A Bi-Directional Fiber-FSO-5G MMW/ 5G NR Sub-THz Converged System

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Abstract: A bi-directional fiber-FSO-5G wireless converged system with downlink 40-Gb/s/100-GHz 5G NR sub-THz, and uplink 10-Gb/s/28-GHz and 10-Gb/s/24-GHz 5G MMW signals is constructed. It develops a brilliant convergence for high-speed and long-reach transmission with qualified performance.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2605) Free-space optical communication; (350.4010) Microwaves.

1. Introduction

Fifth-generation (5G) and 5G new radio (NR) evolution are expected to provide a variety of mobile and multimedia services, such as augmented/virtual reality, ultra-HD video conference, mixed reality (virtual reality and augmented reality), autonomous vehicle, and Internet of everything (IoE). However, due to their low RF power trait, 5G millimeter-wave (MMW) and 5G NR operation in sub-THz communications cannot provide long-distance wireless transmission. Providing broadband integrated applications with high traffic capacity and long-reach transmission is critically important. Free-space optical (FSO) communication is a type of optical wireless communication that has obtained extensive attention for overcoming the challenge of short-distance 5G wireless communication. With the rapid developments of FSO and 5G wireless communications, FSO-5G MMW/5G NR sub-THz convergence has been enhanced to reduce the number of 5G MMW/5G NR sub-THz base stations and provide several tens of gigabit transmission through a long-distance free-space transmission with a short-distance 5G wireless extension [1-2]. In the work, we report the implementation of a bi-directional fiber-FSO-5G MMW/5G NR sub-THz converged system with parallel/orthogonally polarized dual-carrier mechanism to establish an intensity-modulated downlink transmission operating with 40 Gbit/s/100 GHz 5G NR sub-THz signals, as well as phase modulators and remote injection locking distributed feedback laser diodes (DFB LDs) to construct a phase-modulated uplink transmission operating with 10 Gbit/s/28 GHz and 10 Gbit/s/24 GHz 5G MMW signals. To the best of our knowledge, this is the pioneering demonstration of a bi-directional fiber-FSO-5G MMW/5G NR sub-THz converged system that provides high traffic capacity with qualified transmission performance.

2. Experimental Setup

Fig. 1 presents the architecture of constructed bi-directional fiber-FSO-5G MMW/5G NR sub-THz converged system with parallel/orthogonally polarized dual-carrier mechanism to deliver intensity-modulated downlink *x*- and *y*-polarized 40 Gbit/s/100 GHz 5G NR sub-THz signals, as well as phase modulators and DFB LDs to transmit and detect phase-modulated uplink 10 Gbit/s/28 GHz and 10 Gbit/s/24 GHz 5G MMW signals. A laboratory-made weather simulator is placed in the path of the 500 m free space link to simulate poor weather (heavy rain/snow/fog) condition. The weather simulator includes a sprinkler-based rain generator, a snowmaking machine-based snow generator, and a fog machine-based fog generator. For downlink transmission, the optical signal is received by *x*-polarized (*y*-polarized) receiver through a fiber-FSO link of 20.5 km (20 km SMF + 500 m FSO). A power amplifier (PA), with 85-100 GHz frequency band, amplifies the *x*-polarized (*y*-polarized) 40 Gbit/s/100 GHz 5G NR sub-THz signal. After amplification, a set of W-band horn antennas (HAs) wirelessly transmits the *x*-polarized (*y*-polarized) 40 Gbit/s/100 GHz 5G NR sub-THz signal. After 1 m RF wireless transport, the 40 Gbit/s/100 GHz 5G NR sub-THz signal is detected by a Schottky diode-based envelope detector (ED) with 75-110 GHz frequency band. A low-noise (LN) driver drives the 40 Gbit/s PAM4 signal and next feeds it into a 28-Gbit/s error detector for real-time BER measurement. The BER performance is analyzed at clear weather and poor weather (heavy rain/snow/fog) conditions using a laboratory-made weather simulator.

