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Gigabit close-proximity wireless connections supported by 60 GHz RoF links with low carrier suppression

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Abstract: We present an experimental investigation of the 60 GHz optical carrier suppressed radio over fiber systems with less than 5 dB carrier suppression. As a case study, the 60 GHz RoF signal is generated using a 12.5 Gb/s commercially available Mach-Zehnder modulator biased at its minimum point. We report on error free transmission over 20 km of standard single mode fiber and 1 m of wireless distance. Furthermore, the efficiency of photonic RF generation depending on the value of carrier suppression is reported. We argue that transport of RoF signals with low carrier suppression assisted with simplified techniques of lightwave generation, baseband data modulation, and RF downconversion might be a promising enabling technology for fiber support of close-proximity wireless terminals.

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

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1. Introduction

Low bandwidth availability within the microwave spectrum of radio communication frequencies may hinder the development of novel services and applications. Hence, it has been proposed to employ the 60 GHz band where up to 9 GHz of unlicensed spectrum [1] has been allocated. Research and development to utilize the 60 GHz band have been conducted by organizations such as the Wireless Gigabit Alliance (WiGig, IEEE 802.11 ad), which proposed a specification to deliver data rates up to 7 Gb/s and enable tri-band networking (2.4-, 5- and 60GHz). ABI Research forecasts that by 2016, annual shipments of devices equipped with both Wi-Fi and WiGig technology will approach 1.8 billion [2].

Radio over fiber (RoF) technologies are providing methods to generate, transport and detect wireless signals at high bitrates in diverse fiber-optic systems [3]. RoF technologies aim at simplification of base station (BS) and access point (AP) units which is crucial in case of the 60 GHz millimeter wave (mm-wave) transmission where coverage is limited by high attenuation due to the free space path loss and absorption on molecules of oxygen and water vapour, and therefore higher density of BSs/APs is required [4].

Recent research on the RoF technology includes studies of the diversified fiber infrastructure for multiband wireless services [5], bidirectional 60 GHz RoF [6] and systems combining RoF and fiber-to-the-home delivery [7]. The development of highly linear high power 60 GHz analog photoreceivers [8] and compact E-band (60-90 GHz) wireless transmitters [9] combining progress in optoelectronic and mm-wave components further strengthens the potential for commercial deployment of mm-wave RoF links. However, a major impediment for widespread adoption of RoF technology is the utilization of costly high

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bandwidth optical components to perform the electro-optical (E/O) conversion, especially when dealing with mm-wave signals [10].

In order to alleviate the requirements for high frequency RF generation, optical carrier suppressed (OCS) RoF transmission is used [11] yielding the desired RF after photomixing by doubling the original RF frequency applied at the E/O conversion point. OCS RoF technique generates RF signals with an excellent phase noise performance, which is crucial for support of advanced spectrally efficient modulation formats [12].

Previous experimental demonstrations for generation of 60 GHz electrical signals using the frequency doubling technique rely on optical components with bandwidths in excess of 20 GHz [13]. Such large bandwidth is necessary to yield high carrier-to-sideband suppression ratio. Complementarily, filters and optical interleavers are often used to maximize a suppression ratio [14]. However, additional filters and interleavers have very high performance requirements and naturally increase the cost and complexity of the system.

We have previously reported on transmission of Gigabit data in 60 GHz RoF systems with high carrier suppression using a distributed feedback laser integrated with an electroabsorption modulator (DFB-EAM) and a vertical cavity surface emitting laser (VCSEL) for lightwave generation and data modulation [15, 16].

In this paper, we present novel results demonstrating generation and delivery of 60 GHz OCS RoF signals with low carrier suppression for Gigabit wireless systems. Bit error rate (BER) performance below 10^{-9} level after fiber transmission and 1 m of wireless transmission is reported. We argue that low carrier suppression RoF systems are suitable to enable wireless applications with ultrashort reach.

This paper is organized as follows: in Section 2, potential applications are examined. In Section 3, we present the laboratory setup built to study the performance of low carrier suppressed 60 GHz RoF signals. Discussion of the performance of the low carrier suppression OCS 60 GHz RoF link is conducted in Section 4. Finally, we provide a summary and conclusions in Section 5.

2. 60 GHz links supported by fiber for close proximity wireless communications

60 GHz high-capacity links have been widely adopted by industry to provide private corporate connections reaching 1 km wireless distance [17–19], recently their use has been also proposed for mobile backhaul applications [20].

