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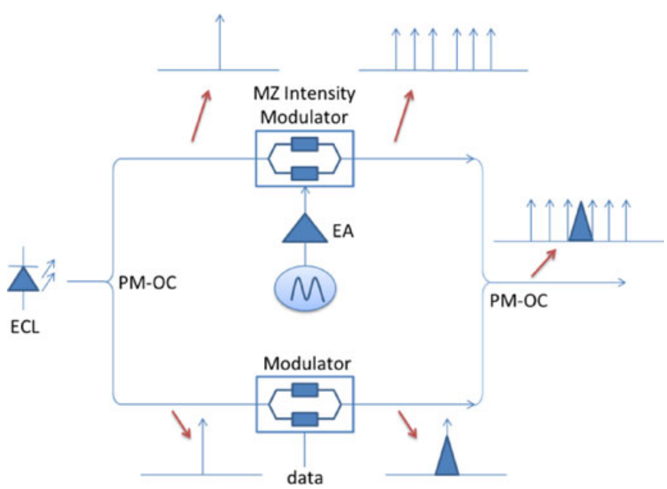

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Generation of Multiple-Frequency Optical Millimeter-Wave Signal With Optical Carrier Suppression and No Optical Filter

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Abstract: We propose and experimentally demonstrate the generation of a multiple-frequency optical millimeter-wave (mm-wave) signal an without optical filter at the transmitter side. Forty, 80, and 120-GHz multiple-frequency optical mm-wave signals are generated simultaneously in our experiment. After 20 km standard single-mode fiber transmission, high-quality eye diagrams with large opening and high stability are obtained at these frequency bands.

Index Terms: Multiple-frequency, millimeter-wave (mm-wave) signal, intensity modulator (IM).

1. Introduction

Wireless fidelity (WiFi) is widely used at homes and offices for providing broadband wireless services [1]. In order to meet different requirements such as distance and bandwidth, usually the frequencies at WiFi standard include the 2.4, 3.6, 4.9, 5 and 5.9 GHz bands. Usually, two or three different frequency bands (2.4 and 5 GHz) at one WiFi device are available [1]. Currently the WiFi can only provide megabit-per-second service. In order to provide more bandwidth, such as over $1-10$ Gb/s signal, the carrier frequency should be higher, and millimeter-wave (mm-wave) frequency will be necessary in the future. Radio-over-fiber (ROF) has the advantages of optical fiber bandwidth and mobility of wireless, which can provide long-distance and broadband service [2]–[11]. The future mm-wave wireless WiFi devices should provide multiple-frequency service to meet different requirements, and therefore how to generate one multiple-frequency mm-wave signal with simple architecture is one interesting topic [12]. Optical mm-wave generation by using one external

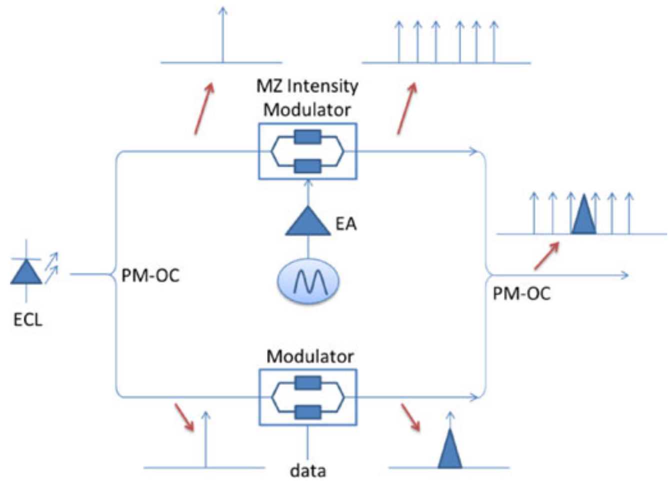

Fig. 1. Principle of multiple-frequency optical mm-wave signal generation without optical filter.

