Bidirectional MMWoF-wireless convergence system based on a 1610 nm L-band quantum-dash laser

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Abstract: We report bidirectional 25/28 GHz millimeter wave (MMW)-over-fiber (MMWoF) and MMWoF-wireless (MMWoF-WL) transmission systems employing a single self-injection locked InAs/InP quantum-dash dual-mode laser (QD-DML) as a MMW source. Besides, we demonstrate the entire system exploiting the challenging mid-L-band wavelength window (1610 nm) to substantiate this source’s potential, which exhibits tunability from C- to L-bands, in next-generation optical networks covering these wavelengths’ window operations. While exhibiting 28 GHz mode spacing between the two optical carriers of QD-DML, a downstream (DS) transmission of 4.0 Gbaud (8 Gbits/s) quadrature-phase-shift-keying (QPSK) signal is conducted over this carrier. In addition, a simultaneous 2.0 Gbaud (8 Gbits/s) 16-level quadrature amplitude modulation (16-QAM) upstream (US) transmission on a 25 GHz MMW beat-tone is also achieved by exploiting one of the DS optical tones. A rigorous transmission characterization of variable DS and US QPSK/16-QAM data rates over MMWoF (10 km SMF) and MMWoF-WL (10 km SMF and up to 4 m wireless) are performed, showing a strong influence of phase noise on the DS link and hence the receiver sensitivity.

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1. Introduction

At present, due to the perpetual introduction of bandwidth-intensive applications, optical network infrastructures are struggling to meet the exponentially rising data capacity demand around the globe, which is expected to increase to 396 Exabytes/month by 2022 [1]. Therefore, standardization has been set forward to meet the next-generation optical network requirements, for instance, 100G and 400G, underlining the need to increase the transmission capacity, particularly at first/last mile access (i.e., user end). Moreover, this unceasing requirement for high-speed, high data rate, and lower latency wireless broadband coverage call for technological advancement for fifth-generation (5G) networks, which has already been deployed in several countries and is expected to enable seamless connection of different platforms, flexible enough to support various usage patterns [2–4]. In this regard, radio-over-fiber (RoF) technology is garnering recent attention as a potential technology, thanks to its seamless integration with the existing fiber infrastructure, hence converging radio frequency (RF) and optical domains. In particular, 24-30 GHz millimeter (MMW) frequencies have been identified by several countries [5,6] as a potential wireless band to ease microwave spectrum congestion. Hence, RoF, along with
wavelength division multiplexing (WDM) (RoF-WDM), is considered as a promising solution for access networks (first/last mile) [7] in diverse environments such as densely populated residential areas, shopping malls, stadiums, houses, and office interior, etc., while exploiting MMW band as well as regulated microwave band where necessary. The RoF-based access network architecture concept has been illustrated in Fig. 1, which integrates MMWoF and hybrid MMWoF-wireless (MMWoF-WL) solutions as candidates for next-generation converging networks.

**Fig. 1.** Schematic representation of hybrid MMWoF-WL bidirectional RoF-WDM access network, a potential technology for next generation optical networks. MMW: Millimeter wave.

Several optical MMW sources have been proposed in recent years with assisting techniques in the generation [8–14] and subsequent demonstration of bidirectional MMWoF-WL architectures with application in access or metro domain [8,11–13]. For instance, distributive-feedback (DFB) laser diodes (LD), vertical-cavity surface-emitting lasers (VCSEL) [8], colorless Fabry-Perot (FP) laser diodes (LDs) [9,10], external cavity lasers (ECLs) [11,12], DFB-LD based gain-clamped comb source [13,14], Mach Zehnder modulator (MZM)-optoelectronic oscillator (OEO) based source [15], etc., operating in 1540-1550 nm C-band region, have been reported in tandem with external injection locking (EIL) technique. Moreover, other assisting schemes besides EIL, such as orthogonal polarization splitting/combining [16,17], polarization multiplexing [18], sideband routing [19], and wavelength reuse [13,14,18], have also been deployed in the system architectures to facilitate bidirectional transmission. For instance, Fang et al. employed five 1550 nm external cavity laser (ECL) sources in tandem with external-injection locking (EIL) for bi-directional transmission of 10 Gbits/s quadrature-phase-shift-keying (QPSK) signal in the E-band over 20 km single-mode fiber (SMF) - 1 m wireless - 20 km SMF MMWoF-WL link, where 71-76 GHz has been used for DS and 81-86 GHz for US [11]. On the other hand, Pang et al. utilized three ECL with separate DS and US MMWoF-WL (20 km SMF - 1 to 15 m WL - 10 m SMF) link and demonstrated 16 Gbits/s QPSK for the US and 1.25 Gbits/s amplitude shift keying (ASK) DS transmission [12]. Moreover, Ref. [14] deployed a single 1540 nm gain-switched laser comb source with EIL and accomplished successful bidirectional transmission of 56 GHz DS and 61 GHz US 0.89 Gbits/s 16 quadrature amplitude modulation (16-QAM) signal over 12 km SMF [14]. Polarization multiplexing, wherein x-polarization of 1550 nm tunable laser for DS 18GHz MMW carrier carrying 50 Mbaud 16-QAM, and y-polarization for US 18 GHz MMW carrier with 2 Gbits/s pseudo-random-bit-sequence (PBRS) data is demonstrated over 150 m SMF [16]. Nevertheless, in general, these schemes, which employ multiple optical sources in the C-band, exploited EIL assisted method for various purposes such as the selection of DS/US wavelengths and improved spectral purity and coherency of optical tones to ascertain narrow linewidth and low phase noise ($S_{\Phi}$) of heterodyned MMW beat-tones.

