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Total number of authors:
12

Published in:
Optics Express

Link to article, DOI:
10.1364/OE.19.024944

Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Pang, X., Caballero Jambrina, A., Dogadaev, A. K., Arlunno, V., Borkowski, R., Pedersen, J. S., Deng, L., Karinou, F., Roubeau, F., Zibar, D., Yu, X., & Tafur Monroy, I. (2011). 100 Gbit/s hybrid optical fiber-wireless link in the W-band (75–110 GHz). *Optics Express*, *19*(25), 24944-24949. https://doi.org/10.1364/OE.19.024944

100 Gbit/s hybrid optical fiber-wireless link in the W-band (75–110 GHz)

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Abstract: We experimentally demonstrate an 100 Gbit/s hybrid optical fiber-wireless link by employing photonic heterodyning up-conversion of optical 12.5 Gbaud polarization multiplexed 16-QAM baseband signal with two free running lasers. Bit-error-rate performance below the FEC limit is successfully achieved for air transmission distances up to 120 cm.

OCIS codes: (060.5625) Radio frequency photonics; (060.2330)Fiber optics communications.

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#155359 - $15.00 USD Received 27 Sep 2011; revised 10 Nov 2011; accepted 14 Nov 2011; published 22 Nov 2011

1. Introduction

Hybrid optical fiber-wireless transmission systems with ultrahigh capacities will serve as the key building block to support the next generation truly user-centered networking. Users will create a virtual 'personal atmosphere' of connectivity to the world, that will follow the users whether they are on their workplace, traveling or at home. This user personal atmosphere will be powered by ubiquitous access and control to services and application enabled by seamless broadband wireless-fiber connections to a large range of devices in their near vicinity. To realize the seamless integration of wireless and fiber-optic networks, the wireless links needs to be developed to match the capacity of high-speed fiber-optic communication systems, while preserving transparency to bit-rates and modulation formats [1].

Currently, the W-band (75-110 GHz) has attracted increasing interest as a candidate radio frequency (RF) band to provide wireless communication links with multi-gigabit data transmission. Technology roadmap studies show that there is a conceivable demand in the years to come for 100 Gbit/s wireless capacity links [2]. Among current and emerging applications to use such high capacities are wireless closed-proximity transmission links and short range wireless communications. As an example, transmission of super Hi-Vision format is expected to require a transmission speed of 24 Gbit/s [2]. These trends accompanied by the growing demand for flexible access to cloud services with high speed peripherals motivate us to look for technologies and techniques to realize 100 Gbit/s fiber-wireless transmission links.

Wireless data transmission above 10 Gbit/s with simple amplitude shift-keying modulation (ASK) in the W-band have been demonstrated by mainly using millimeter-wave electronics [3] and hybrid photonic-electronic techniques [4, 5]. More advanced modulation formats in the W-band such as differential phase shift-keying (DPSK), binary/quadrature phase shift-keying (BPSK/QPSK) with data rates of 10 Gbit/s and 20 Gbit/s are reported in [6–8]. Most recently, 40 Gbit/s 16-level quadrature amplitude modulation (16-QAM) wireless transmission in the W-band is presented [9]. We have previously demonstrated 40 Gbit/s signal generation in the W-band by employing photonic up-conversion of all-optical frequency division multiplexed (OFDM) QPSK signals, with detection performed by photonic down conversion supported by digital coherent demodulation [10]. Regarding achieved air transmission distances for bit-rates above 20 Gbit/s in the W-band, so far 20 cm for 20 Gbit/s ASK transmission [5] and 3 cm for 40 Gbit/s 16-QAM transmission [9] are reported. However, both capacity and wireless transmission distance need to be further developed.

In this paper, we report on a hybrid optical fiber-wireless transmission link achieving 100 Gbit/s by transparent photonic up-conversion of a polarization multiplexed (PolMux) 16-QAM optical baseband signal with wireless transmission in the W-band. Bit-error rate (BER) performance below 2×10^{-3} is successfully achieved for wireless transmission distances up to 120 cm. Considering a 7% FEC overhead, error free transmission of an overall net bit rate of 93 Gbit/s can be expected. We believe this is a breakthrough in hybrid optical fiber-wireless transmission systems that open the door for ultra-high capacity short range and close-proximity user-centered networking.

