A Full-Duplex Optical Millimeter Waves (60-100 GHz) Radio-over-Fiber System

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***Abstract*— In this paper, we propose and simulate the most compact full-duplex optical millimeter wave radio-over-fiber (mmW-RoF) system employing binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) with error-free transmission over 10, 25 and 50 km of single mode fibers (SMF) in up-link (UL) and down-link (DL). We evaluate the EVM values for DL and UL are < 24% for BPSK and QPSK over the 10, 25 and 50 km of SMF.**

Keywords— ***full-duplex optical millimeter wave radio-over-fiber(Optical mmW-RoF); dual parallel Mach-Zehnder modulator (DP-MZM); error vector magnitude (EVM); power loss (PL)***

I. Introduction

Radio-over-fiber (RoF) has been identified and established as a platform, which can enhance the already congested radio frequency (RF) bandwidth. The advantage of RoF system is evident in moving the signal processing task from the base station (BS) to the central station (CS) in order to achieve a centralized system, which results in the reduction of the system complexity and costs. To increase the data rate microwave (mW) and millimeter wave (mmW) carrier frequencies at < 30 GHz and in the range of 30 – 300 GHz, respectively have been investigated. However, high losses, multipath induced inter-symbol interference (ISI) [1] and Rayleigh fading effect [2] in non-line-of-sight links are the major issues in mW and mmW-based wireless communications. As a consequence, the transmission span is typically limited to a few meters [3] and there is the need for higher signal-to-noise ratio (SNR).

Knowing such limitations at higher frequencies, the RoF technology, which offers a high bandwidth, lower attenuation (i.e., 0.2 dB/km for a single mode fibre (SMF)) and immunity to electromagnetic interference (EMI), has been proposed. In RoF systems generating mW or mmW carriers signals in the optical domain has been investigated through exploring the nonlinear characteristics of the system. Note, generating higher order carriers is possible using a local oscillator (LO), which operates at frequencies half, a quarter or a sixth of the final carrier frequency. Moreover, the RoF system compactness and a wide range of carrier frequency generation can be achieved [4-6]. In [7], an external modulator was proposed to increase the maximum achievable transmission spans. In [8, 9], the sextupling method of generating optical mmW was proposed for a full-duplex RoF system, where the generated optical mmW carrier signal frequency is the 6^{th} harmonic of the LO. However, the disadvantages of this scheme are (i) its practicality, where fibre nonlinearity, photodetector (PD) sensitivity and lower SNR at high frequencies over longer haul transmission links making signal detection extremely challenging; and (ii) the overall cost and complexity of electro-optic components such as arrayed waveguide grating (AWG) and optical tunable filters.

In [10], an architecture of full-duplex mmW RoF system based on polarization division multiplexing (PDM) and wavelength division multiplexing (WDM) technology has been proposed. Chen et al. [10], has incorporated polarization beam splitter (PBS) to rotate the optical carrier by 90° so it is easier compared to the rotated signal by 45°. Although, the proposed model has less complexity compared to polarized signal by 45°, the overall complexity of the system due to PBS is more against other has been porposed full-duplex models. For instance, it is not clear how the polarized signal can maintain its polarization while propagating in the fibre and whether it affect the complexity of the receiver ends on each sides of the transmission.

In [11], a totally different approach has been adapted. A series of RF signals generated at 1 GHz and separated by 1 GHz channel spacing. The RF signal directly modulated the distributed feedback (DFB) laser with 5 dBm output power. The unconventional approach in [11], is in the remote antenna unit (RAU). The RAU is used to upconvert the 1 GHz RF signal to 60 GHz before feeding to the antenna unit. However, such design is a major contradiction to the initial purpose of the RoF design which is to reduce the complexity of RAU by moving the local oscillator (LO) to the central station (CS).

Another example of the full-duplex in RoF optical mmW has been reported in [12]. In the experimental proposed setup transmission of carrier aggregation (CA) long-term evolution-advanced (LTE-A) signals over the fibre. The paper has implemented a more standard approach, which is more acceptable to industry, in which optical circulator is used instead of using PBS or other methods.