Recently, InAs/InP quantum-dash LD (QD-LD) has found significant research attention as a promising photonic MMW source [20–25] due to superior noise and dynamic characteristics despite broadband lasing emission and covering emission wavelengths from C- to L-bands. In fact, recent demonstrations of 40-146 GHz [21–25] MMW carrier beat-tones generation and
subsequent wireless (WL) unidirectional transmission of various modulating signals viz. 1.0 Gbits/s on-off keying (OOK) [21], 2 Gbits/s 4-level pulse amplitude modulation (PAM-4) [22], 10 Gbits/s orthogonal frequency division multiplexing (OFDM) [23], and 16 Gbits/s 4-level QAM [25]; utilizing 1550 nm QD-LD uphold the benefits offered by this new-class of quantum-confined nanostructure-based MMW sources. Furthermore, very recently, we exploited the wavelength tunability of dashes and engaged QD-LD in exploring the extended L-band window to support this source’s potential covering both C- and L- communication bands, which is very promising for next-generation optical networks. Our preliminary results demonstrated the generation of 28-60 GHz MMW beat-tones signals and their unmodulated wireless transmission at 1610 nm [25]. It is to be noted that a thorough search of the literature yielded no article related to bidirectional transmission employing QD-LD in the C-band, let alone the L-band.

As such, to the best of the authors’ knowledge, this is the first work that demonstrates (i) bidirectional MMWoF-WL convergence system employing a centralized single quantum-dash-dual-mode laser (QD-DML) together with wavelength reuse strategy, (ii) in the challenging mid-L-band region utilizing a bare (unbounded) 1610 nm QD-LD, (iii) by exploiting self-injection locking (SIL) scheme rather than energy-taxing, bulky and expensive EIL, to realize QD-DML. Thus, the proposed system would considerably improve the capital and operational expenditure if deployed in future fiber-wireless networks. Moreover, extending the dual-mode emission of QD-LD to highly coherent multiwavelength lasing could serve as a single source for several channels in MMWoF-WDM architecture [19,20]. Furthermore, simultaneous error-free transmission of 28 GHz single sideband (SSB) modulated 8 Gbits/s QPSK signal for DS and 25 GHz double sideband (DSB) modulated 8 Gbits/s 16-QAM signal is demonstrated as a proof-of-concept over a hybrid MMWoF-WL channel (10 km SMF-4 m WL distance).

2. Bidirectional MMWoF-WL convergence system

In this section, the underlying principle behind the proposed bidirectional MMWoF-WL transmission system is discussed briefly, and then details of the experimental setup are provided.

2.1. Principle of operation

Figure 2 shows the MMWoF-WL bidirectional transmission system with QD-DML serving as a single optical source. The two-mode laser exhibits 28 GHz free-spectral-range (FSR), generated by exploiting SIL QD-LD, thus exhibiting superior coherency and less noise across the modes [25]. As illustrated in Fig. 2, the two optical tones of QD-DML at the central office (CO) serves as optical carriers for US (shorter wavelength mode $\lambda_1$) and DS (longer wavelength mode $\lambda_2$) transmission, as shown in the inset (i) of Fig. 4. The dual modes are separated, and the DS optical carrier is then SSB modulated with data before combing with the unmodulated US optical carrier and transmitted over a 10 km SMF link. At the remote access unit (RAU), part of the optical carrier pair power is heterodyned in a photodiode to retrieve the modulated 28 GHz MMW carrier signal, which is wirelessly transmitted over 0-4 m distance using a pair horn antenna before being received and analyzed at remote radio head unit (RRU).

