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Multicore Fiber-assisted Photonic sub-THz Generation for Full-Duplex Wireless Transmission

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ABSTRACT

This paper evaluates experimentally a centralized radio access network (C-RAN) based on multi-core fiber (MCF) for the transmission of high-bandwidth signals in the sub-THz band. We compare the system performance when the data and carrier wavelengths to be mixed at the receiver for optical heterodyning are transmitted over the same or over different cores of a MCF link. Full-duplex transmission on MCF is evaluated using the same received wireless signal downconverted and transmitted back as uplink over the same carrier wavelength. The performance with different digital signal processing (DSP) configurations and with higher-power interference in the other cores are also analyzed in this work. Successful provision of 12.5 GBd 16QAM signals is achieved after 1-km of 7-core MCF transmission including a short wireless link at 182 GHz, obtained with optical heterodyning. C-RAN implementation with MCF simplifies the remote nodes as all the lasers can be located in the central office, while minimizing the number of lasers needed at the central office thanks to wavelength re-use. It also provides more flexibility to the system, as it enables using the same LO for different purposes (i.e. THz generation of other data or optical modulation for uplink transmission).

Keywords: Centralized-radio access network (C-RAN), photonic THz generation, sub-THz communications, multi-core fiber (MCF), backhaul, full-duplex photonic transmission, digital signal processing (DSP)

1. INTRODUCTION

In order to sustain the ever-growing demand of data rate, next-generation 5G and beyond-5G mobile networks are expected to provide massive data throughput and ubiquitous wireless connectivity everywhere. The proposed implementations are based in (i) increasing the bandwidth by operating in higher frequency bands (e.g. the large unlicensed band in the mm-wave spectrum and up to 300 GHz in the sub-THz band), and (ii) increasing the spectral efficiency using advanced modulated schemes or multiplexing techniques. In this work, we propose and validate experimentally a centralized radio access network (C-RAN) combining both implementations with (i) the provision of high-bandwidth signals and wireless transmission in the sub-THz band and (ii) spatial multiplexing in a multi-core fiber (MCF).

C-RANs enable the mass deployment of cell sites with optimized capital and operational expense, with resource optimization while minimizing power consumption [1]. In order to be able to distribute THz signals over wire areas, a combination with a fiber-based access network (e.g. C-RANs) is proposed while maintaining acceptable wireless power budgets [2]. In the last years, research in the W-band (75-110 GHz) and higher mm-wave bands has shown a lot of interest for broadband wireless applications [2]. In this work, we demonstrate the photonic sub-THz generation at 182 GHz, suitable for the FCC operation frequency proposed in the band from 174.8 to 182 GHz [3]. Photonic sub-THz generation is achieved with optical heterodyning: employing two different wavelengths generated with free-running lasers that are mixed at the receiver photodiode, producing an electrical signal which frequency is equal to the frequency difference between both wavelengths.

In addition, a complete full-duplex system requires the transmission of both the downlink (DL) and uplink (UL) signals. In the literature, several techniques have been evaluated for bi-directional systems, proving that when both DL and UL are propagated simultaneously in two directions of a single mode fiber, unwanted Brillouin and Rayleigh backscattering degrades the system performance [4][5]. Noise produced by backscattering can be avoided using MCF to transmit the different DL and UL signals. In addition, MCF can be used for implementing efficient wavelength reuse techniques [5].

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In this work, we propose using MCF for full-duplex C-RAN transmission including photonic generation in the sub-THz band. In particular, we compare the experimental performance of transmitting both the data and carrier wavelengths for optical heterodyning over the same or over different cores of a MCF link.

This approach provides complete flexibility to the system, as it enables using the same LO for different purposes (i.e. THz generation of other data or optical modulation for UL). It also simplifies the remote nodes as all the lasers can be located at the central office (baseband unit or BBU). With this approach, only 3 cores are required for bidirectional transmission and photonic THz generation, supporting N times of user numbers with a 2N+1 core media [5]. The proposed system is also compatible with wavelength division multiplexing (WDM) transmission, which enables further capacity extension when more wavelengths are used.