For uplink transmission, a 10 Gbit/s/28 GHz (10 Gbit/s/24 GHz) 5G MMW signal passes through a modulator driver and then sends to a phase modulator. Over 20 km SMF transmission and 500 m free-space link, OC1/OC3 circulates the optical signal and injects it into the DFB LD2/LD4 to perform PM-to-IM conversion and optical detection. A PA with 27-31/17-24 GHz frequency band, amplifies the 10 Gbit/s/28 GHz (10 Gbit/s/24 GHz) 5G MMW signal. After amplification, a set of Ka-band/K-band HAs wirelessly transmits the 10 Gbit/s/28 GHz (10 Gbit/s/24 GHz) 5G MMW signal. Through 4 m RF wireless transmission, an ED detects the 10 Gbit/s/28 GHz (10

Gbit/s/24 GHz) 5G MMW signal, which is then driven by a LN driver. Besides, a DSO is deployed to catch the 10 Gbit/s NRZ stream's eye diagrams.

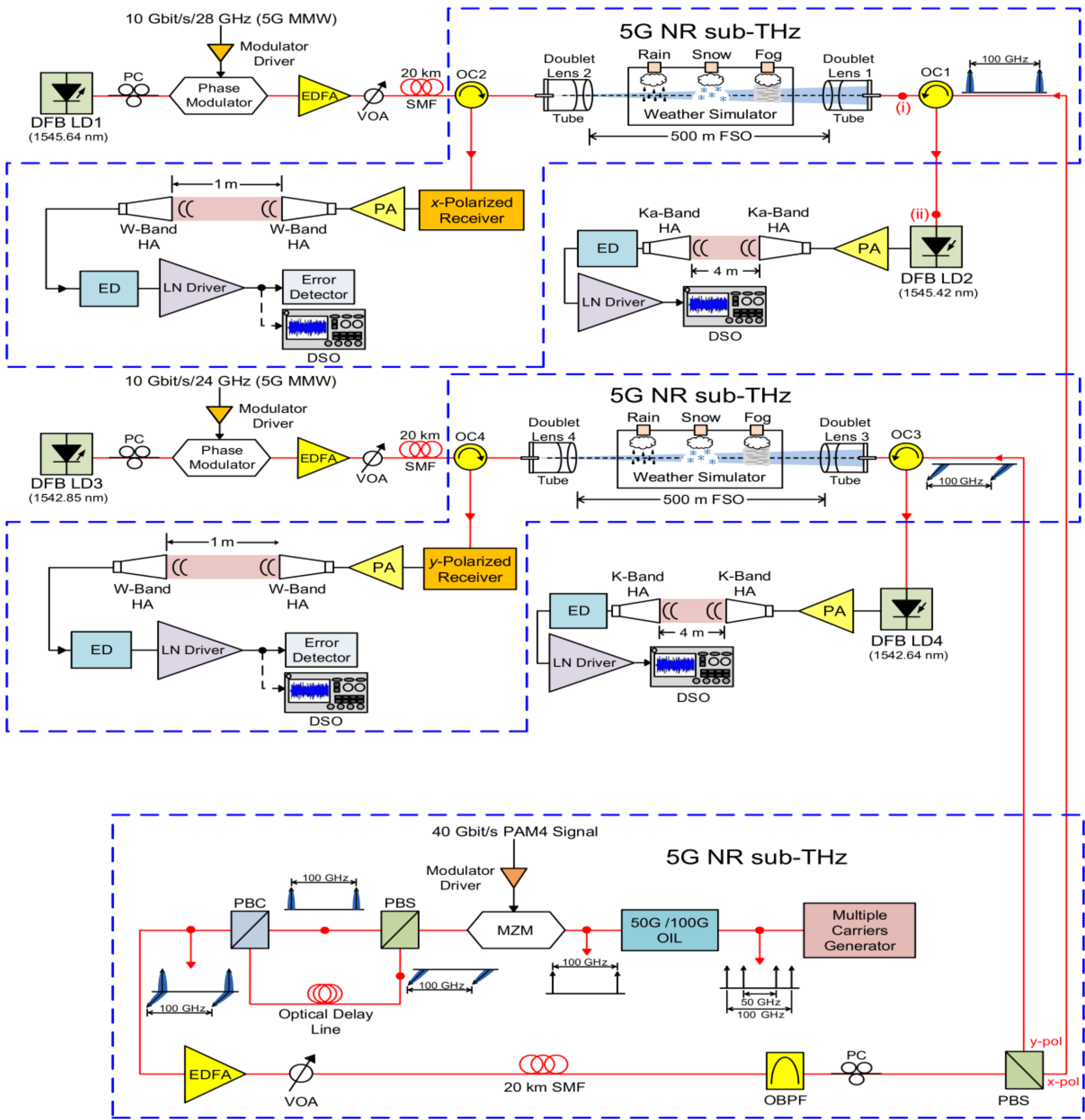

Fig. 1. Architecture of constructed bi-directional fiber-FSO-5G MMW/5G NR sub-THz convergence with parallel/orthogonally polarized dual-carrier mechanism to transmit intensity-modulated downlink *x*- and *y*-polarized 40 Gbit/s/100 GHz 5G NR sub-THz signals, and phase modulators and DFB LDs to transport and detect phase-modulated upstream 10 Gbit/s/24 GHz and 10 Gbit/s/28 GHz 5G MMW signals.

3. Results and Discussions

Table 1 exhibits the states of DFB LD2 with remote injection in different wavelength detuning. In -0.21 to 0.31nm wavelength detuning range, injection locking can be achieved. With injection locking, DFB LD2 operates PM-to-IM conversion and optical detection. Table 1 also exhibits the upstream modulation response in oscillation and injection locking states. In remote injection locking state, an improved upstream modulation response (>28 GHz) can be achieved. Additionally, at 0.21 or -0.12 nm wavelength detuning, an optimum injection locking happens. A 28.2-GHz highest upstream modulation response can be attained as a DFB LD is in the state of optimum injection locking.