2. Principle of heterodyne up-conversion and two stage down-conversion

In our proposed system, the RF signal is generated by direct heterodyning with two free running lasers. After the wireless transmission, two stage down-conversion is implemented before signal demodulation. First stage is electrically down-converting the RF signal to a lower intermediate frequency (IF) and the second stage is implemented in digital domain using digital signal processing (DSP) method. The block diagram of this architecture is shown in Fig. 1.

At the transmitter, an I/Q modulator is used to generate signals with high level modulation format. The inphase and quadrature branches are respectively modulated with multilevel signals

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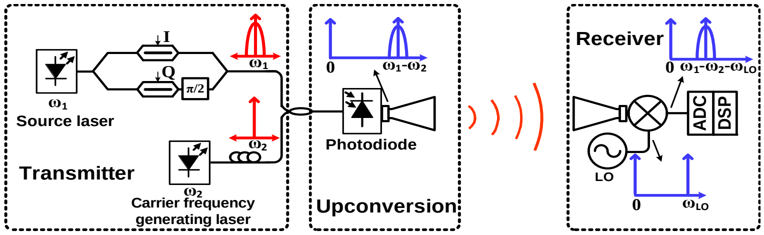

Fig. 1. Block diagram of hybrid optical fiber-wireless system using heterodyne up-conversion and two stage down-conversion.

$I(t)$ and $Q(t)$. The output optical baseband signal at frequency ω_1 from the I/Q modulator is combined with a carrier frequency generating laser with frequency ω_2 before the photodiode. The optical baseband signal $\hat{\mathbf{E}}_s(t)$ and the carrier frequency generating laser signal $\hat{\mathbf{E}}_c(t)$ can be represented as:

$$\hat{\mathbf{E}}_s(t) = \sqrt{P_s} \cdot [I(t) + jQ(t)] \cdot \exp[-j(\omega_1 t + \phi_1(t))] \cdot \hat{\mathbf{e}}_s \tag{1}$$

$$\hat{\mathbf{E}}_c(t) = \sqrt{P_c} \cdot \exp[-j(\omega_2 t + \phi_2(t))] \cdot \hat{\mathbf{e}}_c \tag{2}$$

where P_s, P_c are optical power of the signal laser and the carrier frequency generating laser, $\phi_1(t)$ and $\phi_2(t)$ are phases of the signal and carrier frequency generating laser, and $\hat{\mathbf{e}}_s$, $\hat{\mathbf{e}}_c$ are the polarization unit vectors.

After heterodyne beating at the photodiode, the generated electrical signal consists of a baseband component and a RF signal with carrier frequency $\omega_{RF} = |\omega_1 - \omega_2|$. So the RF signal transmitted into the air can be expressed as:

$$E_{RF}(t) = 2\sqrt{P_s P_c} \cdot [I(t)\cos(\omega_{RF} t + \phi_{RF}(t)) + Q(t)\sin(\omega_{RF} t + \phi_{RF}(t))] \cdot \hat{\mathbf{e}}_s \hat{\mathbf{e}}_c \tag{3}$$

with phase of $\phi_{RF}(t) = \phi_1(t) - \phi_2(t)$. At the receiver, an electrical local oscillator (LO) (Eq. (4)) signal is mixed with the received RF signal at a balanced mixer to firstly down-convert the RF signal into an IF signal. Equation (5) describes the down-converted IF signal.

$$E_{LO}(t) = \sqrt{P_{LO}} \cdot \cos(\omega_{LO} t + \phi_{LO}(t)) \tag{4}$$

$$\begin{aligned} E_{IF}(t) = \langle E_{RF}(t) \cdot E_{LO}(t) \rangle = \sqrt{P_s P_c P_{LO}} \cdot [I(t)\cos(\omega_{IF} t + \phi_{IF}(t)) \\ + Q(t)\sin(\omega_{IF} t + \phi_{IF}(t))] \cdot \hat{\mathbf{e}}_s \hat{\mathbf{e}}_c \end{aligned} \tag{5}$$