The full-duplex performance is evaluated with the transmission of a 12.5 GBd 16-quadrature amplitude modulation (QAM) signal over 1-km of 7-core MCF. Recently, MCF has been proposed as a suitable medium to transport the different signals access, fronthauling and backhauling [6]. As novelty in this work, we compare experimentally the system performance when the downlink (DL) data and carrier wavelengths to be mixed at the receiver for optical heterodyning are transmitted over the same or over different cores. In Section 2, the deployed system for photonic sub-THz generation using MCF is described in detail, including the coherent digital signal processing (DSP) algorithm used at the receiver. Next, in Section 3, we evaluate the full-duplex transmission using wavelength re-use of the carrier used for optical heterodyning in the DL and for UL transmission. This demonstration includes the analysis of the DSP configurations for both DL and UL reception. The experimental evaluation of the possible inter-core crosstalk interference for higher optical power levels at the input of the MCF is also reported in this paper. Finally, in Section 4, the main conclusions of this work are highlighted.

2. PHOTONIC THZ GENERATION WITH MCF

Figure 1(a) shows the experimental setups developed in the laboratory, emulating an optical backhaul system where the data wavelength (λ_D) and the wavelength used for optical heterodyning (λ_U) are transmitted over the same or over different cores of a MCF. The full-duplex transmission performance is evaluated experimentally with a 16-quadrature amplitude modulation (QAM) 12.5 GBd signal, including 1-km of MCF transmission and a short-reach wireless link at 182 GHz.

The electrical signals is generated with an arbitrary waveform generator (AWG Tektronix 70001A) operating at 50 GSa/s, defining the in-phase and quadrature (I/Q) components of an analog 16-QAM signal. The digital I/Q signals are defined with Matlab® with four 2^{11} de Bruijn bit sequences mapped into 12.5 GBd 16-QAM symbols, filtered with root raised cosine (RRC) filters with $\alpha = 0.1$ and a passband bandwidth of 13.75 GHz. The complex signal is upconverted and filtered for single sideband (SSB) signal transmission. Before I/Q optical modulation, the resulting electrical signals are time-aligned with two phase-shifters and amplified (with two electrical amplifiers with 23 dB gain). This signal is modulated over λ_D for downlink transmission using a $LiNbO_3$ dual-drive I/Q Mach-Zehnder modulator (MZM). The optical signal is generated with a tunable external cavity laser (ECL) at λ_D=1552.62. The modulated signal is amplified with an Erbium doped fiber amplifier (EDFA) and filtered with an optical band pass filter (OBPF).

A second ECL is used to generate a carrier at λ_U=1554.03 nm for optical heterodyning that will be used also for uplink transmission. The optical signals at λ_D and λ_U are transmitted through different cores –core 7 and core 4, respectively– or over the same core 7, as depicted in Figure 1(a).

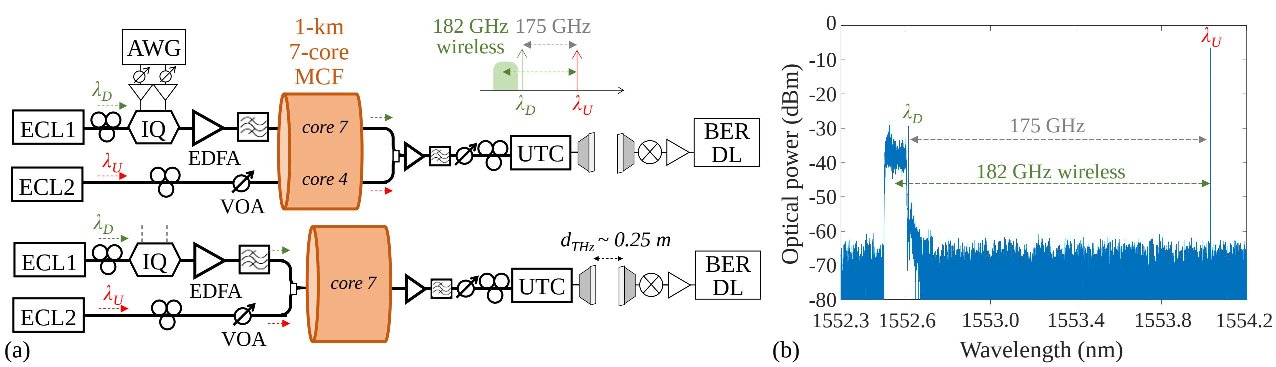

Figure 1. (a) Experimental setups developed for photonic THz generation usign the same or different cores of a 1-km 7-core MCF link including wireless transmission at 182 GHz. (b) Measured optical spectrum at the UTC.

