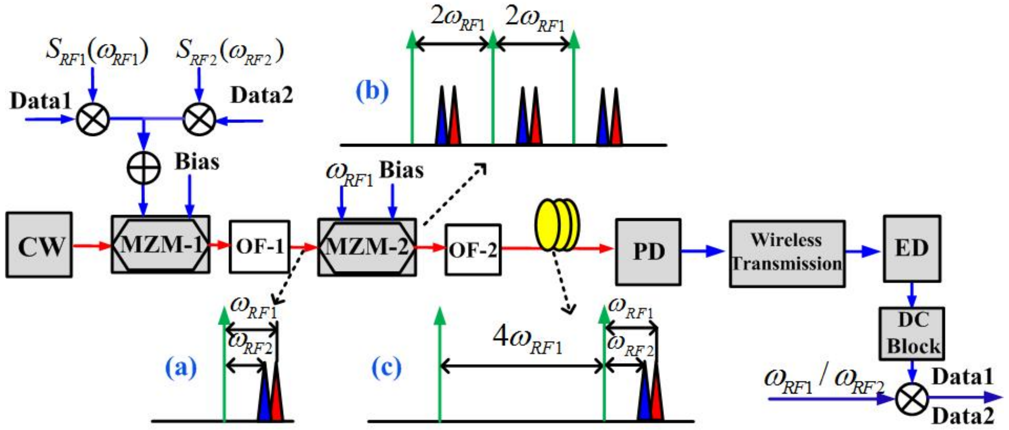

Fig. 1. Principle of multiband MMW-signal generation based on frequency quintupling technique.

Figure 1 shows the principle of multiband MMW-signal generation based on frequency quintupling technique. An IF clock S_{RF1} is mixed with an electrical signal Data1 to produce an electrical subcarrier multiplexed (SCM) signal, which is then combined with another electrical SCM signal realized by mixing an IF clock S_{RF2} with an electrical signal Data2. MZM-1 is driven by the combined signal and biased at the quadrature point of the transmission curve. The output of MZM-1 is input to an optical filter (OF-1) to generate a SSB signal (Fig. 1(a)), which consists of an un-modulated tone and two modulated tones carrying Data1 and Data2. The generated SSB signal can be expressed as:

$$E_{out1} = E_0\cos(\omega_c t) + D_1(t)\cos[(\omega_c+\omega_{RF1})t] + D_2(t)\cos[(\omega_c+\omega_{RF2})t] \qquad (1)$$

where E_0 and ω_c are the normalized amplitude of the un-modulated tone and the frequency of the input continual wave (CW) light, respectively. In order to keep MZM-1 operating in the linear region, the amplitude of the driven data should be properly controlled and the un-modulated tone should have much higher power (>10 dB) than that of the modulated tones. $D_1(t)$ and $D_2(t)$ are the two electrical data, which have the values of 0 or 1. ω_{RF1} and ω_{RF2} are the frequencies of the two IF clocks. The signal after the optical filter (OF-1) is up-converted by a second MZM (MZM-2), biased at the peak of the transmission curve and driven by another IF clock with a frequency of ω_{RF1}. At the output of MZM-2, another optical filter (OF-2) is employed to select the wanted bands (Fig. 1(c)), which can be illustrated as:

$$\begin{aligned} E_{out2} = {} & E_0\cos[(\omega_c-2\omega_{RF1})t] + E_0\cos[(\omega_c+2\omega_{RF1})t] \\ & + D_1(t)\cos[(\omega_c+3\omega_{RF1})t] + D_2(t)\cos[(\omega_c+2\omega_{RF1}+\omega_{RF2})t] \end{aligned} \qquad (2)$$

After fiber transmission, at the base station (BS), a high-speed PD is utilized to detect the upcoming signal. The output of the PD can be expressed as:

$$E_{out3} = \mu E_0^2\cos(4\omega_{RF1}t) + \mu D_1(t)E_0\cos(5\omega_{RF1}t) + \mu D_2(t)E_0\cos[(4\omega_{RF1}+\omega_{RF2})t] \qquad (3)$$

where μ is the responsivity of the PD. In Eq. (3), only the MMW components are considered, while the low-frequency components are ignored since they will be filtered out by the 60-GHz band-pass antennas and amplifiers. From Eq. (3), one can find that frequency quadrupling RF clock ($4\omega_{RF1}$) and frequency quintupling multiband MMW signals ($5\omega_{RF1}$ and $4\omega_{RF1}+\omega_{RF2}$) are achieved. After wireless transmission, at the user-terminal, an envelope detector (ED) is employed to down-covert the wireless signal and the output can be illustrated as [17]:

$$\begin{aligned} E_{out4} = \mu'\left|E_{out3}\right|^2 = {} & \frac{1}{2}\mu'\mu^2 E_0{}^4 + \frac{1}{2}\mu'\mu^2 D_1(t)^2 E_0{}^2 + \frac{1}{2}\mu'\mu^2 D_2(t)^2 E_0{}^2 \\ & + \mu'\mu^2 E_0{}^3\cos(\omega_{RF1}t) + \mu'\mu^2 E_0{}^3\cos(\omega_{RF2}t) \\ & + \mu'\mu^2 E_0{}^2\cos[(\omega_{RF1}-\omega_{RF2})t] \end{aligned} \tag{4}$$

where μ' is the responsivity of the ED. In Eq. (4), the high-frequency ($>4\omega_{RF1}$) components are not considered due to the limited bandwidth of the ED output. Besides, a direct current (DC) block can be used to eliminate the DC components (the first three terms). Furthermore, the last term with a frequency of $\omega_{RF1}-\omega_{RF2}$ is negligible since it has much smaller power compared with the other two IF signals with frequencies of ω_{RF1} and ω_{RF2} . As a result, only the forth and fifth terms of Eq. (4) are considered. A second-stage down-conversion is realized by mixing the IF signals with the low-frequency IF clock (ω_{RF1} or ω_{RF2}). It is noted that if proper frequencies are chosen for ω_{RF1} and ω_{RF2} , both the IF clocks (ω_{RF1} and ω_{RF2}) could be extracted from the downstream RF clock ($4\omega_{RF1}$). For example, if ω_{RF1} = 12 GHz and ω_{RF2} = 8 GHz, the two IF clocks can be generated from the received 48-GHz RF clock using factor-four and factor-six frequency dividers, respectively. In that case, no clock sources are required in the user-terminal, which eliminate the clock synchronization and reduce the system cost.

3. Experimental setup and results

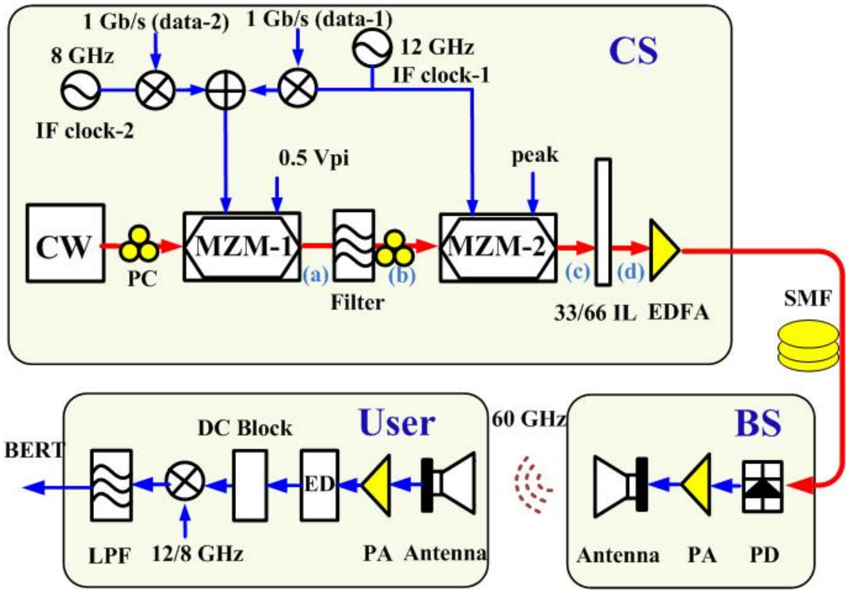

Fig. 2. Experimental setup of the proposed 60-GHz multiband RoF system, (a)-(d) correspond to the optical spectra shown in Fig. 3.