modulator has been widely researched [12]–[34], and most of them need optical filter to select optical carriers for mm-wave generation [12]–[30]. To remove optical filter can reduce the cost of the transmitter and simplify the architecture [31]–[34]. On the other hand, only single-frequency optical mm-wave signal is generated in these schemes [12]–[34], except that [12] can provide dual-frequency mm-wave signal generation. Also, the signals at different frequencies are different in [12], which cannot be used for WiFi system because we need the same signal at different frequencies. Here we propose one new scheme to realize multiple-frequency optical mm-wave signal generation without optical filter at the transmitter. 40, 80, and 120 GHz mm-wave signals, carrying the same transmitter data, are generated, and the transmission of these mm-wave signals over 20 km standard single mode fiber (SMF) is experimentally demonstrated. Since only one sideband of these mm-wave signals carry transmitter data, there exists no dispersion-induced walk off effect during fiber transmission, which, however, is common for the typical double-sideband (DSB) mm-wave signals [35]. Clear and widely open eye diagrams of 10 Gbaud on-off-keying (OOK) signal carried by these mm-wave signals at 40, 80, and 120 GHz are measured after transmission over 20 km SMF, which well demonstrates the potential of our proposed scheme to be used for WiFi system.

2. Principle of Multiple-Frequency Optical mm-Wave Signal Generation without Optical Filter

Fig. 1 shows how to realize multiple-frequency optical mm-wave signal generation without optical filter. The continuous-wave (CW) lightwave is separated into two paths by using one polarization maintaining optical coupler (PM-OC). The CW lightwave at the upper path is modulated by one Mach-Zehnder modulator to generate multi-carrier optical signal with optical carrier suppression, and that at the lower path will be modulated by one modulator to realize electrical-to-optical (E/O) conversion to generate baseband optical signal at the center carrier wavelength. At the upper path, the Mach-Zehnder modulator is driven by relatively high RF power at one frequency of f, and we can generate multiple-carrier optical signal with optical carrier suppression after we adjust the DC-bias on the Mach-Zehnder modulator. Because the carrier at the center wavelength is suppressed, we can combine the multi-carrier optical signal with the baseband signal at the center carrier wavelength. The generated multi-carrier optical signal is combined with the baseband signal by the second PM-OC. This way, we can realize multi-frequency optical mm-wave signal generation without any optical filter.

Fig. 2 shows the ROF architecture to generate and deliver different frequency mm-wave signals over fiber and detect these mm-wave signals in the receiver side. As one example, here we show

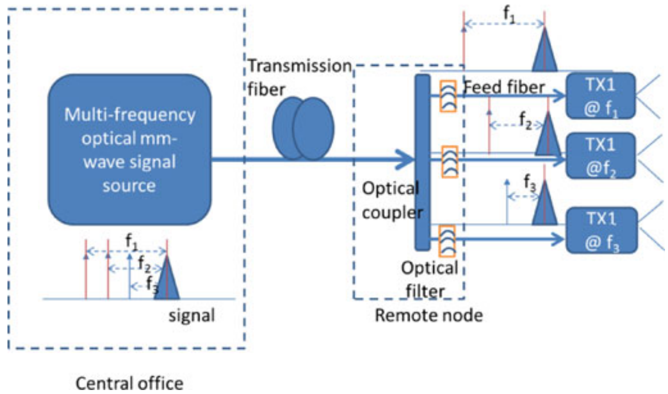

Fig. 2. Multiple-frequency mm-wave generation and transmission in one ROF system.

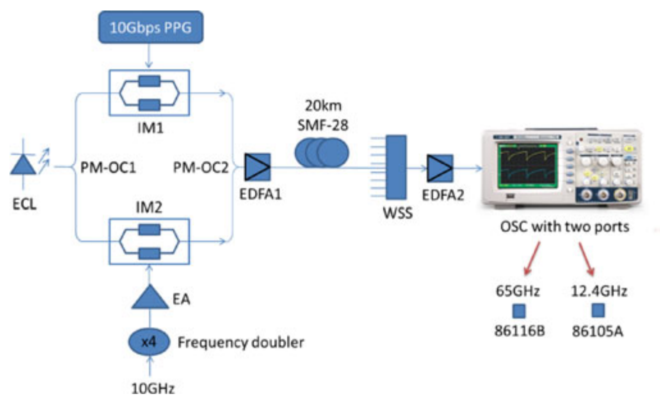

Fig. 3. Experimental setup. ECL: external cavity laser, IM: intensity modulator, EA: electrical amplifier, PM-OC: polarization maintaining optical coupler, EDFA: erbium-doped fiber amplifier, WSS: wavelength selective switch, PD: photodiode.