On the other hand, a 25 GHz US MMW carrier, carrying data from the RRU, is again wirelessly transmitted to RAU via another pair of horn antennas before being intensity DSB modulated to the US optical carrier. The US optical carrier is essentially retrieved from the remaining optical power of the received optical carrier pair from the SMF, hence reusing the shorter wavelength optical tone. The modulated 25 GHz US optical carrier is then transmitted over the same 10 km SMF, then separated and recovered at the CO. Hence, two optical tones are utilized for a single channel bidirectional system. It is to be noted that in Fig. 2, the modulated US 25 GHz carrier is generated by a vector signal generator (VSG) for proof-of-concept purposes. Moreover, coupler CP1 (50/50%) and two tunable optical bandpass filters (TF1 and TF2) may be replaced by a wavelength selective switch to filter the modes of QD-DML or by a multiplexer should it
be commercially available in the wavelength band of interest (mid-L-band), thus simplifying
the architecture. This is the first step where we realized the extended L-band system with
SIL-based QD-DML. In the future, this source could potentially be replaced by a highly coherent
multiwavelength single QD-LD device by exploiting single-section passive mode-locking once
this technique is witnessed in the L-band region (presently, this coherency preserving scheme
across all wavelength modes is noted only in C-band QD-LD [20–22]). Hence, our work further
strengthens this promising QD-LD feature, thereby serving as a single source for several channels
in MMWoF-WDM bidirectional networks [19].

2.2. Experimental setup

The complete laboratory assembled experimental setup is illustrated in Fig. 2, along with the
utilized abbreviations, whereas Fig. 3 depicts a few physical key components employed. The
configuration consists of a MMW transceiver situated at the CO and comprises a DS transmitter
(Tx) and a US receiver (Rx) holding a single coherent QD-DML with 28 GHz FSR. On the
other hand, the RRU encompasses the DS Rx and US Tx, which includes separate horn antennas
(25-40 GHz bandwidth, 25 dBi gain) for receiving and transmitting purposes, as well as digital
storage oscilloscope (DSO, Keysight DSOX 932048) to analyze the DS signal and VSG (Keysight
E8267D) that serves as a modulated US MMW carrier source. Finally, the RAU serves as a
distribution system or a base station, converting the DS modulated optical MMW beat-tone to an
RF signal and vice versa for the US signal. A single 10 km SMF with measured ∼0.4 dB/km
attenuation at ∼1610 nm serves as an optical channel between CO and RAU, while a 0-4 m long
wireless channel links RAU with RRU with a pair of horn antenna as depicted in Fig. 3 residing
in each unit. While RAU includes the DS transmitting and the US receiving horn antennas (25-40
GHz bandwidth, 25 dBi gain), RRU consists of the otherwise.

Given DS Tx unit, the longer wavelength mode $\lambda_2$ is filtered by first passing the output
of QD-DML, depicted in the inset (i) of Fig. 4, through CP1 (50/50%) and then tuning the
filter TF1 (EXFO XTM-50), which is then SSB modulated with DS QPSK data signal in
an in-phase-quadrature modulator (IQM). The pre-processed DS QPSK signal is generated via
MATLAB by generating a pseudo-random binary sequence (PRBS) with a length of $2^{11} - 1$ via
an arbitrary waveform generator (AWG, Keysight M8195A) and an applied root raised cosine
(RRC) filter with a roll-off factor of 0.35 for Nyquist pulse shaping to obtain the symbols. More
details can be found from Ref. [26]. On the other front, the shorter wavelength $\lambda_2$ mode is
selected from the lower arm of CP1 output via TF2 (Santec OTF-350), whose optical power
Fig. 3. Experimental configuration of the bidirectional MMWoF convergence system employing single QD-DML. Insets show the bare QD-LD bar and the probing station.

is controlled with a variable optical attenuator (AT1, Agilent N7764A) before combining with the modulated $\lambda_1$ mode via CP2, which is available in the upper arm of CP1 output. The other observed optical lasing modes at various places (ii)-(v) within DS Tx are shown as respectively numbered insets in Fig. 4. Thus, a QPSK modulated 28 GHz DS MMW beat-tone is realized in the optical domain. This signal is then transmitted through SMF via two optical circulators (OC1 and OC2) that separate the US and DS data at CO and RAU.