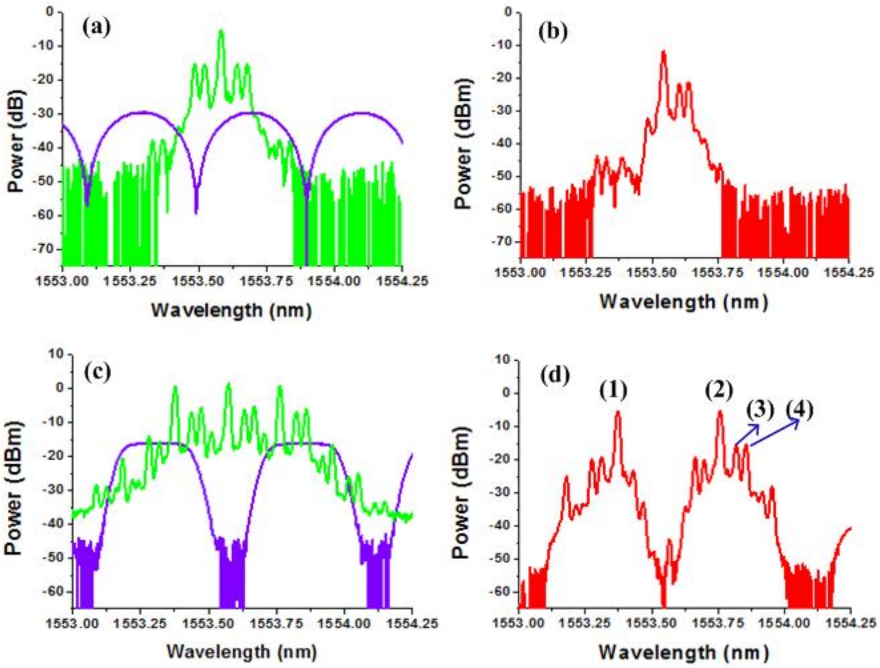

Fig. 3. Optical spectra taken at different positions as indicated in Fig. 2. Spectral resolution: 0.02 nm. (a) Multiband optical SCM signal (green line) and the pass-band of the optical filter (purple line), (b) generated SSB signal after the filter, (c) output of MZM-2 (green line) and the pass-band of the 33/66 IL (purple line), and (d) output of the 33/66 IL.

We perform an experiment to verify the feasibility of the proposed scheme, with a setup shown in Fig. 2. In the central station (CS), a CW light originated from a tunable laser with a wavelength of 1553.6 nm is fed into a single-drive MZM. Two streams of 1-Gbit/s pseudo-random bit sequence (PRBS) data with a word length of 2^{31}-1 are mixed with 8-GHz and 12-GHz IF clocks. The output of the mixers are combined and amplified to drive the MZM biased at the quadrature point of the transmission curve. An optical multiband SCM signal (Fig. 3(a)) is obtained at the output of the MZM, which is fed into a periodic band-pass filter to generate a SSB signal (Fig. 3(b)). The SSB signal is up-converted by a second MZM, biased at the peak of the transmission curve and driven by an amplified 12-GHz IF clock. The spectrum of the up-converted signal is shown in Fig. 3(c), whose unwanted bands are suppressed by a 33/66 interleaver (IL). After the IL, we achieve a four-tone signal (Fig. 3(d)), where tone-1 and tone-2 are un-modulated carriers, tone-3 and tone-4 are modulated with data-1 and data-2, respectively. The frequency spaces between tone-1 and tone-2, tone-3, tone-4 are 48 GHz, 56 GHz and 60-GHz, respectively. The optical signal is amplified by an erbium-doped fiber amplifier (EDFA) to reach a power of 6 dBm and then transmitted to the BS through 50-km single mode fiber (SMF).

At the BS, a high-speed PD (u2t XPDV 2020R) is used to detect the coming signal, whose spectrum is illustrated in Fig. 3(d). The beating of the un-modulated tone-1 and tone-2 generates a 48-GHz RF clock. The 56-GHz and 60-GHz multiband MMW signals are obtained through the beatings of tone-1 and tone-3 (tone-1 and tone-4). The electrical spectrum of the PD output is depicted in Fig. 4(a), which is input to a power amplifier (Narda West NW 06-0023). A pair of rectangular horn antennas (Ducommun ARH-1525-62) with a gain of 25 dBi at the range of 45-75 GHz are employed to broadcast and receive the wireless signals. After transmission over 10-ft wireless link, at the user-terminal, the wireless signals, including 48-GHz RF clock, 56-GHz and 60-GHz multiband MMW signals, are fed into an envelope detector (ED). Down-conversions are realized through the beatings of the 48-GHz clock and the multiband signals consisting of 56-GHz and 60-GHz MMW. After the ED, we obtain two IF signals with frequencies at 8-GHz and 12-GHz, whose eye diagrams are shown in Fig. 4(b) and 4(c). A second-stage down-conversion is realized by mixing the IF signals with 8-GHz or 12-GHz IF clock. After the IF mixing, a low-pass filter is employed to select the baseband signal for performance testing. It is noted that both the 8-GHz and 12-GHz IF clocks can be achieved through the de-multiplication of the 48-GHz clock. Consequently, no clock sources are needed in the user-terminal, thus greatly reducing the system cost. In practical experiment implementation, due to the lack of frequency dividers, an additional clock source is used to down-convert the 8-GHz and 12-GHz IF signals to baseband, with eye diagrams shown in Fig. 4(d) and 4(e), respectively.