Figure 1(b) shows the optical spectra of the SSB modulated data over λ_D=1552.62 nm after 1-km of a commercially available 7-core MCF –Fibercore SM-7C1500(6.1/125)–. The separation between λ_D and λ_U is of 175 GHz, as it can be observed in Figure 1(b). As it can be seen in the received spectrum, as the transmitted data signal corresponds to the upper sideband of the SSB signal, the actual wireless frequency is located in a higher frequency at 182 GHz.

For THz generation, an unpackaged uni-travelling carrier (UTC) photodiode is used as optical receiver, biased with -2V, where both λ_D and λ_U are mixed. A variable optical attenuator (VOA) is included before the UTC to test the performance with the received optical power level. The maximum optical power available at the input of the lensed fiber connected to the UTC was measured to be 16.5 dBm. A short-distance wireless communication link is included in the system with horn antennas (20 dBi gain) separated 0.25 m. In order to increase the collimation of the sub-THz beam at 183 GHz RF, two Teflon lenses with 5-cm diameter and 75 mm back focal length are included between the horn antennas with 0.1 m separation. After wireless transmission, the received wireless signal is downconverted to intermediate frequency (IF) with a second-harmonic mixer (Virginia Diodes WR5.1SHM), electronically amplified (40 dB gain) and sampled with a high-bandwidth oscilloscope (LeCroy LabMaster 10-36Zi) operating at 80 GSa/s.

At the receiver, a coherent digital signal processing (DSP) routine is implemented before bit error rate (BER) calculation. The main steps in the coherent DSP algorithm can be summarized in:

i) Complex down-conversion considering the IF measured at the scope (f_{up}).

ii) RRC matched filtering with $\alpha = 0.1$.

iii) Radius directed equalization (RDE) with order 18 and step vector = [0.01 0.001 0.0001].

iv) Power-of-4 frequency offset estimation (FOE) using FFT.

v) Blind phase noise compensation (PNC) with delta angle of $\pi/64$.

vi) Decision directed equalization (DDE) with decision-driven least mean squares (DD LMS). The order of the DD LMS equalization (number of taps minus 1) is reduced (in steps of 2) until a bit error rate of BER < 0.5 is obtained.

vii) Differential decoding is applied to the first two bits only in order to remove the quadrant ambiguity associated with square QAM constellations. For the rest pair of bits, no differential decoding is implemented.

After this processing, the received de Bruijin symbol sequence is retrieved. Then, cross correlation and BER calculation is implemented, analyzing $2.5\cdot10^5$ bits per point (making the lowest reliable measured BER value to be around 10^{-5}). In the following graphs, the BER recommendation of $3.8\cdot10^{-3}$ for error free transmission with 7% redundancy hard-decision forward error correction (HD-FEC) [7] is included as a dashed line for reference.

Figure 1 shows the performance evaluation when the data and optical carrier wavelengths used for photonic sub-THz generation at 182 GHz are transmitted over the same or over different cores of 1-km of 7-core MCF. It can be observed that the performance is very similar for low power current levels measured at the UTC. The performance when both wavelengths are transmitted in the same core is saturated for squared received current levels higher than 20 mA^2.