Fig. 4. Optical (i)-(vi) and electrical (vii)-(viii) characteristics of the proposed bidirectional MMWoF-WL convergence system, and observed at various locations (i)-(viii) shown in Fig. 2. The insets of (i)-(vi) illustrate the pictorial representation of the corresponding observed experimental spectra. Insets of (vii) and (viii) represent 1 Gbaud and 2 Gbaud modulated QPSK and 16-QAM data signal on the MMW carrier, respectively.

At the RAU, the DS photonic 28 GHz MMW carrier signal is amplified via OA1 (Amonics AEDFAL-EX2-B-FA) before passing through another 50/50% CP3. The upper arm of CP3 output (i.e., 50% output) is then utilized to obtain the 28 GHz modulated MMW carrier RF signal by heterodyning in a 70 GHz photodiode (PD1, Finisar XPDV3120) after passing through AT2 (Agilent N7764A), which is used to attenuate the optical power for DS performance characterization. The DS MMW carrier is then wirelessly transmitted to the RRU via a horn antenna after amplifying in a low-noise amplifier (EA1). The receiving horn antenna at RRU is
then manually aligned for maximum electrical power reception and ultimately connected to DSO to analyze the retrieved DS QPSK signal.

At the RRU US Tx unit, the US QPSK/16-QAM baseband (BB) IQ multilevel signals are generated using 12 GSa/s Keysight AWG (M8190A) with PRBS length of $2^{11} - 1$, then frequency up-converted to 25 GHz using Keysight VSG (E8267D), and this RF signal is then transmitted wirelessly via the horn antenna, which is then received by a manually aligned horn antenna in the RAU. This US electrical signal is then converted into the optical domain by intensity modulating, in an MZM (EOspace 40 GHz), both $\lambda_1$ and mode $\lambda_2$ optical carriers that are recovered from the lower output arm of CP3. The output of MZM, which is the US optical equivalent MMW signal, is then transmitted to the CO via the same 10 km SMF using the OCs. At the CO, the US signal is separated from DS data by OC1 and directed to the US Rx unit, which then converts the DS modulated 25 GHz MMW beat-tone into electrical domain by heterodyning in another 70 GHz photodiode (PD2, Finisar XPDV3120) before passing through an optical attenuator (AT3, Agilent N7764A) that is used for US transmission performance characterization. The electrical amplifier (EA2) amplifies the output of PD2, and the resultant US QPSK/16-QAM data signal is analyzed coherently in real-time on a 32-GHz bandwidth and 80 GSa/s speed Keysight DSOX 932048 utilizing a vector signal analysis software (89600 VSA). The received signal is first downconverted and digitized and then undergoes several digital signal processing operations starting quadrature detector and filtering to recover the I and Q timing signals. Next, carrier frequency estimation, clock frequency, and clock phase estimation are carried out to recover carrier frequency and symbol clock. Finally, baseband filtering (RRC matched filtering), adaptive equalization, and symbols detection have been performed for bit recovery. Moreover, two polarization controllers (PC1 and PC2) are engaged at the output of IQM and at the optical carrier input of MZM to facilitate coherency optimization of the dual-modes carrying the DS and US MMW beat-tones, respectively.

Finally, the QD-DML consists of a bare QD-LD bar as depicted in Fig. 3, whose as-cleaved single facet output power is coupled into an in-house made lensed SMF. This Fabry-Perot device is probed with a continuous wave current of 150 mA (\(\sim 1.3I_{th}\) where \(I_{th}=115\) mA is the threshold current) using a laser diode probing system (Keithley2520). Next, self-injection locking of a single longitudinal mode at $\lambda_1$ is achieved by selectively re-injecting that particular wavelength free-running mode power back into the QD-LD active region while controlling its polarization for optimum locking efficiency. Lastly, QD-DML is realized by generating an adjacent copy of this SIL mode, exhibiting identical characteristics but at wavelength $\lambda_2$. We accomplished this task via phase modulating the single SIL mode at $\lambda_1$ with an RF signal, whose frequency is dictated by the FSR, and selective optical filtering. However, as discussed earlier in section IIA, the QD-DML may be replaced by a mid-L-band single section passively mode-locked QD-LD in the future should this device observe mode-locking.

