Multiband Signals Generation and Transmission over Fiber and Air by a Novel Frequency-Doubled, Radio-Over-Fiber Architecture without Expensive Carrier Suppression Filters

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Abstract: We demonstrate a novel frequency-doubled wireless over fiber system to offer multiband services including baseband, 60-GHz millimeter-wave and 15-GHz microwave without carrier suppression. Multiband wireless signals are successfully transmitted through both fiber and air channels.

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1. Introduction

In recent years, with the increasing demand for high bandwidth, millimeter-wave radio-over-fiber (RoF) technology especially for 60-GHz band, has received considerable research interest for providing super-broadband wireless services for customers [1,2]. Multiband modulation in RoF which simultaneously delivers baseband, microwave (MW), and millimeter-wave (MMW) signals can offer a cost-effective configuration for the future integrated platform and several approaches have been demonstrated [3,4]. However, in order to multiply the beating frequency and then reduce the system cost, these works need either optimal bias control or interleavers or narrowband optical notch filters to achieve carrier suppression.

In this paper, a new architecture of frequency doubled multiband RoF system without carrier suppression is first proposed and experimentally demonstrated, which can simultaneously generate and transmit wired signal through fiber and 60-GHz MMW and 15-GHz MW via fiber and air. This scheme is based on an intensity modulator, double-sideband phase modulation (DSB-PM) and a broadband filter without suppressing carrier. Error-free transmission of 2.5-Gb/s at 60-GHz band is successfully demonstrated over a combined distance of 10 km single-mode-fiber (SMF-28) and 5 m free space propagation with 20-dBm equivalent isotropically radiated power.

2. Concepts and Theoretical Analysis

Figure 1 shows the setup of the proposed RoF system. The continuous wave (CW) from a distributed feedback laser diode (DFB-LD), which is represented by $E_{in}=E_o exp(j\omega_c t)$, is modulated by two driving signals, $V_1(t)$ and $V_2(t)$, via a dual-arm Mach-Zehnder modulator (MZM). $V_1(t)$ consisting a 15-GHz RF sinusoidal clock and a dc bias voltage is written as $V_1(t) = V_{bias} + Acos(\omega_{rf}t)$. $V_2(t)$ consisting of a 2.5-Gb/s baseband data can be written as $V_2(t) = B(t)$. We assume the power splitting ratio of two arms of the MZM is 1/2.The electrical field at the output of the MZM is given by

$$E_{out-1} \approx \frac{\sqrt{\alpha}}{2} E_0 e^{j\omega_c t}[J_0(m_A) + jJ_1(m_A)e^{j\omega_{rf}t} + jJ_1(m_A) + e^{-j\omega_{rf}t} e^{j\left(\frac{\pi}{V_\pi}(B(t)+V_{bias})\right)}] \qquad (1)$$

Here, α is the insertion loss of the MZM. $J_k(x)$ is the Bessel function of the first kind of order k, and $m_A = \pi A/V_\pi$. Then the signal is modulated by a sinusoid signal, $V_3(t)$, with sweep frequency $2\omega_{rf}$ via a phase modulator. Next, we reject the higher order optical subcarriers by using an optical filter with a wide bandwidth larger than $4\omega_{rf}$, and the electric field at the output of the filter can be written as