In this paper, we propose and investigate a compact full-duplex optical mmW-RoF system, binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) at 2 Gb/s of data rate and a carrier frequency of 20 GHz for DL and UL, respectively. In DL path, the optical mmW is generated at 60 GHz by running local oscillator at 30

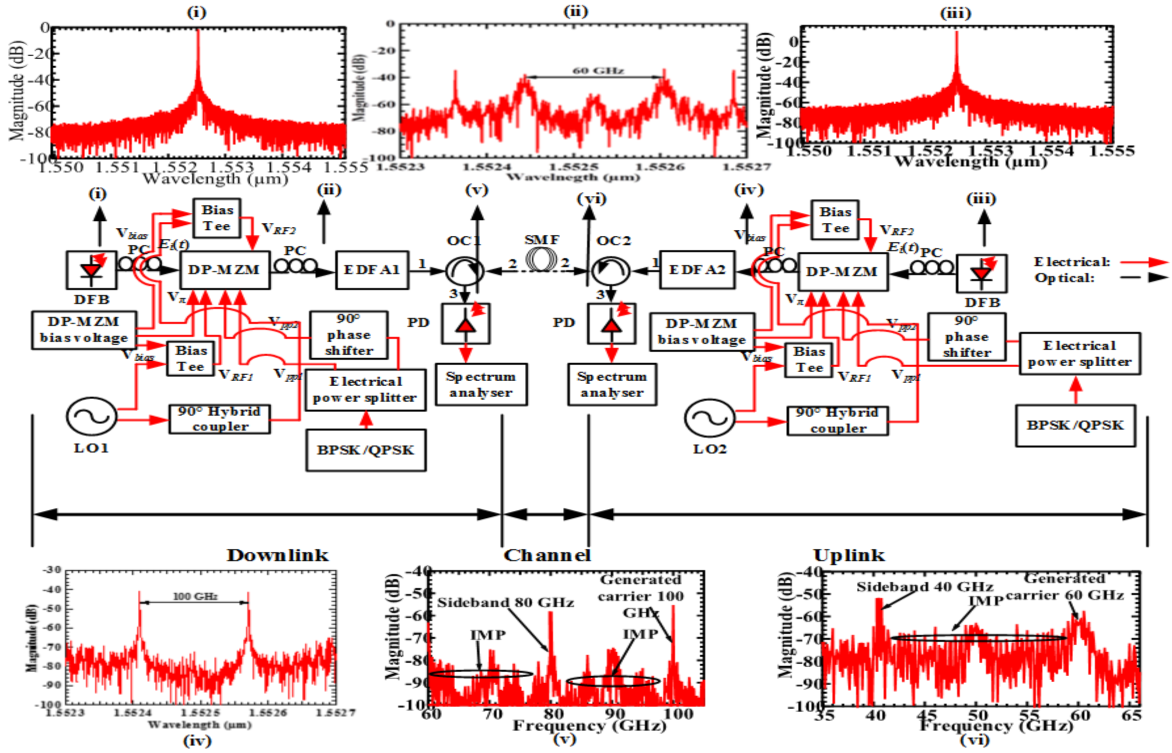

Fig. 1: Simulated proposed topology for full-duplex optical MMW-RoF consists of DP-MZMs; insets i-vi illustrates corresponding optical and electrical spectrums in particular measured points

GHz and in UL 100 GHz signal has been generated using a local oscillator at 50 GHz. The modulated data has been evaluated in terms of power loss (PL) and error vector magnitude (EVM) at 40 and 80 GHz sidebands in DL and UL paths, respectively. Standard bit error rate (BER) communication has been achieved over full-duplex SMF at 10, 25 and 50 km. In the proposed model, dual parallel-Mac Zehnder Modualtor (DP-MZM) to generate optical double sideband suppressed carrier (ODSB-SC), optical insertion loss (OIL), fiber linear and nonlinear impairments namely chromatic dispersion (CD), attenuation, self-phase modulation (SPM) and cross-phase modulation (XPM) are have been taken into consideration in the proposed model.