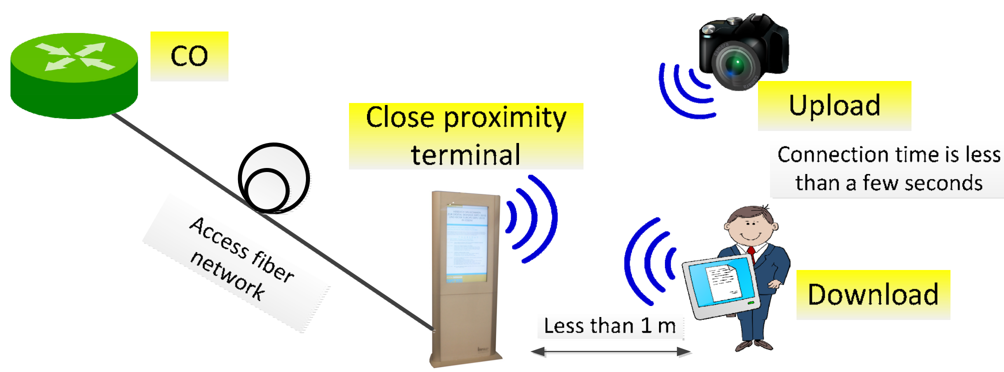

Fig. 1. Network scenario for 60 GHz RoF signals' delivery to close proximity communication terminals. CO: central office.

However, there are a few emerging scenarios for 60 GHz wireless systems that alleviate requirements for wireless transmission distance. First scenario is connectivity in data centers [21–23] where 60 GHz wireless links promise to reduce cabling complexity and related costs of maintenance. Second, we believe that high-capacity 60 GHz links should be considered for close-proximity applications because they naturally fit the close-proximity scenario where

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large capacity is required but over a short wireless distance e. g. when digital kiosks are installed in public locations to enable ultrafast upload/download of high-definition video, interactive maps etc. [24]. Furthermore, close-proximity applications may benefit from integration with optical fiber networks if they utilize cost-effective transceivers for fiber-wireless distribution.

We depict the proposed hybrid fiber-wireless architecture to enable close proximity applications in Fig. 1. In this paper, a low complexity RoF system for fiber support of close proximity wireless applications is proposed and experimentally demonstrated.

3. Experimental setup description

In order to confirm the suitability of the 60 GHz RoF transmitter with low carrier suppression, we built an experimental setup and performed quantitative measurements after fiber and wireless transmission. This section describes the experimental setup.

The experimental setup is shown in Fig. 2. We used a single module combining lightwave generation and data modulation composed of a distributed feedback laser integrated with a 12.5 Gb/s electro absorption modulator producing + 4 dBm of optical output power. The baseband data signal imposed on the lightwave were generated by a pulse pattern generator (PPG) producing a pseudorandom binary sequence (PRBS) with a word length of 2^{15}-1. The lightwave was then modulated by a 29.54 GHz RF signal of 18 dBm RF power using a 12.5 Gb/s Mach-Zehnder modulator (MZM, Covega Mach-10) biased at its minimum point. By biasing the MZM at the minimum point, the carrier is suppressed and the double sideband with suppressed carrier RoF signal is generated. The polarization controller (PC) was installed before the MZM to ensure the polarization alignment necessary for maximum achievable carrier suppression.

High RF power and subsequently modulation indices not following small signal modulation criteria have been shown to be beneficial when the bias is set at V_π where a modulation index equal to 0.97 has been shown as optimal [25]. We also note that higher order harmonics appearing when higher modulation index is used are later mitigated by the frequency response of the O/E conversion device and the use of mm-wave bandpass filters and amplifiers.

