Experimental demonstration for 40-km fiber and 2-m wireless transmission of 4-Gb/s OOK signals at 100-GHz carrier

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We experimentally demonstrate a 4-Gb/s radio-over-fiber (RoF) system with 40-km fiber and 2-m wireless distance downstream at 100-GHz carrier. To the best of our knowledge, this is for the first time in China to realize optical wireless link at 100 GHz. In this letter, simple intensity modulator with direct detector (IM-DD) modulation is employed and optical power penalty after 40-km single mode fiber (SMF)-28 and 2-m air link is 3.2 dB with bit-error-rate (BER) at 1×10^{-9}.

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Radio-over–fiber (RoF) technology, regarded as one of the most promising solutions to break the last mile bottleneck imposed by the copper network, has attracted much attention recently[1−11]. It features low transmission loss, extremely wide bandwidth, availability of optical amplifiers, and broad coverage by making full use of the enormous bandwidth of the fiber and the flexibility presented by wireless communication system. To realize the seamless integration of wireless and fiber-optic networks, the wireless links need to be developed to match the capacity of high-speed fiber-optic communication systems. Moreover, the access network is expected to carry more data to provide the increasing broad-band radio services such as voice over IP and video on demand. As the capacity of the air link is relate to the frequency of the carrier, a higher carrier frequency with a large bandwidth is becoming indispensable. This is due to its broad spectrum that the higher frequency W-band (75 GHz –0.11 THz), avails of us a new approach for realization of the RoF system. For example, to our knowledge recently, Nokia and Samsung have introduced 8 k and 4 k super high definition (SHD) video camera in smart phones that require transmission speed for uncompressed SHD video images of 60 and 30 Gb/s, respectively. Evidently, it is not desirable to require such thin and light-weight mobile terminals to install heavy high definition multimedia interfaces (HDMIs) or fiber cables. Meanwhile, due to wider bandwidth and higher frequency, the fiber-wireless link in the W-band based on optically-modulated signal generation technique, is expected to provide multi-gigabit mobile data transmission, and has been intensively studied in research community[4−11]. However, many of research findings concentrate on using high spectral efficient data formats to transmit more data per symbol[6−10], making the transmitter and receiver complex and real-time system difficult to build up. In addition to improving the 100-GHz RoF system's performance, coding[8] or equalization[9,10] is also proposed in some reports. Thus, simplicity and practical applications for the RoF technology are still problems should be addressed.

In this report, a downstream RoF system employing IM-DD modulation at 100 GHz is experimentally proposed. In the system, the on-off keying (OOK) signal was generated by an intensity modulator at the central station (CS) and a photo detector (PD) was deployed at the base station (BS) for direct detection. We have realized 4-Gb/s OOK signal transmission over 2-m wireless link and 40-km fiber and assessed performance of the 100-GHz RoF system under different transmission conditions. Compared to optical power without fiber transmission, the power penalty with bit error rate (BER) at 1×10^{-9} after 40-km SMF-28 and 2-m wireless link was 3.2 dB.

Figure 1 shows the experimental setup, which is composed of three modules: central office, base station, and W-band wireless receiver. The central office consists of two laser sources, an intensity modulator (IM) and a polarization maintaining optical coupler (PM-OC), to generate optically-modulated baseband signal. Two laser sources are centered at different frequency and frequency spacing between them is located in the W-band in order to generate the W-band wireless carrier. The base station's main component is remote antenna unit (RAU) which up-converts the optical baseband signals into the W-band. When the data is delivered into the free space, it will be received and down-converted into the baseband by a W-band wireless receiver.