$$\begin{aligned} E_{out-2} \approx 1/2 \cdot E_0[&\alpha_0(J_0(m_A)J_0(Z) + J_0(m_A)e^{j(\pi/V_\pi)(B(t)+V_{bias})})e^{j\omega_c t} + \alpha_1(jJ_1(m_A)J_0(Z) - J_1(m_A)J_1(Z))e^{j(\omega_c+\omega_{rf})t} + \\ &\alpha_1(jJ_1(m_A)J_0(Z) - J_1(m_A)J_1(Z))e^{j(\omega_c-\omega_{rf})t} + \alpha_2(jJ_0(m_A)J_1(Z) + jJ_1(Z)e^{j(\pi/V_\pi)(B(t)+V_{bias})})e^{j(\omega_c+2\omega_{rf})t} + \\ &\alpha_2(jJ_0(m_A)J_1(Z) + jJ_1(Z)e^{j(\pi/V_\pi)(B(t)+V_{bias})})e^{j(\omega_c-2\omega_{rf})t} + \alpha_3(-J_1(m_A)J_1(Z) - jJ_1(m_A)J_2(Z))e^{j(\omega_c+3\omega_{rf})t} + \\ &\alpha_3(-J_1(m_A)J_1(Z) - jJ_1(m_A)J_2(Z))e^{j(\omega_c-3\omega_{rf})t} + \alpha_4(-J_0(m_A)J_2(Z) - jJ_2(Z)e^{j(\pi/V_\pi)(B(t)+V_{bias})})e^{j(\omega_c+4\omega_{rf})t} + \\ &\alpha_4(-J_0(m_A)J_2(Z) - jJ_2(Z)e^{j(\pi/V_\pi)(B(t)+V_{bias})})e^{j(\omega_c-4\omega_{rf})t} \end{aligned} \qquad (2)$$

where α_0, α_1, α_2, α_3, and α_4 are the insertion losses for the central carrier and each sidebands, respectively. The filter spectrum is assumed to be fully symmetric and no group delay is introduced. After detected by a photodiode (PD), the output photocurrent $I \approx C_0 + C_1 cos(\omega_{rf}) + C_2 cos(4\omega_{rf})$, where C_0, C_1 and C_2 are coefficients for DC, 15-GHz and 60-GHz signals, respectively. It is unnecessary to suppress the carrier to double beating frequency to get $4\omega_{rf}$ RF signal in this scheme. The coefficient C_2 for 60-GHz signal after transmitting through fiber of length L can be expressed by

$$\frac{1}{2}\mu E_0^{\,2}[(\alpha_2^{\,2} J_1^{\,2}(Z) - 2\alpha_0\alpha_4 J_0(m_A)J_2(Z)\cos(\frac{-4\pi c D\cdot(2\omega_{rf})^2\cdot L}{\omega_c^{\,2}}))\cdot(J_0^{\,2}(m_A)+2J_0(m_A)\cos(\frac{\pi}{V_\pi}(B(t)+V_{bias})+1)] \qquad (3)$$

where c is the speed of light, μ is the responsivity of PD, and D is dispersion coefficient. From (3), we can find the 60-GHz RF power would vary from maximum to minimum value after every ~2 km SMF transmission for light source with wavelength of 1550 nm. Fig. 2(a) also shows the simulated 60-GHz RF power variation versus fiber transmission distance with two 4^{th} order Gaussian filters of different 3 dB bandwidths. The variation of RF power would be reduced while the bandwidth of filter is narrowed down. This is because the power of sidebands at $\omega_c+4\omega_{rf}$ and $\omega_c-4\omega_{rf}$, which act negatively to the amplitude of 60-GHz signal as indicated in (3), are suppressed more by a filter with narrow bandwidth.