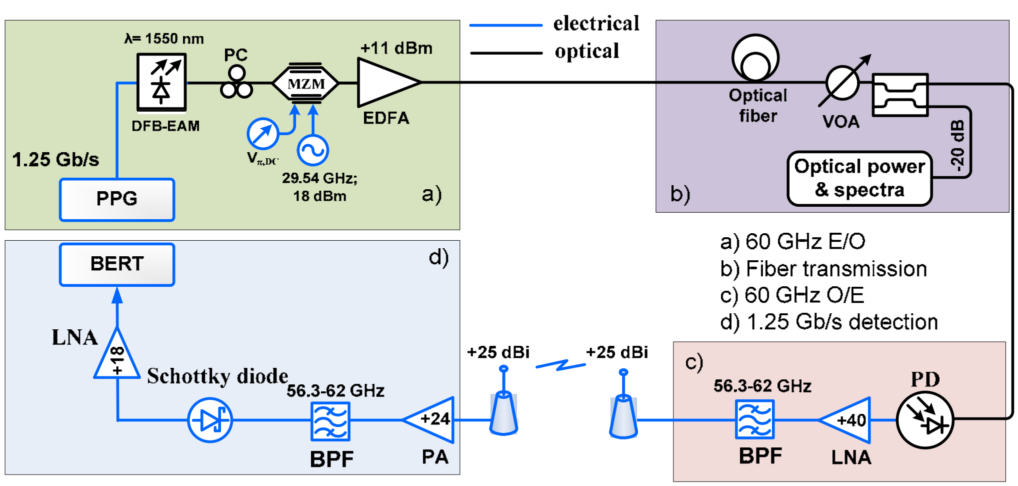

Fig. 2. Experimental setup demonstrating 60 GHz RoF generation, fiber and wireless transmission and baseband data recovery with low carrier suppression. PPG: pulse pattern generator, DFB-EAM: distributed feedback laser integrated with electro absorption modulator, PC: polarization controller, MZM: Mach-Zehnder modulator, EDFA: Erbium doped fiber amplifier, VOA: variable optical attenuator, PD: photodiode, LNA: low noise amplifier, BPF: bandpass filter, PA: power amplifier, BERT: bit error rate tester, E/O: electrical-to-optical conversion, O/E-optical-to-electrical conversion.

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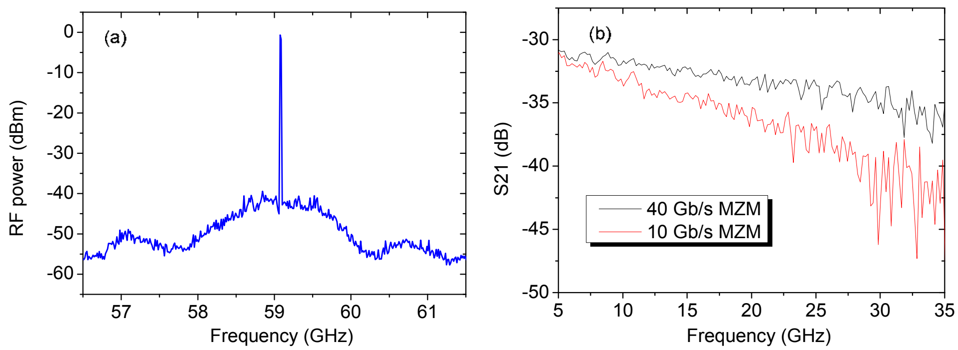

Fig. 3. RF spectrum of the signal (a) and S21 performance of 12.5 Gb/s and 40 Gb/s MZMs (b).

The optical signal was then boosted to + 11 dBm power with an erbium doped fiber amplifier (EDFA). To test the diverse fiber infrastructure, we employed links of dispersion shifted fiber (DSF), nonzero DSF (NZDSF), and standard single-mode fiber (SSMF). After the fiber transmission, the signal was detected with a 75 GHz bandwidth photodiode (PD), and subsequently amplified and filtered (+ 40 dB gain and 56.3-62 GHz passband). The signal was then fed into an antenna for radiation. High directivity horn antennas of 25 dBi gain were used at the wireless transmitter and receiver side. On the receiver end, the signal was amplified (24 dB) and filtered (56.3-62 GHz passband). Downconversion was subsequently performed by a Schottky diode working as an envelope detector (ED). Recovered baseband data were passed on for further detection of bit errors at the bit error rate tester (BERT).

In Fig. 3(a), we depict the RF spectrum of the signal at the output of the 60 GHz low noise amplifier (LNA) on the transmitting side when the 0.4 V peak-to-peak data signal is applied to the DFB-EAM. In Fig. 3(b), we depict the S21 performance of the system employing 12.5 Gb/s MZM (Covega Mach-10) in comparison to a 40 Gb/s MZM that was used in [15, 16]. The S21 performance was measured excluding EDFA from the link, where port 2 was the output of the PD, and port 1 – the MZM RF input. Given the lower E/O conversion performance of the 12.5 Gb/s modulator, higher power RF has been applied to the MZM.