II. Simulation Setup

The proposed simulated topology is illustrated in Fig. 1 using OptiSystem® software. The DFBs are tuned to generate 11 dBm (Fig. 1(i), λ_{DL} = 1550.52 nm and (iii), λ_{UL} = 1550.49 nm). In order to maintain the polarization of the laser beam, two polarization controllers (PC) are used before and after DP-MZM. To generate ODSB-SC, the DP-MZM is biased at a minimum transmission biasing (MITB) point. For the DL connection, the local oscillator (LO1) operates at 30 GHz, which is doubled in optical domain, see Fig. 1(ii). The LO1 operates at 30 GHz generates in-phase and quadrature sinusoidal carrier using a 90° hybrid coupler. The LO1 in-phase and quadrature signals are applied via the bias tee to bias DP-MZM. In the proposed configuration, DP-MZM can modulate the electrical signal and generate optical mmW at the same time. Hence, the most compact configuration can be achieved. Both BPSK and QPSK are split into in-phase and quadrature components and applied to the DP-MZM (V_{PP1} and V_{PP2}).

In the proposed full-duplex optical mmW-RoF system DP-MZM's OIL is equal to 25 dB, which is due to the nonlinear operation region around the MITB point. Consequently, the optical amplification has been utilized using erbium doped fiber amplifiers (EDFA1 for DL and EDFA2 for UL) in order to compensate for the power loss due to DP-MZM OIL. In order to evaluate the performance of the proposed system the optical launch power (OLP) is varied between 0 – 20 dBm using EDFA1 and EDFA2 for the DL and UP paths. The same process is applied to the UP path except for theLO2 operating at 50 GHz, which generates an optical carrier at 100 GHz, see Fig. 1(iv). The performance of the system is evaluated in terms of PL and EVM over three different fibre spans of 10, 25 and 50 km.

III. Results and Disscussions

It is significant to note that, the proposed full-duplex system can deliver error free communications for different modulation schemes over 10, 25 and 50 km of fibers as well as being compact. Initially, we evaluate the system PL with respect to the OLP at a bit error rate (BER) of 10^{-5}. The simulated optical and electrical spectrums of the system simulation are illustrated in Fig. 1(i)-(v), whereas the measured spectrums following DP-MZM are in Fig. 1(ii) and (iv) referring to ODSB-SC. The sidebands are separated from each other with magnitude equals to double the frequency of the LO1 and LO2 for DL and UL, respectively. Following photodetection, the electrical spectrum is presented in Figs. 1(v) and (vi) for UL and DL,