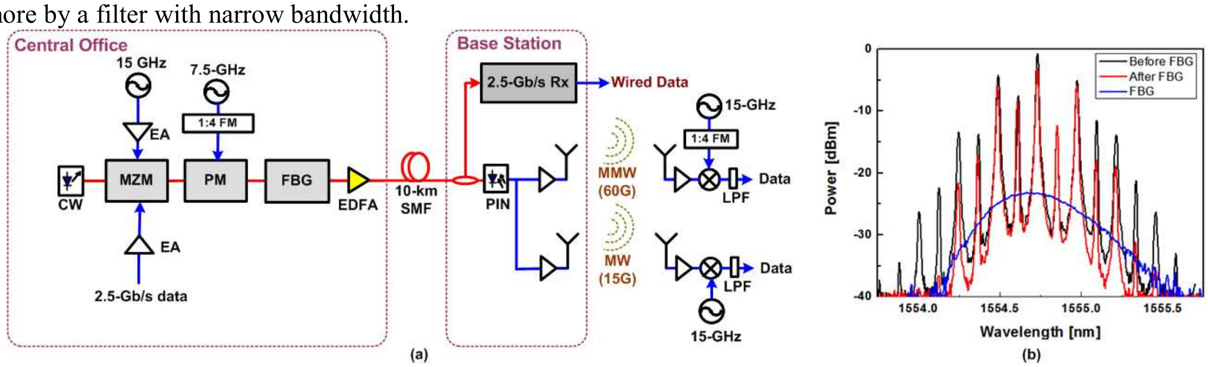

Fig. 1 (a) Experimental setup of wireless over optical fiber system. (MZM: Mach-Zehnder modulator; PM: phase modulator; FM: frequency multiplier; EA: electrical amplifier; FBG: fiber brag grating; LPF: low pass filter), (b) Optical Spectra before and after FBG, and FBG reflective spectrum. (resoluation: 0.01 nm).

3. Experimental Setup and Results

Figure 1(a) illustrates the experimental setup for the proposed multiband optical-wireless access system over fiber and air links. At the central office, a CW lightwave is generated by a tunable laser at 1554.73 nm and followed by a LiNbO3 dual-arm MZM. One arm is driven by an amplified 15-GHz sinusoidal wave, and the 2.5-Gb/s data with pseudorandom binary sequence (PRBS) word length of 2^{31}-1 is used to drive the other arm of the modulator. Next, the signal is modulated by a 30-GHz sinusoidal wave, which is generated by 1:4 frequency multiplier and 7.5-GHz clock source, via an optical phase modulator. A fiber Bragg grating (FBG) filter with 3dB bandwidth of 0.65nm is then utilized to suppress higher order sidebands. Fig. 1(b) shows the optical spectra before and after FBG and the reflective spectrum of FBG. After amplified by an EDFA and 10 m SMF transmission, some part of signal is directly detected by a 2.5-Gb/s receiver for the wired baseband connection. Optical to electrical conversions of the 60-GHz and 15-GHz signals are completed by a 60-GHz PIN photodiode followed by a splitter to separate received signal into two parts. One part is boosted by an electrical amplifier (EA) and then directly down-converted to baseband form by mixing the converted electrical signal with a 15-GHz LO signal. The BER performance of 15-GHz signal is shown in Fig. 2(b), and the power penalty after transmitting after 10-km SMF-28 is very small and can be ignored. The wireless transmission of 15-GHz MW signal is not implemented on account of the absence of the antennas at 15-GHz band.

An EA with 5-GHz bandwidth centered at 60-GHz is used to boost the other part of signal after 60-GHz PIN. One pair of rectangular horn antennas with a gain of 25-dBi at the range of 50-GHz to 75-GHz are utilized to broadcast and receive the 60-GHz signal. After wireless detection, the down-conversion is achieved by a balanced mixer and a 60-GHz LO signal, which was generated by 15-GHz clock signal and a 1:4 frequency multiplier. Fig. 3(a) shows the bit error rate (BER) performance as a functional of free space propagation distance with equivalent isotropically radiated power (EIRP) is around 20dBm, adhering to the 40 dBm limitation for in-building 60GHz radio by FCC regulation. The results show the performance after 10 km SMF-28 transmission is better than B-T-B performance, and the error-free wireless distance is 4 m. This is because the two sidebands at $\omega_c+4\omega_{rf}$ and $\omega_c-4\omega_{rf}$