where angular frequency ω_{IF} equals to $\omega_{RF} - \omega_{LO}$ and phase $\phi_{IF}(t)$ equals to $\phi_{RF}(t) - \phi_{LO}(t)$. The angle brackets denote low-pass filtering used for rejecting the components at $\omega_{RF} + \omega_{LO}$. The IF signal is then converted into the digital domain for digital down-conversion and demodulation. The signal after the digital down-converter can be expressed as:

$$E_{Rx}(t) = \langle E_{IF}(t) \cdot \exp(j\omega_{IF} t) \rangle = \frac{1}{2}\sqrt{P_s P_c P_{LO}} \cdot [I(t) + jQ(t)] \cdot \exp(-j\phi_{IF}(t)) \cdot \hat{\mathbf{e}}_s \hat{\mathbf{e}}_c \tag{6}$$

It is noted that the system loss is not considered in the expressions. From Eq. (6) we can see that the transmitted baseband signal $I(t) + jQ(t)$ can be recovered at the DSP receiver. The accumulated phase offset and phase noise during transmission is contained in the term $\phi_{IF}(t)$, which can be later corrected in DSP [10]. Maximum value of the RF signal power is achieved when the polarization states $\hat{\mathbf{e}}_s$ and $\hat{\mathbf{e}}_c$ are aligned.

3. Experimental setup

Figure 2 presents the experimental set-up of the W-band wireless link under consideration. We adopt the 16-QAM baseband transmitter proposed in [11]. The ECL feeds a integrated LiNbO3 double-nested Mach-Zehnder modulator (MZM) with V_π of 3.5 V. The in-phase (I) and quadrature (Q) branches of the modulator are driven by 12.5 Gb/s four-level electrical signals.

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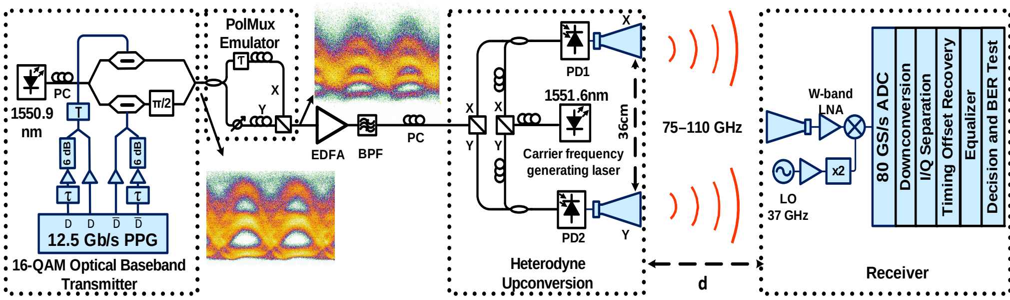

Fig. 2. Experimental setup for generation and detection of 100 Gbit/s PolMux 16-QAM wireless signals in W-band. (The eye diagrams of the 16-QAM signal before and after polarization multiplexing are shown in the inset).

Each four-level signal is derived from two copies of pseudorandom bit sequences (PRBS) of length $2^{15}-1$, decorrelated with a relative delay of 6 bit periods. The two four-level signals were decorrelated by 33 symbol periods before being applied to the modulator. The output of the modulator is a 16-QAM optical baseband signal with a data rate of 50 Gbit/s, whose capacity is doubled to 100 Gbit/s by implementing polarization multiplexing.

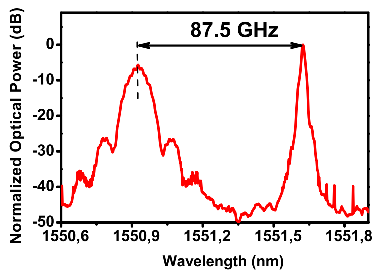

Fig. 3. Optical spectra of the 16-QAM signal and carrier frequency generating laser signal before the photodiode.

Up-conversion to the W-band is performed by direct heterodyning in a fast response 100 GHz bandwidth photodetector (PD, u^{2}t XPDV4120R). An erbium-doped fiber amplifier (EDFA) is used to boost the signal power before heterodyne beating. Heterodyning is performed for each of the polarization states (X and Y) of the optical baseband signal with the correspondent aligned polarization state of an carrier frequency generating laser signal. An ECL with 100 kHz linewidth is used as the carrier frequency generating laser with a wavelength separation of 0.7 nm from the PolMux 16-QAM optical signal, resulting in an 87.5 GHz central carrier frequency for the up-converted W-band wireless signal. Figure 3 shows the optical spectra of the signals before the PD.