the case with three RF frequencies. The generated optical mm-wave signals at three frequencies are delivered to remote node by the transmission optical fiber. Usually, the optical spectrum is symmetrical after Mach-Zehnder modulator [16], [21], and here, we only show the negative order mm-wave signal for simplification. In the remote node, we use one optical coupler and optical filters, such as wavelength selective switch (WSS), wavelength-division-multiplexing (WDM) coupler or arrayed waveguide gratings (AWG), to separate the three-frequency optical mm-wave signals. After transmission over the feed fiber, it will be detected by one photodiode (PD) to realize optical-to-electrical (O/E) conversion. The optical spectra at different locations are inserted in the figure.

3. Experimental Setup

The experimental setup is shown in Fig. 3. The CW lightwave generated from one ECL at 1552.5 nm has 14.5 dBm output power and 100 kHz 3 dB linewidth. Then one PM-OC is used to separate the CW lightwave into two parts. 10 Gb/s binary signal with a pseudo-random binary sequence (PRBS) length of $2^{23} - 1$ is generated from one pattern generator with 2 V_{pp} amplitude, and it is used to drive the IM modulator (27 GHz bandwidth and 5 dB insertion loss) to generate optical 10 Gb/s OOK signal. 40 GHz clock source is generated by one frequency multiplier, which can realize 10 GHz to 40 GHz frequency multiplication. After it is boosted to 15 V_{pp} amplitude by one electrical power amplifier, it drives one intensity modulator with 3 dB bandwidth of 37 GHz and half-wave voltage of 2.7 V at 1 GHz. This intensity modulator has one insertion loss of 5 dB. The output power from the IM versus DC bias is shown in Fig. 4. The DC bias is set at 6.6 V in this

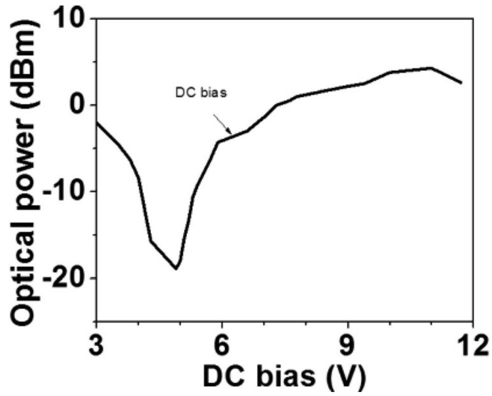

Fig. 4. Output power versus DC bias without RF driving signal.

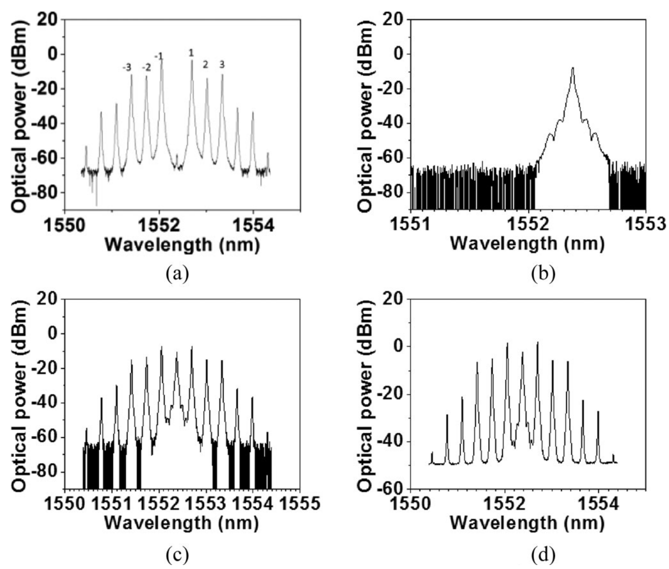

Fig. 5. Optical spectra (0.01 nm resolution) at different locations in Fig. 3, (a) after IM2, (b) after IM1, (c) after PM-OC2, and (d) after EDFA1.

experiment. Then, we use one PM-OC to combine the two path optical signals. One erbium-doped fiber amplifier (EDFA) is employed to boost the optical signal to 9 dBm before it is transmitted over 20 km single-mode fiber-28 (SMF-28) fiber with 0.2 dB/km insertion loss and group velocity dispersion (GVD) of 17 ps/nm/km at 1550 nm. After transmission over fiber, we use one WSS with the smallest grid of 10 GHz to select the mm-wave signal with different frequencies at 40, 80 or 120 GHz. Then we use one sampling oscilloscope with two optical ports with different bandwidth to measure the eye diagram. One port has 65 GHz bandwidth and the other one has 12.4 GHz bandwidth to simulate the mm-wave signal after down-conversion [20].