4. Results and discussion

In this section, performance of the setup in terms of BER and RF O/E conversion efficiency is presented and the sources of impairments are reported and analyzed. First, we characterized the conversion efficiency of optical power to 60 GHz RF power depending on the suppression of the optical carrier. Power of the generated 60 GHz RF signal as a function of carrier suppression is depicted in Fig. 4. The carrier suppression was changed by varying a bias voltage of the MZM, and measured as observed in optical spectrum analyzer. As it can be seen from Fig. 4 the slope of the curve flattens at about 0 dBm suppression value. These results are consistent with the results that we previously reported in the case of 40 Gb/s MZM when the carrier suppression was varied from 0 to 20 dB [26]. Reported degradation in RF power after E/O, fiber transmission, and O/E conversion is overcome by using a double-stage LNA. For example, 0 dBm optical signal at the PD is converted to −32 dBm 60 GHz RF signal for 4 dB carrier suppression value, and boosted to + 8 dBm RF power for radiation.

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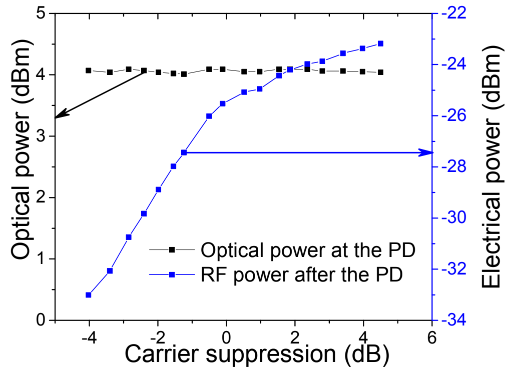

Fig. 4. 60 GHz RF power after the PD as a function of carrier suppression for a constant level of optical power.

From optical spectra depicted in Fig. 5, we can observe the presence of positive frequency chirp and four-wave mixing (FWM). In Fig. 5(a), optical spectra before fiber transmission are presented. Splitting of the carrier at low bitrates indicates the presence of frequency chirp that is caused by the electrical crosstalk due to the integration of laser and modulator sections in the same chip of the DFB-EAM module [27]. However, given the low bitrate and the fact that we model access fiber deployment, chirp does not impose a power penalty. As defined in [28], chirp-induced power penalty at the receiver is measured as a function of $|\beta_2|B^2L$, where $\beta_2 \approx -20$ ps^2/km is a group velocity dispersion parameter for SSMF, B = 1.25 Gb/s is a bitrate of the system, and L = 20 km is a fiber link length. For our system, $|\beta_2|B^2L$ is equal to 0.625 × 10^{-3}, which according to [28] brings a negligible receiver sensitivity penalty across possible chirp values.

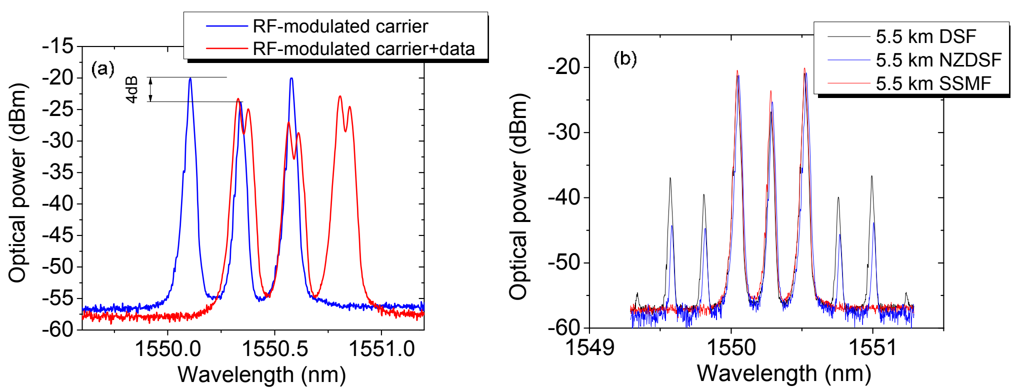

Fig. 5. Optical spectra of the RF- and data-modulated lightwave before fiber propagation (a) and after fiber propagation at 16 dBm optical power into the fiber (b).

It can be observed from Fig. 5(b) that FWM-produced lightwaves start to be noticeable in case of fibers with a low dispersion parameter at 1550 nm. FWM is independent of channel bitrate, but depends critically on the spacing between lightwaves [28]. Power of the signal at new frequencies can be calculated analytically as a function of the effective cross-sectional area of the fiber, the nonlinear refractive index and the fiber length [28]. In our experiment, to confirm that FWM does not influence the performance of the system, we tested that increase in optical power at the EDFA output from 11 to 16 dBm increases power of FWM-generated lightwaves, but does not reduce the BER of the transmitted data signal. It should be noted that

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FWM brings a receiver sensitivity penalty for wavelength division multiplexed systems in the case of equally spaced channels through introduction of the inter-channel crosstalk, however it is not an obstacle for a single-channel system under study.