In the experiment, the laser sources were full tunable C-band external cavity lasers (ECL). The output power of the ECLs was 14.5 dBm and the line width was less than 100 kHz. The light wave from ECL_1 was at 1 548.61 nm and ECL_2 at 1 549.46 nm, so the frequency spacing between ECL_1 and ECL_2 was 105 GHz, enabling data signals to be carried near 100 GHz. The IM, driven by a word length of $(2^{31}–1)$, was used to induce 4-Gb/s optical

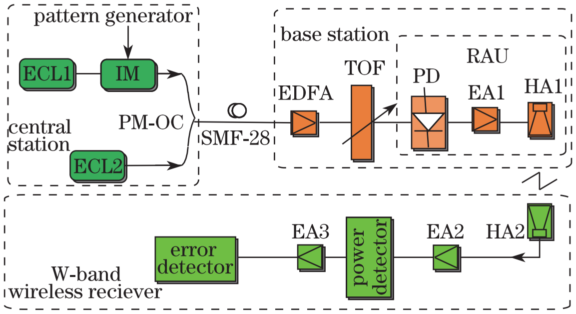

Fig. 1. Experimental setup.

OOK signals, which together with output of ECL_2 acted as input of the PM-OC.

After 40-km SMF-28 transmission, in order to obtain the optimal output which requires that the input power into the PD cannot be too small, a following erbium-doped fiber amplifier (EDFA) was firstly utilized to compensate the attenuation of the fiber. And the useful data was extracted by using a tunable optical filter (TOF) with 3-dB bandwidth of 1 nm before it was converted into the W-band signal. Then a PD (the 3-dB bandwidth and 6-dB bandwidth were 75 and 100 GHz, respectively) was employed to detect the optical signal realizing W-band signal conversion. And an electrical amplifier (EA_1) with central frequency of 98 GHz and 3-dB bandwidth of 10 GHz was followed. Through a horn antenna (HA_1) whose gain was 25 dBi and 3-dB bandwidth was larger than 30 GHz, the 4-Gb/s data was transmitted into the free space.

After 2-m wireless delivery (in our experiment, due to the limited gain of the millimeter-wave amplifier, the wireless transmission distance is limited to 2 m. If one high-power amplifier is available, the transmission distance can be extended over 10 meters at least), the data was received by another HA_2 whose parameters are identical to HA_1 and amplified by EA_2. Then, a power detector was used to down-convert the data into the baseband. The power detector's effective frequency spaced from 75 to 110 GHz and sensitivity was 800 mV/mW. After a broadband EA (EA_3) with 3-dB bandwidth of 40 GHz compensating insertion loss, signal was launched into an error detector to measure the BER index.

The measured optical spectra and electrical spectra of the data signal at different location are shown in Fig. 2. Figures 2(a) and (b) are respectively the optical spectrums before fiber transmission and after transmission. The power of the measured optical spectrum is a relative power. They were firstly attenuated by an attenuator before they were measured, since the maximum power injected into optical spectrum analyzer is 10 dBm. Electrical spectrum of 4-Gb/s OOK signal in radio frequency can be found in Fig. 2(c). This spectrum was measured by the electrical spectrum analyzer (Agilent E4407B) with an external mixer (Agilent 11970W). When down conversion into the baseband is processed, the electrical spectrum presents as Fig. 2(d). And electrical power of the baseband signal is about –37 dBm at 4-GHz frequency.

We have measured the BER performance of the data signal under different conditions which is shown in Fig. 3. It should be noted that the optical power presented as x-axis in Fig. 3 is the input power into EDFA. There is about 3 dB power penalty at the BER of 1×10^{-9}, which is caused by fiber dispersion[11]. The insert (a) of Fig. 3 is the eye diagram of OOK signals after IM modulation. For the 4-Gb/s data with only 2-m wireless transmission (the eye diagram is shown in insert (b) of Fig. 3), the optical power at the BER of 1×10^{-9} is about –21 dBm. With 40-km SMF-28 transmission and 2-m air link, the optical power at the same bit rate and BER index is –17.8 dBm, so the optical power penalty is 3.2 dB. Its eye diagram is presented in the insert (c) of Fig. 3. It should be addressed that inherently, there is no obvious difference in eye diagrams and slopes of BER curve with or without fiber transmission because the fiber length is short. With BER index increasing, gap of optical power with or without fiber transmission becomes smaller.