4. Experimental Results

The generated optical spectrum after IM2 is shown in Fig. 5(a). The optical power at 1552.056 nm (−1, the negative first-order carrier), 1551.736 nm (−2, the negative second-order) and 1551.416 nm (−3, the negative third-order) is −3.3, −12.4, and −11.6 dBm, respectively. Because we will use the negative order carriers, we only show the wavelength and power of the negative order carriers. In fact, the positive ones can be also used. The maximal power difference of the three carriers is about 9 dB. The smallest signal to noise ratio of the three carriers is over

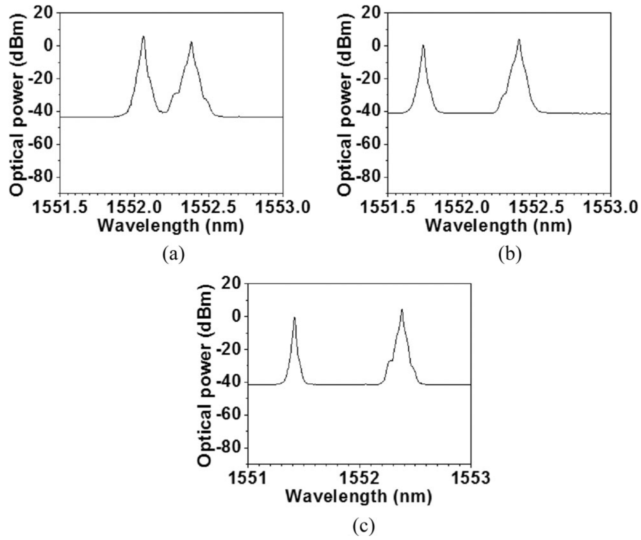

Fig. 6. Optical spectrum after transmission over 20 km and WSS (0.01 nm resolution). (a) 40 GHz, (b) 80 GHz, and (c) 120 GHz.

50 dB. The optical carrier at the center wavelength at 1552.5 nm is −60 dBm, which means that the suppression ratio relative to the negative first-order (−1) optical carrier signal is over 56 dB. The optical spectrum after IM1 is shown in Fig. 5(b). The bandwidth after modulation at 10 Gb/s at 20 and 30 dB is 0.1 and 0.23 nm, respectively. Because the bandwidth of the signal is small, there is no crosstalk after combined with the mm-wave signal from IM2. Fig. 5(c) shows the optical spectrum after PM-OC2, and Fig. 5(d) shows the optical spectrum after EDFA1.

After transmission over 20 km SMF-28, one WSS and one EDFA, the optical spectra of 40, 80 and 120 GHz optical mm-wave signals are shown in Fig. 6(a), (b) and (c), respectively. For 40 GHz optical mm-wave signal, the signal at the center wavelength at 1552.5 nm and the negative first-order optical carrier are selected. This WSS has one input port and 4 output ports, and the insertion loss is 7 dB. Here we only use one input port and one output port. For 80 GHz and 120 GHz, we will choose the negative second-order and negative third-order optical carriers, respectively. Compared to the signal at 1552.5 nm, the power of the optical carriers at different sidebands is different. This will not affect mm-wave signal generation. But for the receiver sensitivity measurement of mm-wave signal, the power of the sideband signal and that of the signal at the center wavelength should be equal [16].