3. Results and discussion

This section presents a rigorous analysis of the proposed bidirectional MMWoF and MMWoF-WL systems employing QD-MMS. For the optical characterization, OSA has been deployed at various locations (see Fig. 4) to obtain the emission spectrums. On the other hand, for $S_{\Phi}$ characterization of the generated and unmodulated US and DS MMW carriers, the Electrical Spectrum Analyzer (ESA, Keysight N9010B) is engaged after PD1 and PD2, respectively, by removing the 10 km SMF and making WL link distance 0 m.

3.1. Optical and electrical characterization of the system

Figure 4 summarizes the optical characterization of the bidirectional MMWoF-WL system. As shown in the system configuration of Fig. 2, location (i) corresponds to the spectrally pure and coherent dual-wavelength QD-DML emission before CP1, while (ii) and (iii) depict the emission
spectrum of DS and US filtered wavelength mode. Besides, inset (iv) of Fig. 4 shows the DS SSB QPSK modulated optical carrier $\lambda_2$ that experiences $\sim 14$ dB insertion loss of the IQM modulator. The output of CP2 combines both optical carriers (i.e., DS modulated $\lambda_2$ and US unmodulated $\lambda_1$), thus realizing a photonic DS MMW carrier signal (at location (v) of Fig. 2). A peak optical power variation of $\sim 15$ dB is apparent when comparing both optical carriers. Hence, we utilized AT1 to control this peak power difference and PC1 to optimize both modes’ coherency to improve the generated 28 GHz MMW carrier quality. Later, this MMW beat-tone is passed through a 10 km SMF whose attenuation reduced the signal power by $\sim 4.0$ dB, as reflected by comparing emission spectrums at location (v) a and b in Fig. 4. Location (vi) depicts the optical spectrum of the US modulated 25 GHz MMW carrier before (a) and after (b) DSB intensity modulation in MZM. Visible side modes and their harmonic on either side of the US optical carrier $\lambda_1$ are evident in Fig. 4. It is worth mentioning here that both optical carriers ($\lambda_1$ of DS and $\lambda_2$ of US) are available at the MZM input and undergo intensity modulation with the US 25 GHz modulated carrier, pictorially depicted in the inset (vi) of Fig. 4. However, $\lambda_2$ optical carrier eventually dominates since its optical peak power is maintained $\sim 15$ dB higher than $\lambda_1$, thus exhibiting better optical-electrical conversion at the CO. It is worth mentioning that a TF could be engaged before the MZM and PC2 to filter only the required $\lambda_1$ mode; however, this step is not performed here due to this optical equipment’s unavailability. Finally, both the unmodulated and modulated (inset) MMW carriers’ electrical signal for DS and US, obtained after PD1 (location (vii)) and PD2 (the location (viii)), exhibiting frequencies of 28 GHz and 25 GHz, respectively, are displayed in Fig. 4. Moreover, high-resolution RF $S_\Phi$ characterization for 28 GHz DS MMW carrier demonstrated a value of $\sim -80$ dBc/Hz at 1 kHz offset frequency while 25 GHz US carrier showed $\sim -89$ dBc/Hz as depicted in Fig. 5, suggesting inferior phase correlation between the optical tones of the DS MMW carrier compared to the US counterpart. This is attributed to the group velocity difference between $\lambda_1$ and $\lambda_2$ propagating in the upper and lower arms of different fiber lengths of the DS Tx unit. This could be minimized by integrating a mid-L-band operating delay line in one of the DS Tx system arms but unfortunately could not be employed in this work due to this passive component’s unavailability.

Fig. 5. RF $S_\Phi$ characterization of (a) DS 28 GHz and (b) US 25 GHz MMW carriers as a function of offset frequency.