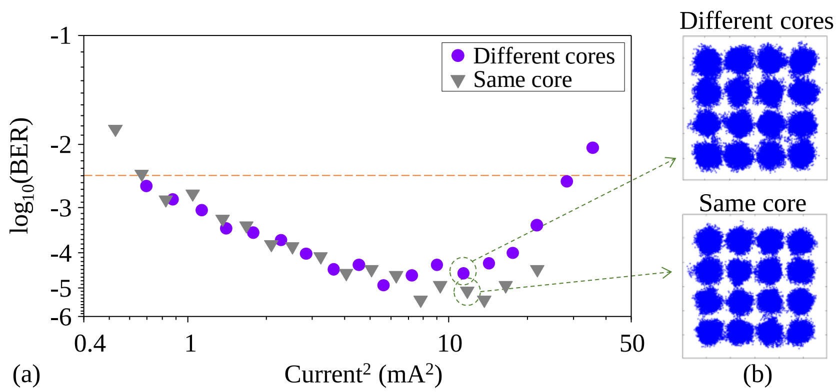

Figure 2. (a) BER performance vs. received squared photocurrent after 1-km MCF transmission over the same and over different cores (both processed with 71 taps in the DD LMS equalization) and (b) received constellations when both signals are transmitted over different cores (core 7 and 4) and over the same core (core 7).

3. FULL-DUPLEX EXPERIMENTAL EVALUATION

Figure 3 shows the experimental setup used for full-duplex evaluation. Full-duplex transmission is evaluated experimentally re-using the received IF from the DL signal and modulating it for UL transmission over the same wavelength transmitted via core 4 (λ_U=1554.03 nm). Thus, with this implementation, all the lasers are located at the BBU, simplifying the remote node.

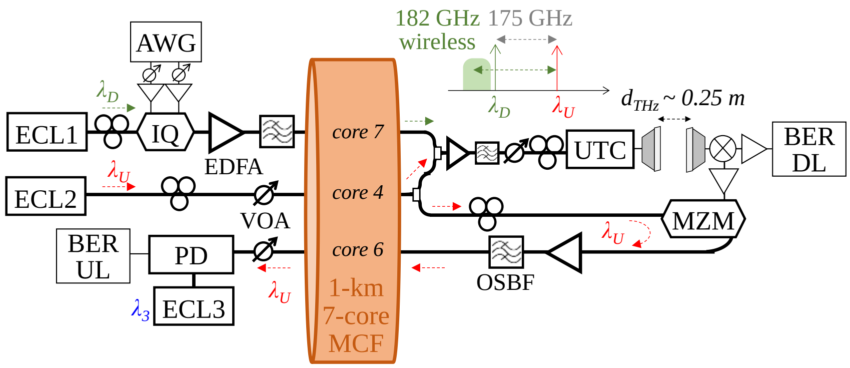

Figure 3. Experimental setup used for full-duplex transmission using the same wavelength for optical heterodyning at the DL and for UL transmission after 1-km of 7-core MCF and including a short-distance wireless link at 182 GHz.

In this case, the DL transmission is evaluated with λ_D and λ_U transmitted over different cores (core 7 and core 4, respectively). After a short wireless link at 182 GHz, the received signal is the signal is down-converted to an IF with a second-harmonic mixer (Virginia Diodes WR5.1SHM). The local oscillator feeding the SHM is generated with an RF synthesizer followed by a ×6 multiplier. For UL evaluation, this IF signal is modulated with a MZM biased at minimum transmission point. The modulated UL signal is amplified and filtered with a narrowband OBPF to suppress the upper frequency sideband. The filtered signal is transmitted back to the BBU via core 6 of the MCF. After 1-km of 7-core MCF transmission, the received UL signal is combined with an optical carrier generated at λ_3=1553.94 nm, obtaining a frequency separation of 20 GHz. As optical received in the UL, a single-ended PD is used. A VOA is included before the PD to test the performance with the received optical power level. The same DSP algorithm is used at the receiver for BER evaluation as described in Section 2.

Figure 4 shows that UL transmission requires higher received levels compared to its DL counterpart. UL transmission of the 12.5 GBd 16QAM signal requires higher received squared photocurrent levels higher than 8 mA^2, while DL transmission meets the BER recommendation for 0.7 mA^2.