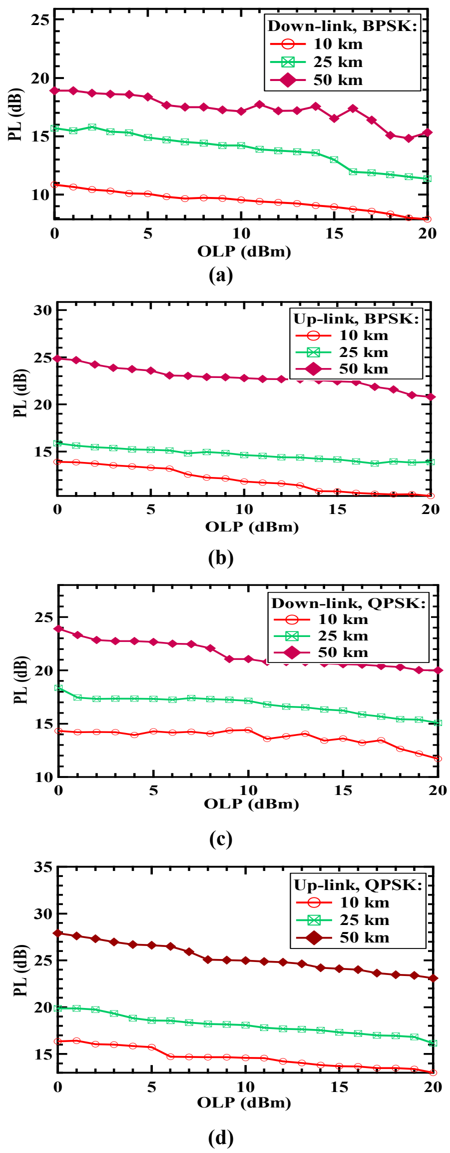

Fig. 2: PL at OLP for: (a) BPSK modulation 40 GHz, DL, (b) BPSK modulation 80 GHz, UL, (c) QPSK modulation 40 GHz, DL, and (d) QPSK modulation 80 GHz, UL

respectively. Also shown are the (i) sidebands for DL and UL at 40 and 80 GHz for the BPSK and QPSK RF signals at 20 GHz prior to external modulation; and (ii) the intermodulation products (IMP) caused by nonlinearity of the DP-MZM is one of the major factors affecting the magnitude response of the frequency harmonics. In addition, the standard SMF nonlinear characteristics such as self-phase modulation (SPM) caused by the Kerr effect and cross-phase modulation (XPM) due to Kerr effect and different wavelengths, respectively will affect the link performance.

Fig. 2(a) illustrates the measured PLs over a range of OLPs for DL BPSK for 10, 25 and 50 km of fiber spans. Considering a 10 km of SMF, increasing the OLP from 0 to 20 dBm results in ~11 and ~8 dB of PL for DL sidebands at 40 GHz, respectively. For a 25 km of SMF the PL increases to ~16 dB at and ~12 dB at OLP values of 0 and 20 dBm, respectively. At 50 km of fiber the PL increases to ~19 and ~16 dB at OLP values of 0 and 20 dBm, respectively. For DL BPSK we also observed the same profile for PL as function of OLP (i.e., decreasing PL with increasing OLP).

The same investigation was performed for UL BPSK. As it is expected in the UL path, where the sideband is at 80 GHz, see Fig. 1(v), higher PL values are expected due to higher operating frequencies. Fig .2(b) depicts the PL as a function of OLP for BPSK-based UL. The PL decreases from ~4 to ~10 dB for OLP of 0 to 20 dBm for a 10 km of SMF. For longer length fibres of 25 and 50 km, the drop in PL from ~16 to ~14 dB and ~25 to ~21 dB, respectively over the same OLP range.

Fig. 2(c) depicts the QPSK DL path exhibiting a steady decrease in PL with the increase in OLP. At 10 km of SMF, PL is dropped from ~14 to ~12 dB over OLP range of 0 to 20 dBm. For longer length fibre the same pattern as in Fig. 2(b) is observed. Similarly, for the QPSK UL path, we observe the same trend as in Fig. 2(a)-(c). e.g., at 10 km of SMF PL varies from ~16 to ~13 dB for OLP increasing from 0 to 20 dBm.

Fig. 3 illustrates the EVM as a function of OLP for a BER of 10^{-5}, UP and DL and 10, 25 and 50 km of SMF. For BPSK DL with a 10 km SMF, the EVM values are ~17% and ~12% for OLP values of 0 and 20 dBm, respectively. For 25 and 50 km long SMFs, the EVM decreases from ~19 to ~12% and ~22% to 13%, respectivey over the OLP range of 0 to 20 dBm.

At 50 km, the EVM values are ~22% and ~13% for OLP values of 0 and 20 dBm, respectively. Standrd EVM for BPSK modulation scheme should remain below 34% [13] which is the case for BPSK in DL path at 40 GHz sideband.

Fig. 3(b) depicts the EVM for BPSK modulation in UL path at 80 GHz sideband. The same investigation was performed for UL. For BPSK UL with a 10 km SMF, the EVM values are ~17% and ~12% for OLP values of 0 and 20 dBm, respectively. For 25 and 50 km long SMFs, the EVM decreases from ~20% to ~14% and ~22% to ~12% respectively over the OLP range of 0 and 20 dBm.