At the wireless transmitter side, each up-converted signal, corresponding to the X and Y PolMux components, is fed to a W-band horn antenna with 24 dBi gain. The two transmitter antennas radiate simultaneously facing a receiver antenna. Detection is performed aligning a transmitter-receiver antenna pair at a time by aligning the receiver angle to a given transmitter antenna. No crosstalk is observed from the second antenna due to high directivity of the system. After air transmission, the signals are received by a horn antenna with 25 dBi gain and amplified by a W-band 25 dB gain low-noise amplifier (LNA) (Radiometer Physics W-LNA) with a noise figure of 4.5 dB. Subsequently, electrical down-conversion is performed by using a W-band balanced mixer driven by a 74 GHz sinusoidal LO signal obtained after frequency doubling from a 37 GHz signal synthesizer (Rohde & Schwarz SMF 100A). In this way, the detected wireless signal located in the 75-100 GHz frequency region is translated to the 1-26 GHz band with a central frequency around 13.5 GHz. Analog-to-digital conversion is performed by an

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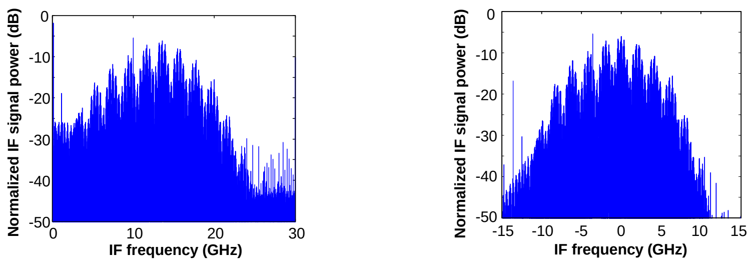
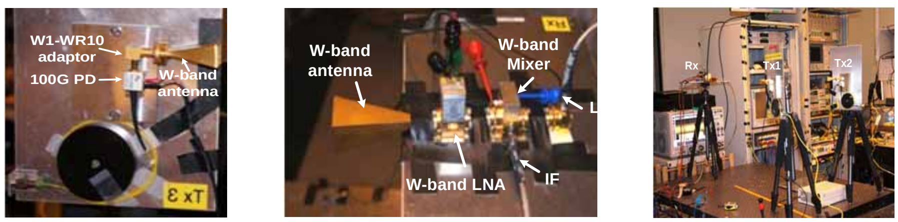


(a) (b)

Fig. 4. Electrical spectra of (a) received IF signal and (b) after digital down-conversion and filtering.



(a) (b) (c)

Fig. 5. (a). Wireless transmitter: High-speed photodetector and W-band horn antenna; (b) Wireless receiver: W-band antenna, LNA, mixer (c) Global view of the wireless link setup with both the wireless transmitter and receiver.

80 GS/s real-time digital sampling oscilloscope (DSO, Agilent DSAX93204A) with 32 GHz analog bandwidth. Offline signal demodulation is performed by a DSP-based receiver, consisting of frequency down conversion, I/Q separation, carrier recovery and filtering, equalizer, symbol decision and BER tester [10]. Figure 4a and Figure 4b shows the electrical spectra of the received IF signal and the signal after digital down-conversion and low pass filtering with cutoff frequency of $0.75\times$baud rate, respectively. From the figures it can be seen that there are narrow lobes within the main lobes of the signal spectra, resulting from the delayed PRBS at the 16-QAM baseband transmitter as well as the fast frequency shifting after heterodyning beating up-conversion. The photographs of the wireless transmitter, receiver and the whole wireless setup are shown in Fig. 5a, 5b and 5c, respectively.

4. Results and discussions

Bit-error rate (BER) measurements are performed for both cases of single polarization (without polarization multiplexing) and PolMux 16-QAM signals achieving total bit rate of 50 Gbit/s and 100 Gbit/s respectively, with total number of 320000 bits for error counting. The BER results are shown in Fig. 6 as a function of the received optical power into the photodiodes for a given air transmission distance *d*.