We then evaluated the performance of the system in terms of BER. In Fig. 6(a), we depict the performance of the setup without wireless transmission, when only fiber transmission is considered. BER is measured for different distances and types of fibers in order to account for the effects of dispersion and nonlinearities. Fiber transmission results show a negligible power penalty when compared to the back-to-back transmission, clustering BER performance equal to 10^{-9} around −9.5 dBm region.

Finally, we added wireless transmission to the system. We measured the performance for two wireless distances, 50cm and 1m, and with or without 20 km fiber transmission. Figure 6(b) depicts the BER performance of the signal including air transmission. BER below 10^{-9} level is achieved in all cases, being the case of 20 km and 1 m transmission the cases sustaining the highest power penalty, less than 2.5 dB compared to the best case. Higher value of optical power into the PD is necessary to yield the performance below 10^{-9} level due to the fact that wireless channel loss is compensated by increasing optical power impinging the photodiode.

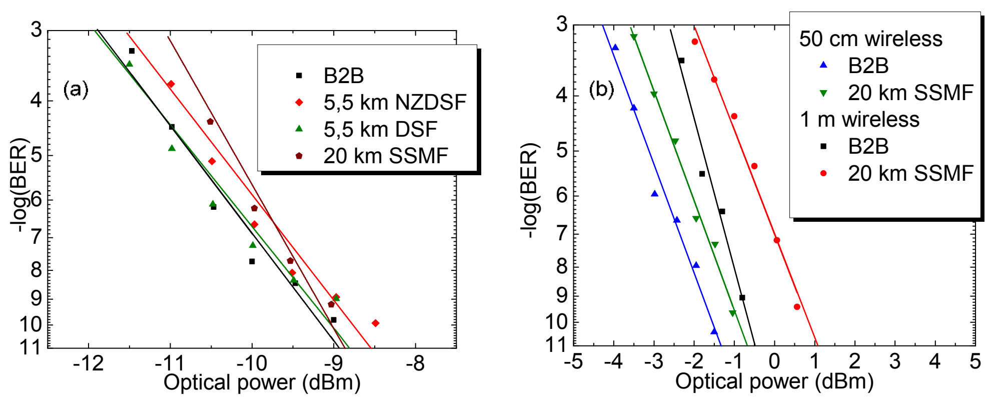

Fig. 6. BER performance back-to-back and after fiber transmission for 2 cases: (a) wireless transmission distance is omitted and (b) up to 1 m wireless transmission is performed. NZDSF: non-zero dispersion shifted fiber, DSF: dispersion shifted fiber, SSMF: standard single mode fiber.

Utilizing E/O components with −3 dB bandwidth lower than a value of the RF frequency used for mm-wave OCS RoF technique leads to certain trade-offs in performance. For given RF signal power at the E/O point and given −3 dB bandwidth of the E/O module, carrier-to-sideband suppression ratio is decreasing with an increase in applied frequency, and, in turn, the amount of the RF power detected after photomixing at the PD is reduced. In this paper, the case study for modulation of 12.5 Gb/s MZM with a 30 GHz RF signal is presented showing that, even when the carrier suppression is decreased to less than 5 dB, excellent transmission performance may still be obtained allowing us to simplify the fiber transport of mm-wave frequencies by utilization of low bandwidth E/O conversion devices. We generalize the presented case by studying the relation between the carrier suppression and the photonically generated RF power for low values of carrier suppression (less than 5 dB).

The choice of lightwave generation, baseband data modulation, and RF downconversion techniques is done in order to further simplify the system. By utilizing the DFB-EAM, we simplify the installation of the system and allow lower driving voltages for baseband lightwave modulation. Performance is constrained by the chirp of the DFB-EAM however the sensitivity penalty is not imposed in our system. The envelope detection technique provides RF downconversion avoiding the use of LO at the wireless receiver.

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5. Conclusion

This paper presents an experimental demonstration of 60GHz signals transmission in OCS RoF links with less than 5 dB carrier suppression. The BER of the transmitted data below 10^{-9} level for transmission of 1.25 Gb/s data signal through 20 km of SSMF complemented with 1 m of the 60 GHz wireless link is reported. Presence of the optical carrier and low separation between the carrier and sidebands leads to FWM, however no error floor due to nonlinearities at 16 dBm optical power into the fiber was observed. Furthermore, the system was simplified by utilizing the integrated module for data modulation and lightwave generation and passive RF downconversion with an ED. Results indicate that the simplified OCS RoF systems with low carrier suppression are an effective solution for close-proximity wireless applications.

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