The QPSK for DL and UL has also been investigated in terms of EVM performances. Standrd EVM for BPSK modulation scheme should not exceed 24% for QPSK modulation [13].

Fig. 3(c) and (d) depicts the DL and UL QPSK at 40 and 80 GHz sidebands. At 10 km of SMF, the EVM decreases from ~17% to 12% and ~19% to ~13% for OLP values of 0 and 20 dBm, respectively. At 50 km, the EVM decreases from ~24% to just above ~16% for OLP values of 0 and 20 dBm, respectively. As expected, the EVM percentage in QPSK modulation is marginally higher than BPSK, which is an anticipated outcome.

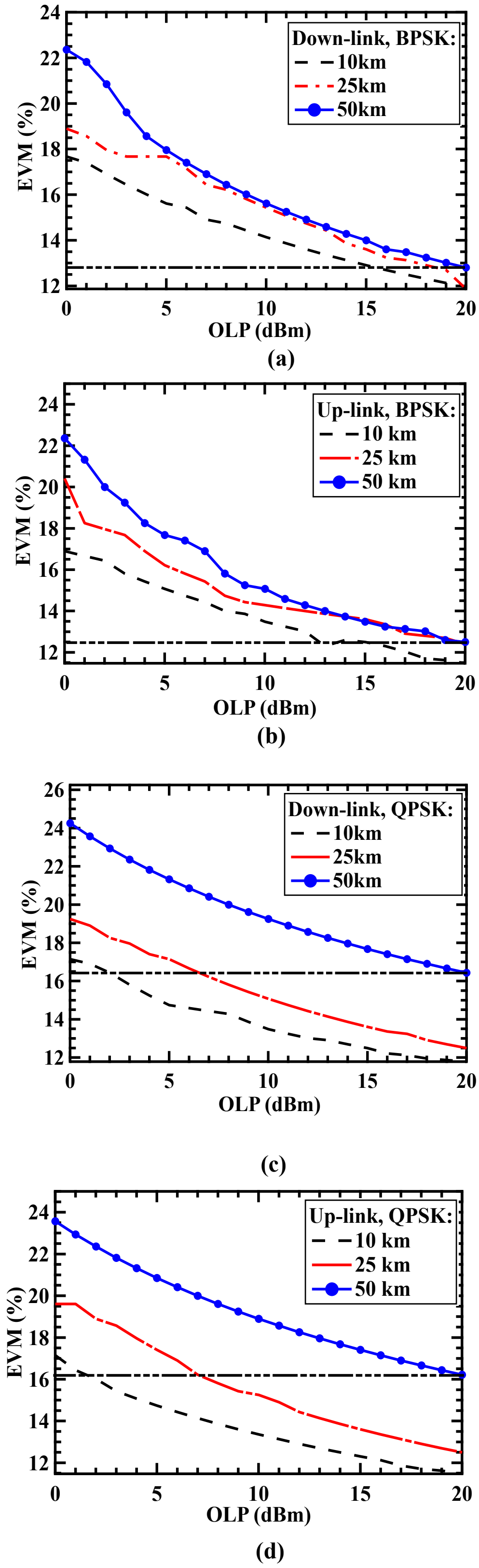

Fig. 3: EVM at OLP for: (a) BPSK modulation 40 GHz, DL, (b) BPSK modulation 80 GHz, UL, (c) QPSK modulation 40 GHz, DL, and (d) EVM at OLP for QPSK modulation 80 GHz, UL. The dotted horizontal line referes to the highest EVM value at 50 km fibre span.

IV. Conclusion

In this paper we proposed and simulated a full-duplex optical mmW-RoF system in which 60 and 100 GHz are modulated with BPSK and QPSK modulation schemes at 20 GHz with data rate at 2 Gb/s in DL and UL paths, respectively. The performance of the system evaluated at 40 and 80 GHz sidebands in DL and UL paths in terms of PL and EVM percentages accordingly. In all cases, the modulation schemes achieved error free communication system at 10, 25 and 50 km with EVM percentages of less than 24% for all investigating scenarios in the proposed system.

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