The optical eye diagrams are measured by one sampling oscilloscope with two optical ports with different bandwidth. One has 65 GHz optical bandwidth (Agilent 86116B) and the other one has 12.4 GHz optical bandwidth (Agilent 86105A). This narrow bandwidth PD is used to simulate the case after mm-wave signal down-conversion. Fig. 7 shows the eye diagrams without transmission fiber. Fig. 7(a)–(c) are measured by the 65 GHz optical port, while Fig. 7(d)–(f) are measured by the 12.4 GHz optical port. Very clear and stable optical eye diagrams are recorded. Because the bandwidth of Agilent 86116B is only 65 GHz, we can see that the mm-wave components are suppressed in Fig. 7(b) at 80 GHz and almost completely suppressed or removed at 120 GHz in Fig. 7(c). We can still see some mm-wave components in Fig. 7(d). This is because the frequency of the mm-wave is 40 GHz, but for 80 GHz or 120 GHz, after the 12.4 GHz filter, the mm-wave components are completely removed.

Fig. 8 shows the experimental results after transmission over 20 km fiber. The eye diagrams for all cases are very stable and clear. Due to fiber dispersion, the eye opening after 12.4 GHz filter (measured by 86105A) is smaller compared to the case without fiber transmission. However, the eye is still widely opened even if the mm-wave signal works at 120 GHz. It should be pointed out that this mm-wave signal, even if working at 120 GHz, can be transmitted over 20 km SMF-28 because the mm-wave signal is single sideband (SSB) modulation [31].

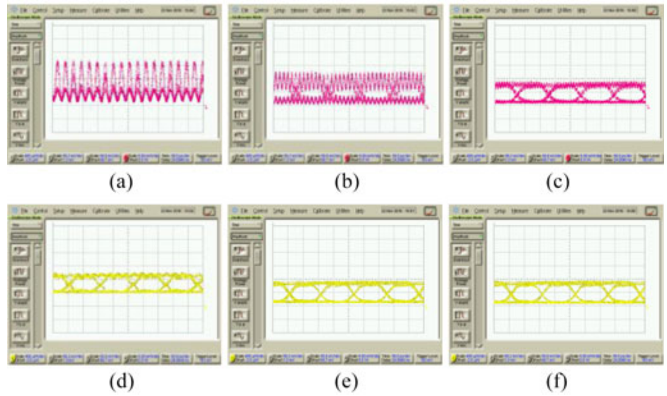

Fig. 7. Eye diagrams without transmission fiber (50ps/div). (a)–(c) are measured by 65 GHz optical port (Agilent 86116B), while (d)–(f) are measured by 12.4 GHz optical port (Agilent 86105A). (a) 40 GHz, (b) 80 GHz, (c) 120 GHz, (d) 40 GHz, (e) 80 GHz, and (f) 120 GHz.

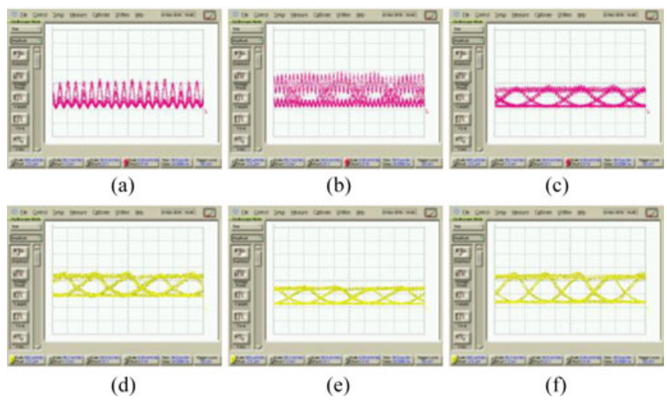

Fig. 8. Eye diagrams after 20 km transmission fiber (50ps/div). (a)–(c) are measured by 65 GHz optical port (Agilent 86116B), while (d)–(f) are measured by 12.4 GHz optical port (Agilent 86105A). (a) 40 GHz, (b) 80 GHz, (c) 120 GHz, (d) 40 GHz, (e) 80 GHz, and (f) 120 GHz.

5. Conclusion

We have proposed and experimentally demonstrated one novel scheme to generate three-band optical mm-wave signals at 40, 80, and 120 GHz by using intensity modulators without an optical filter. Two intensity modulators are employed. One is driven at 15 V with proper DC bias to generate −1-, −2-, and −3-order carriers with high-amplitude and center carrier suppression. The other one is used to generate baseband optical signal at the center wavelength. We measured the eye diagrams before and after down-conversion with or without fiber transmission. Clear and widely open eye diagrams at these mm-wave bands at 40, 80, and 120 GHz after 20 km SMF-28 fiber transmission are recorded.

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