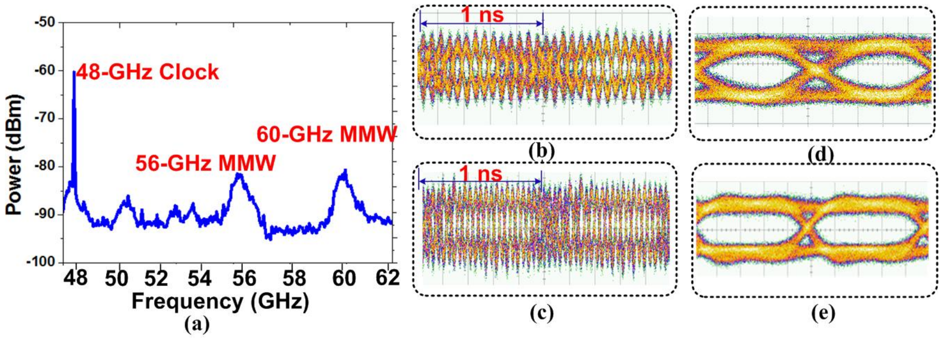

Fig. 4. (a) Electrical spectrum after the PD detection, (b) IF band and (d) baseband eye diagrams for the 56-GHz signal, (c) IF band and (e) baseband eye diagrams for the 60-GHz signal.

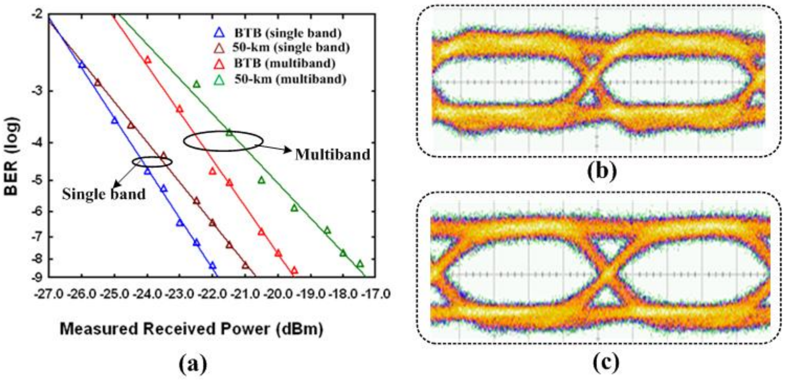

Fig. 5. (a) BER curves of the 60-GHz signal with and without the presence of the 56-GHz signal, baseband eye diagrams for the 60-GHz signal (b) with the presence of the 56-GHz signal, and (c) without the presence of the 56-GHz signal.

We measure bit-error-ratio (BER) performance of the 60-GHz MMW signal with and without the presence of the 56-GHz MMW signal after 10-ft wireless transmission. The 60-GHz signal in the multiband case needs ~2.5 dB more power than the one in single-band case. In addition, the power penalty from the 50-km SMF transmission is ~1 dB for the single-band case, while the penalty is 2 dB for the multiband case, which can be attributed to the interference of the 56-GHz MMW signal. Error-free performances are achieved for all conditions. Figures 5(b) and 5(c) show the eye diagrams of the 60-GHz signal with and without the presence of the 56-GHz signal, respectively.

4. Conclusion

We have proposed a cost-effective RoF system to generate multiband and multi-gigabit MMW signals based on frequency quintupling technique. Theoretical derivation and experimental demonstration are provided. In the CS, the multiband MMW signals at 56-GHz and 60-GHz are obtained with low-frequency (≤12GHz) electronic devices and modulators, which reduce the system cost. At the receiver side, envelope detection has been used to down-convert the MMW signals to IF bands, eliminating high-speed RF synthesizer and critical phase control components. Besides, the IF clocks (8 GHz and 12 GHz) can be obtained from the received clock (48 GHz), enabling a clock-free user-terminal. Error-free performance is achieved for the 60-GHz signal with a 2.5-dB power penalty after 50-km SSMF and 10-ft wireless link transmissions. The experimental results validate our scheme as a desirable candidate for future RoF networks supporting multiband 60-GHz MMW-signal transmission.

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