When the data is at different rate, the eye diagrams after 40-km SMF-28 and 2-m wireless transmission are also measured. The eye diagrams are measured by a high-speed oscilloscope, and there is no low-pass filter (LPF) adopted in the RoF system, so details such as rise and fall curves can be clearly seen from the eye diagrams. As elicited in Fig. 4, subfigure (a–d) is the eye diagram when data rates are 5, 3, 2, and 1 Gb/s, respectively. The

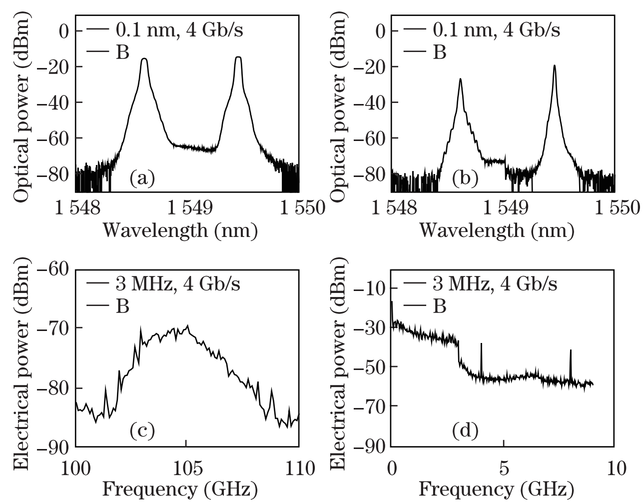

Fig. 2. (a) Monitored optical spectrum (0.01 nm) before fiber transmission, (b) monitored optical spectrum (0.01 nm) after 40-km fiber transmission, (c) RF electrical spectrum of 4-Gb/s OOK signal, and (d) electrical spectrum of 4-Gb/s OOK signal after down conversion.

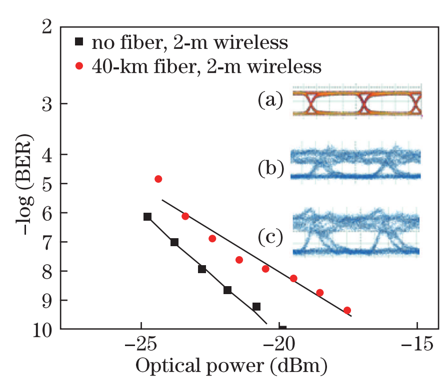

Fig. 3. Measured BER curves of 4-Gb/s signal, insert eye diagrams of signals (a) before the coupler, (b) after 2-m wireless transmission without fiber, and (c) after 40-km fiber and 2-m wireless transmission.

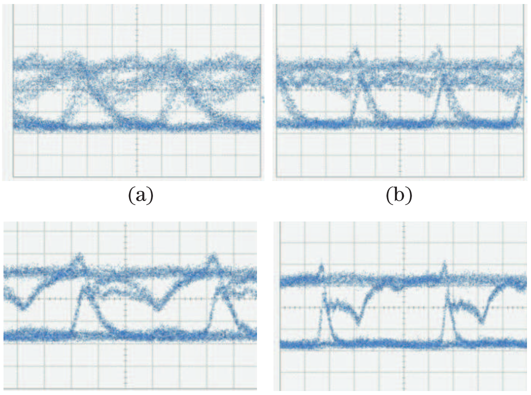

Fig. 4. Eye diagrams after 40-km fiber and 2-m wireless transmission when the data rates are (a) 5, (b) 3, (c) 2, and (d) 1 Gb/s.

results show that when the data rate is set beyond 2 Gb/s, the signal is distorted and its eye diagram will become irregular with twofold upper eyelid. This is because there is a bandwidth limitation of the electrical amplifiers. With data rate increasing, phenomena of double-fold are more outstanding and performance of the RoF system is gradually deteriorated.

In conclusion, downstream transmission experiments on 4-Gb/s RoF signal over 2-m wireless and 40-km fiber at 105-GHz carrier are reported. Simple IM-DD modulation, 40-km fiber and 2-m wireless transmission of 4-Gb/s OOK signals at 100-GHz carrier is utilized. Receiver power penalty with BER index at 1×10^{-9} is 3.2 dB after 40-km SMF-28 transmission.

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