3.2. Performance of the MMWoF bidirectional system

In the MMWoF system, the DS and US antennas of Fig. 2 are replaced by a wired electrical connection. The results of simultaneous QPSK transmission, at different data rates, over 28 GHz DS and 25 GHz US carriers are summarized in Fig. 6(a) and (b), respectively. In each case, the calculated bit-error-rate (BER) is plotted as a function of received optical power at the 70 GHz PD. However, for successful error-free transmission, the maximum limit for forward-error correction (FEC) of BER is considered to be $3.8 \times 10^{-3}$ for the QPSK modulation scheme, which further corresponds to 37% error-vector-magnitude (EVM). Moreover, in each case, the BER values are calculated from the measured root mean square error vector magnitude (EVM) values,
according to [27], and plotted as a function of received optical power. As noted from Fig. 6(a), the 2 Gbaud (4 Gbits/s) QPSK DS transmission signal exhibited a receiver sensitivity of $-6.0$ dBm that overlaps with the back-to-back (BtB) case without fiber (i.e., CS is directly connected to RAU). Hence, a negligible sensitivity penalty is induced by the 10 km SMF at the FEC threshold. In fact, we noted the same observation even at higher QPSK data rates. However, as the QPSK data rate is increased while simultaneously transmitting identical data rate US signal, to 3 (4) Gbaud corresponding to 6 (8) Gbits/s, a power penalty of $\sim 1.0$ (2.5) dB is observed when compared to 2 Gbaud case, thus degrading the receiver sensitivity to $-5.0$ dBm and $-3.5$ dBm, respectively, at the FEC threshold. We attribute this observation to the possible increase in the system noise due to larger bandwidth operation of various components and equipment (AWG, DSO, EA, etc.) owing to increased QPSK data rate, which apparently requires higher optical received power to attain the required electrical signal to noise ratio (ESNR) at FEC threshold. As for the constellations, insets of Fig. 6(a) depict clearly separated clusters of received QPSK signal captured at BER $\approx 10^{-4}$ at the received optical powers of $-4.0$ (−2.0) dBm for the 2(4) Gbaud case.

![Fig. 6. BER versus the received optical power of (a) DS and (b) US QPSK data signals, at different data rates and 10 km SMF channel, for the bidirectional MMWoF convergence system. The results of back-to-back (BtB) case are also shown in (a) for comparison purpose. The top insets of (a) and (b) are the constellations of 2 Gbaud QPSK signal at received optical power of $-4.0$ and $-7.0$ dBm, respectively, while the bottom insets are the constellations of 4 Gbaud and 3 Gbaud QPSK signal at received optical power of $-2.0$ and $-4.0$ dBm, respectively. All QPSK constellations corresponds to BER $\approx 10^{-4}$.](image)

Similar to Fig. 6(a), the calculated BER of 1, 2, and 3 Gbaud US QPSK signal at 25 GHz carrier frequency over 10 km SMF is shown in Fig. 6(b), while simultaneously transmitting identical data rate DS signal at the same time. As noted, the BER increases as the signal data rates get higher for the same received power. In other words, to reach the same BER $\approx 10^{-4}$, 2, and 3 Gbaud QPSK signal requires $-7.0$ and $-4.0$ dBm received optical power, respectively, as depicted by the constellations shown in the insets of Fig. 6(b). This is consistent with the DS transmission case observation, as illustrated in Fig. 6(a). Nevertheless, the receiver sensitivity for error-free transmission at the FEC threshold is noted to be $-10$ dBm, $-8.0$ dBm, and $-6.0$ dBm for 1.0 Gbaud (2 Gbits/s), 2 Gbaud (4 Gbits/s), and 3 Gbaud (6 Gbits/s) QPSK data rates, respectively.

Moreover, US signals’ performance is found to be better than DS signals, with exhibited receiver sensitivity difference of 2.0 (1.0) dB for the 2 (3) Gbaud QPSK signals. This could be possibly due to the optical power difference between the photonic DS and US MMW beat-tones before fiber delivery, as inferred from Figs. 4(v) a and (vi) b curves. However, we attribute this disparity primarily to the noted higher $S\Phi$ of the 28 GHz DS MMW beat-tone than the US counterpart, which is due to group velocity induced time delay between the two optical carriers $\lambda_1$ and $\lambda_2$ propagating in fiber arms of different lengths between CP1 and CP2 (see Fig. 2) during DS 28 GHz MMW beat-tone. We qualitatively explain this phenomenon by considering the
following simplified time-domain equations at the output of PD1 and PD2, respectively [28]:

\[ I_{DS}(t) = 2E_1E_2 \cos(2\pi(f_2 - f_1)t + \phi_2(t) - \phi_1(t - \tau_2)) \]  

(1)

\[ I_{US}(t) = 2E_1E_S \cos(2\pi(f_1 - f_2)t + \phi_1(t) - \phi_S(t - \tau_d)) \]  