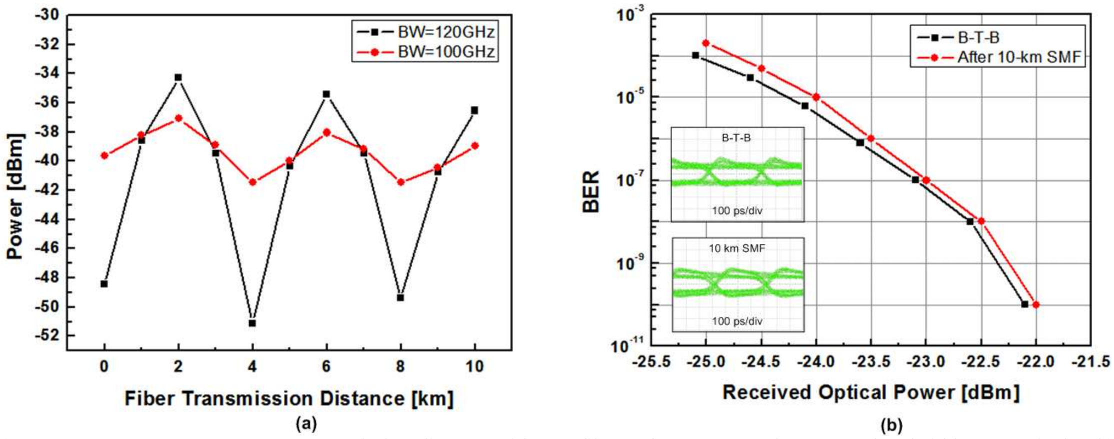

Fig. 2 (a) 60-GHz RF power versus SMF transmission distance with two filters of 100-GHz and 120-GHz bandwidth, respectively. (b) BER performance of 15-GHz signal.

are not suppressed enough to lessen the power variation of 60-GHz RF signal caused by fiber transmission distance as shown in our theoretical analysis. If we have a filter with sharper edge and flatter transmission window, the variation of power and BER performances would be improved. The BER performance with different EIRPs after 10 km SMF-28 and 5 m wireless transmissions is also shown in Fig.3 (b). Moreover, the optical eye diagrams shown in the insets in Fig.3 (a) indicate the appearance of 30-GHz signal after 10 km SMF transmission, which may cause some inter-band interference. By using low-cost zero-dispersion light at 1310 nm, it can not only solve the interference from 30-GHz signal and improve the power vibration of 60-GHz signal caused by dispersion.

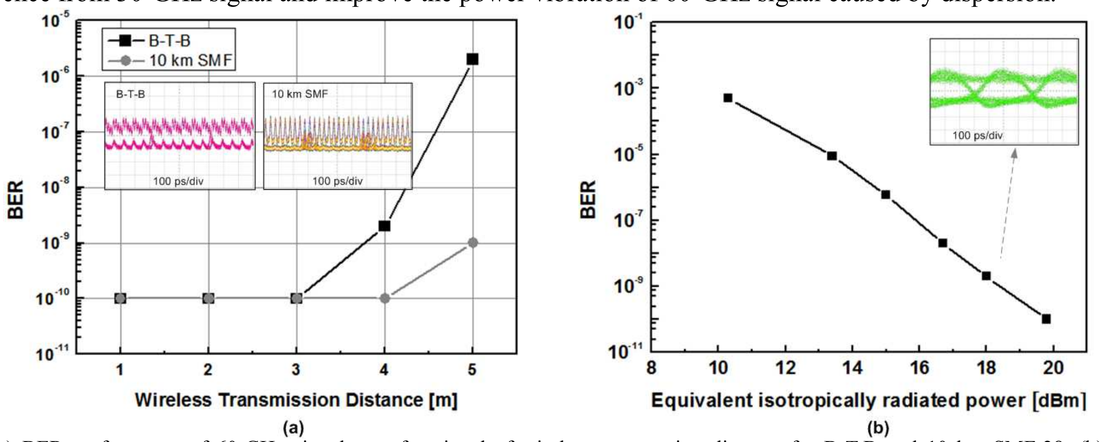

Fig. 3 (a) BER performance of 60-GHz signal as a functional of wireless propagation distance for B-T-B and 10 km SMF-28. (b) BER performance with different EIRPs after 10 km SMF and 5 m wireless transmission, and the inset is electrical eye diagram with EIRP = 18 dBm.

4. Conclusions

We have proposed and successfully demonstrated a novel wireless over optical fiber system to transmit three types of signals: baseband, 15-GHz MW and 60-GHz MMW, with 2.5-Gb/s data via both fiber and air channels without carrier suppression which requires complicated bias control or expensive filters/ interleavers with narrow bandwidth. Moreover, the scheme can be scalable to DWDM systems with 100-GHz channel spacing and be viewed as a versatile and cost-effective solution for future RoF access networks.

5. References

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