Fig. 2 presents the BER performances of *x*-polarized 40-Gb/s/100-GHz 5G NR sub-THz signal in various scenarios. With a 10^{-9} BER operation, a 1.5-dB power penalty occurs between the scenario over 20 km SMF transmission and that over 20 km SMF transmission with 500 m free-space link (clear weather). In clear weather, a slight atmospheric attenuation of 1.5 dB appears because of the 500 m free-space link. In poor weather (heavy rain/snow/fog), however, BER greatly increases to a 10^{-3} order of magnitude due to large atmospheric attenuation. Furthermore, as BER reaches 10^{-9}, a 1.9-dB power penalty exists between the scenario over 20 km SMF transmission and 500 m free-space link, and the scenario over 20 km SMF transmission, 500 m free-space link, and 1 m RF wireless transport (clear weather). Over 1 m RF wireless transport, a 40-Gb/s/100-GHz 5G NR sub-THz signal experiences a certain degree of fading, thus causing amplitude and time variations in the received 40-Gb/s/100-GHz sub-THz signal and resulting in worse BER. However, in poor weather (heavy rain/snow/fog), BER considerably increases to a 10^{-3} order of magnitude because of large atmospheric attenuation.

Figs. 3(a), 3(b), and 3(c) display the eye patterns of the upstream 10-Gb/s/28-GHz 5G MMW signal at different conditions. With 0.21 nm wavelength detuning and 3 dBm injection power, a clear eye pattern [Fig. 3(a)] is acquired. With 0.21 nm wavelength detuning and -3 dBm injection power, an accepted eye pattern [Fig. 3(b)] is obtained. Through 20 km SMF transmission, 500 m free-space link, and 4 m RF wireless transport, DFB LD with proper wavelength detuning and injection power can feasibly convert and detect the transmitted 10-Gb/s/28-GHz 5G MMW optical signal, thus improving the eye pattern. With 0.41 nm wavelength detuning, nevertheless, a turbid eye pattern [Fig. 3(c)] is attained. Unsuccessful injection locking causes great fluctuations in the eye pattern. In addition, Figs. 4(a), 4(b), and 4(c) display the eye diagrams of the upstream 10-Gb/s/24-GHz 5G MMW signal in the same manner as performed by Figs. 3(a), 3(b), and 3(c).