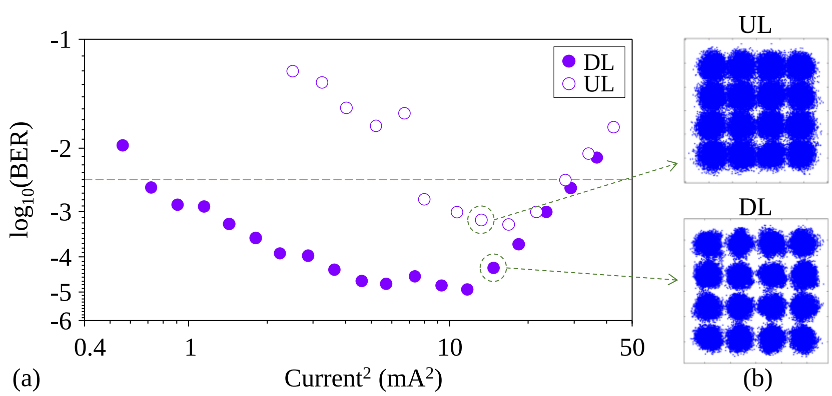

Figure 4. (a) BER performance vs. received squared photocurrent after 1-km MCF full-duplex transmission including DL and UL signals implementing wavelength re-use for DL heterodyning and UL transmision (both processed with 71 taps in the DD LMS equalization) and (b) received constellations for DL and UL.

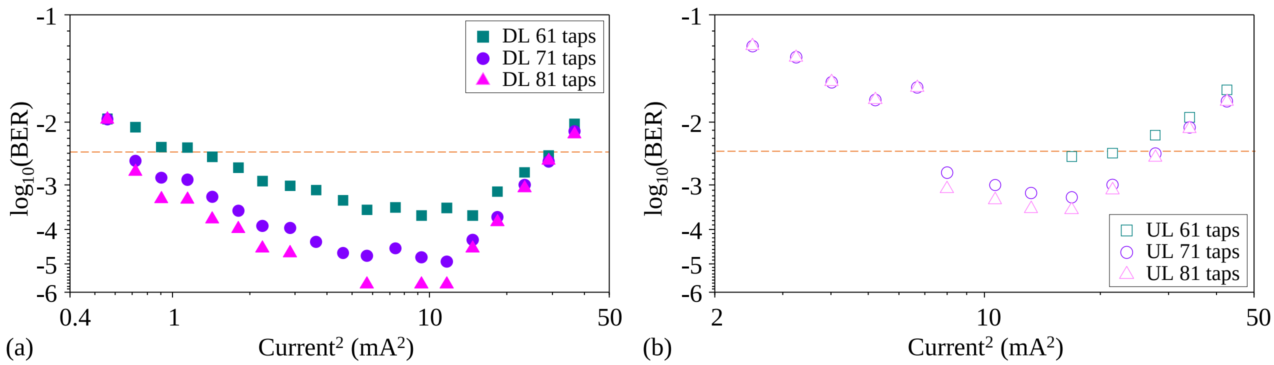

Figure 5. BER performance vs. received squared photocurrent after 1-km MCF transmission with the number of taps used in the DD LMS equalization (a) for DL and (b) for UL signal transmission.

Next, we evaluated the performance of both DL and UL transmission with different DSP configurations. In particular, we processed the BER results for different number of taps used in the DD LMS equalization step. As it can be observed in Figure 5, UL transmission requires a higher number of taps in the equalization in order to meet the BER requirements, with at least 71 taps in the DD LMS equalization. Compared with the DL performance that can operate with only 61 taps. However, in both implementations, a higher number of taps (at least 81) are preferred as it provides a better BER performance. Further studies confirmed that for a number higher of 91 taps, no further improvement is obtained with the DD LMS equalization.