(2)

where \( I(t) \) is the photo detected current at the PD output, \( E_1 \) and \( E_2 \) are the optical field amplitudes of optical carriers \( \lambda_1 \) and \( \lambda_2 \), exhibiting frequencies \( f_1 \) and \( f_2 \), and phases \( \phi_1 \) and \( \phi_2 \), respectively, and \( E_S \) correspond to the optical filed amplitude of the sideband with wavelength \( \lambda_S \), frequency \( f_S \), and phase \( \phi_S \), which is a result of DSB modulation of \( \lambda_1 \) with the US signal. Moreover, \( \tau_d \) is the time delay between \( \lambda_1 \) and \( \lambda_2 \) optical carriers induced by the SMF chromatic dispersion, and \( \tau_d \) is the delay introduced by the optical path length difference between \( \lambda_1 \) and \( \lambda_2 \) optical carriers arm between CP1 and CP2 during DS 28 GHz MMW beat-tone generation. However, as noted from Fig. 6, comparing the BtB and 10 km SMF transmission cases for the 2 Gbaud, the contribution of \( \tau_d \) is negligible in this work. Hence, the leading source for the chromatic dispersion induced phase decorrelation between \( \lambda_1 \) and \( \lambda_2 \) optical carriers in the DS transmission is \( \tau_d \), i.e., \( \phi_1(t) - \phi_2(t - \tau_d) = \phi_1(t) - \phi_2(t - \tau_d) \), thus contributing to high \( S_\phi \) during the heterodyning process and degrading the ESNR. On the other hand, for the US 25 GHz MMW beat-tone counterpart, \( \phi_1(t) - \phi_S(t - \tau_d) = \phi_1(t) - \phi_S(t) = \) constant, and hence \( \lambda_1 \) and \( \lambda_S \) optical tones are relatively phase correlated, thus exhibiting relatively less impairment to the ESNR. Lastly, noise contributions from the relative intensity noise (RIN) of optical carriers cannot be ignored since RIN does affect the noise level of the heterodyned MMW carrier signal [29]. Nevertheless, a difference of 1.0-2.0 dBm in DS and US transmission receiver sensitivity suggests that the QD-DML performance is still satisfactory in dispersive transmission channels in the absence of delay-line.

### 3.3. Performance of the MMWoF-WL bidirectional system

Next, the MMWoF-WL bidirectional convergence system, proposed in Fig. 2, is analyzed by simultaneously transmitting DS and US signals. The calculated BER as a function of received optical power at the DS PD1 and US PD2 is presented in Fig. 7(a) and (b), respectively, after 10 km SMF and 2 m WL delivery. Considering the 28 GHz DS transmission, 2 Gbaud, 3 Gbaud, and 4 Gbaud QPSK data rates showed receiver sensitivity of \(-6.5 \text{ dBm}, -5.5 \text{ dBm}, \) and \(-4.5 \text{ dBm}, \) respectively, exhibiting a power penalty \(-1.0 \text{ dB} \) between them, similar to the observation in MMWoF system, and ascribed to components and equipment related noise enhancements at elevated QPSK data rates. However, these data rates displayed a 0.5-1.0 dB receiver sensitivity improvement in the present MMWoF-WL convergence system despite an additional 2 m WL link compared to the MMWoF system counterpart. Thanks to the further optimization of SIL of the QD-DML optical modes in the present case, that assisted in increasing the photonic DS and US MMW beat-tones optical power, before fiber transmission, by \(-2.0 \text{ dB}, \) thus improving the OSNR and consequently ESNR at the receiver.