For the single polarization 16-QAM case, Fig. 6a presents the BER results for transmission distances of 50 cm, 150 cm and up to 200 cm. As we can see from Fig. 6a, considering a 7% FEC overhead can potentially be effective for BER of 2×10^{-3}, error free transmission of net data rate of 46.5 Gbit/s is achieved for all air transmission cases. For the case of PolMux, the separation between the two transmitting antennas is 36 cm (see Fig. 2) while air transmission is measured for a distance *d* to the receiver antenna of 50 cm, 75 cm and 120 cm. Longer transmission distances were hampered by power budget limitation. The BER performance of 100 Gbit/s PolMux 16-QAM signal is shown in Fig. 6b, by averaging the BER of both X and

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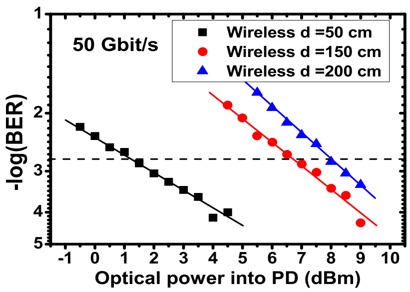
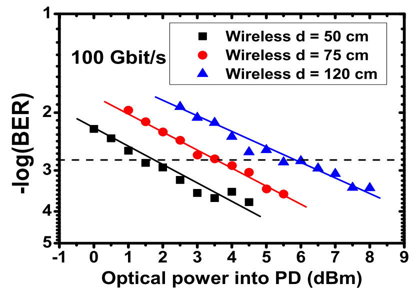
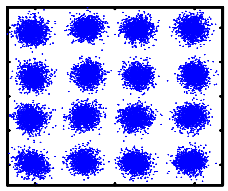


(a)

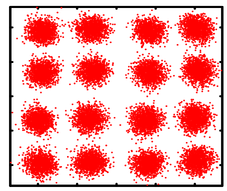


(b)

Fig. 6. Measured BER curves versus optical power into photodiode for: (a) 50 Gbit/s single polarization 16-QAM, (b) 100 Gbit/s PolMux 16-QAM.



(a)



(b)

Fig. 7. Constellations of received signals of (a) X-branch and (b) Y-branch after 120 cm wireless transmission (8 dBm input power into PD).

Y branches. From the figure we can observe that a BER value below 2×10^{-3} is achieved at 1.5 dBm, 3.5 dBm and 5.5 dBm received optical power at PD for air transmission distance of 50 cm, 75 cm and 120 cm, corresponding to radiated RF power of $\sim$-23 dBm, -19 dBm and -15 dBm, respectively. It is noted that far field propagation takes places at air distances more than 36.8 cm by taking into account the type of antennas used in the experiment.

Comparing the BER performance at the BER of 2×10^{-3} for 50 cm air transmission of single polarization in Fig. 6a and PolMux in Fig. 6b, we attribute the observed 0.5 dB optical power penalty to imperfect separation of the two polarization states in the beam splitter used in the up-conversion stage. Figure 6b also indicates the required optical power to achieve 2×10^{-3} BER at 120 cm is 6 dBm, corresponding to an equivalent isotropically radiated power (EIRP) of 12.5 dBm. We believe that longer air transmission distances can be achieved by using a W-band power amplifier at the transmitter and a higher gain LNA at the receiver side. Figure 7 shows the received 16-QAM constellations of the X and Y branches after 120 cm wireless transmission at 8 dBm optical power, with BER of 3.2×10^{-4} and 3.1×10^{-4}, respectively.

5. Conclusion

100 Gbit/s wireless transmission in the 75-110 GHz band employing photonic generation is successfully demonstrated with air transmission distance of 120 cm. A dual-polarization 16-QAM baseband optical signal is up-converted by optically heterodyning with a free-running optical carrier generating laser to generate 100 Gbit/s at 87.5 GHz center wireless carrier frequency. This is the highest achieved capacity for a W-band wireless link, to our best knowledge.

Acknowledgment

The authors would like to acknowledge the support from Agilent Technologies, Radiometer Physics GmbH, Rohde & Schwarz, u^{2}t Photonics and SHF Communication Technologies.