Table 1. The states of DFB LD2 with remote injection in different wavelength detuning, and the upstream modulation response in oscillation and injection locking states.

Tunable Laser Source (nm)	DFB LD2 (nm)	Wavelength Detuning (nm)	State	Upstream Modulation Response (GHz)
1545.83		0.41	Oscillation	Noise
1545.73		0.31		28
1545.63		0.21		28.2
1545.54		0.12	Injection Locking	28.1
1545.42	1545.42	0		28
1545.30		-0.12		28.2
1545.21		-0.21		28.1
1545.11		-0.31	Oscillation	Noise
1545.01		-0.41	Oscillation	Noise

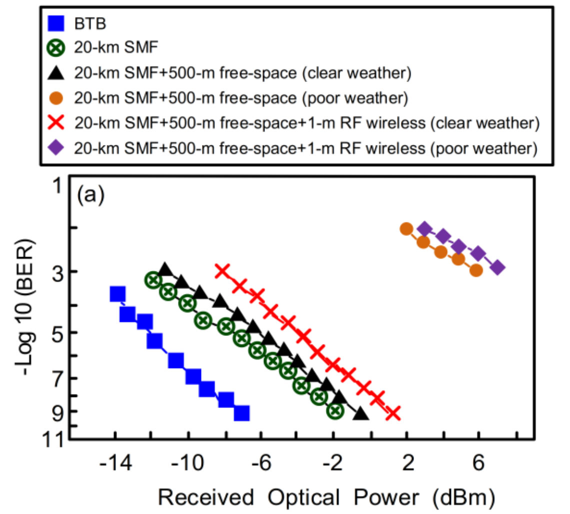

Fig. 2. BER performances of *x*-polarized 40-Gb/s/100-GHz 5G NR sub-THz signal in various scenarios.

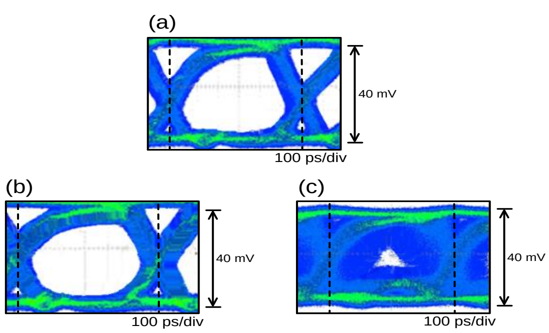

Fig. 3. Eye patterns of the upstream 10-Gb/s/28-GHz 5G MMW signal at different conditions.

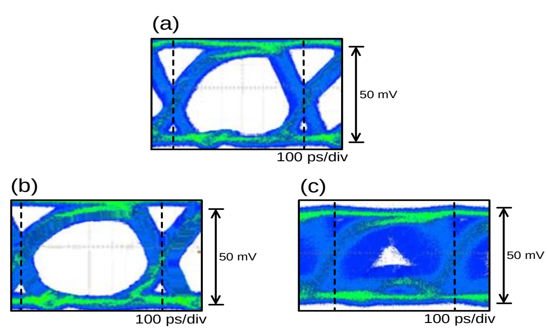

Fig. 4. Eye patterns of the upstream 10-Gb/s/24-GHz 5G MMW signal at different conditions.

4. Conclusion

A bi-directional fiber-FSO-5G MMW/5G NR sub-THz converged system over 20 km SMF transmission, 500 m free-space link, and 1 m/4 m RF wireless transport is built. Such constructed fiber-FSO-5G MMW/5G NR sub-THz convergence is a prominent one to meet the requirements of 5G and 5G NR towards sub-THz communications. It opens an innovative way for the development of bi-directional high-speed and long-reach transmissions.

References

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