And, in order to conclude with the system analysis, we also evaluated the possible impact of inter-core crosstalk (IC-XT) of the MCF. As reference, Figure 6(a) shows the core distribution in the 7-core MCF –Fibercore SM-7C1500(6.1/125)–. It can be observed that core 4 is in the center of the 7-core arrangement, while core 7 is in the external circle around it. The crosstalk evaluation is performed by injecting the signal in core 7 and measuring it in the other cores. Figure 6(b) shows the mean optical power (in dBm) measured at the output of each the cores when the power is injected in core 7. Two injected power levels were evaluated including P_{in}=+5.5 dBm (level used for the experimental demonstration) and a higher power level with P_{in}=+9.5 dBm. Figure 6(c) shows the BER performance for the DL transmission with all cores active and with an interference of +9.5 dBm. According to the previous results, 71 taps were employed in the DD LMS equalization. The BER results are very similar for the complete received current range for both cases, so no impact of inter-core crosstalk was observed.

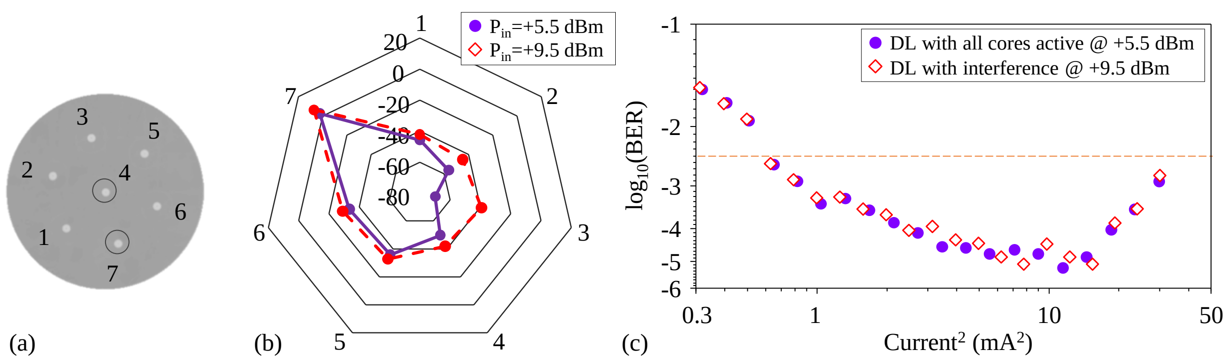

Figure 6. (a) Core distribution in the 7-core MCF. (b) Measured mean power (dBm) in each core of the 7-core MCF with an input power at core 7 of +5.5 dBm and +9.5 dBm. (c) BER performance vs. received squared photocurrent after 1-km MCF transmission for DL transmision (processed with 71 taps in the DD LMS equalization) with all cores active with +5.5 dBm and with +9.5 dBm interference.

4. CONCLUSION

This paper demonstrates experimentally the full-duplex transmission including photonic sub-THz generation and wavelength re-use using a C-RAN based on MCF. We compared the system performance when the data and carrier wavelengths to be mixed at the receiver for optical heterodyning are transmitted over the same or over different cores of a MCF link. The experimental results show that the performance is very similar for low received current levels, while transmission in the same core is limited by saturation effects and reduces the system flexibility. The proposal of using different cores for the transmission of the data and carrier wavelengths provides complete flexibility to the system, as it enables using the same LO wavelength for different purposes (i.e. THz generation of other data or optical modulation for UL). The proposed approach using different cores of the same MCF link also simplifies the remote nodes as all the lasers can be located at the central office and minimizes the number of lasers required thanks to wavelength re-use.

Successful provision of 12.5 GBd 16QAM signals is achieved after 1-km of 7-core MCF transmission including a short wireless link at 182 GHz, obtained with optical heterodyning. Full-duplex communication is demonstrated with wavelength-reuse of the optical carrier for UL transmission (the same wavelength used for optical heterodyning). For the experimental demonstration, the same 12.5 GBd 16QAM received signal after wireless transmission at 182 GHz is downconverted to IF and transmitted back as uplink. The experimental results demonstrate that UL transmission requires higher received levels compared to its DL counterpart. UL transmission also requires higher number of taps in the DSP, with at least 71 taps in the DD LMS equalization. No limitation due to inter-core crosstalk was observed with input levels of up to +9.5 dBm, which confirms the suitability of MCF for C-RAN architectures including photonic sub-THz generation and wavelength re-use.

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