A similar performance is noted for the 25 GHz US transmission of the MMWoF-WL system, summarized in Fig. 7(b) at 10 km SMF and 2 m WL delivery. Moreover, 10 km SMF -0 m WL length and BtB configurations for the 1 Gbaud data rate are also shown for comparison purpose. The system exhibited receiver sensitivity of \(-13 \text{ dBm}, -9.5 \text{ dBm}, \) and \(-8.0 \text{ dBm} \) for the case of 1 Gbaud (0 m WL), 2 Gbaud (2 m WL), and 3 Gbaud (2 m WL), respectively. A large power penalty of 3.5 dBm is apparent between the first two data rates ascribed chiefly to the WL channel’s absence in the 1 Gbaud case. On the other hand, the higher two data rates displayed a power penalty of \(-1.5 \text{ dB} \) under identical channel conditions, analogous with the values noted in the MMWoF system and discussed above. Besides, Fig. 7(b) also shows that the higher two data rates of US 25 GHz MMW beat-tone transmission performed better than the MMWoF system counterpart and are consistent with the DS case observation, which is due to optimized SIL of QD-DML optical tones. In this case, an improvement in receiver sensitivity by 1.0-1.5 dB
Fig. 7. BER versus the received optical power of (a) DS and (b) US QPSK data signals, at different data rates and 10 km SMF-2 m WL link length, for the bidirectional MMWoF-WL convergence system. The results of 0 m WL and BiB for the case of US signal are also shown in (b). The top insets of (a) and (b) are the constellations of 2 Gbaud QPSK signal at received optical power of −4.0 and −8.0 dBm, respectively. while the bottom insets are the constellations of 4 Gbaud and 3 Gbaud QPSK signal at received optical power of −1.0 and −6.0 dBm, respectively. All QPSK constellations correspond to BER ≈ 10\(^{-4}\).

Despite the WL delivery link is noted. Thanks to the larger photocurrent generation in the PD due to higher optical power, exhibiting larger ESNR at the receiver. Nevertheless, the QPSK constellation at BER ≈ 10\(^{-4}\), for both DS 2(4) Gbaud and US 2(3) Gbaud data rates, exhibit clear separation of clusters, showing successful reception of the data signals.

Next, the effect of WL link length on MMWoF-WL bidirectional system performance is investigated, and the results are illustrated in Fig. 8. At 2 Gbaud QPSK DS transmission at various WL lengths, shown in Fig. 8(a), a receiver sensitivity penalty of ~1.1 dB/m is noted, where 0 m, 2 m, and 4 m lengths displayed the FEC threshold optical received power of −8.7, −6.5 and −4.3 dBm, respectively. On the other hand, increasing the WL to 4 m and the data rate to 4 Gbaud (8 Gbits/s), a receiver sensitivity of −2.0 dBm is noted. Besides, comparing this FEC threshold with 2 m (Fig. 7(a)) WL lengths, a similar penalty of ~1.1 dB/m is deduced. In general, this degradation in receiver sensitivity with increasing WL link length is attributed to the combined effect of free-space path loss and possible improper misalignment of horn antennas.

For the case of US transmission, as observed in Fig. 8(b), a similar performance is noted with 2 Gbaud and 3 Gbaud signals exhibiting a receiver penalty of ~1.2 dB/m. In this case, the lower data rate displayed FEC threshold receiver sensitivity of ~12 dBm, −9.5 dBm, and −7.6 dBm for 0 m, 2 m, and 4 m WL delivery lengths, respectively. On the other front, the exhibited receiver sensitivity of 3 Gbaud cases is −8.0 dBm and −5.5 dBm corresponding to 2 m and 4 m WL lengths. Therefore, increasing the data rate and WL length degrades the BER performance because of their mutual effect of decreasing the OSNR and hence ESNR. The top insets of Fig. 8(a) and (b) shows the constellations of the received 2 Gbaud QPSK signal at identical received power for the 0 m and 4 m WL length MMWoF-WL bidirectional convergence system. An apparent effect of free-space path loss and possible channel fading due to increasing WL link is noticeable from DS and US transmissions. Moreover, comparing various DS data rates QPSK constellations at similar BER=10\(^{-3}\) from the insets of Fig. 8(a) shows similar clustering and reveals the impact of phase noise, thus further supporting the inferior performance of the DS system compared to the US counterpart.

Subsequently, we have investigated the effect of WL link length on MMWoF-WL bidirectional system performance by considering the 16-QAM signal format, and the results are illustrated in Fig. 9(a) and (b). A successful US 25 GHz MMW beat-tone transmission at 1 Gbaud (4 Gbits/s) is achieved, as shown in Fig. 9(a). The corresponding measured optical received power at FEC threshold for data rate at 0 m, 2 m, and 4 m lengths are −7.9, −5.9, and −3.9 dBm, respectively, thereby translating to a penalty of ~1.0 dB/m and similar to the case of QPSK transmission.
Fig. 8. BER versus the received optical power of (a) DS and (b) US QPSK data signals, at different data rates and 10 km SMF - 4 m WL link lengths, for the bidirectional MMWoF-WL convergence system. The results of 0 m and 2 m WL lengths for both, DS and US cases, are also shown in respective plots. The top insets are the constellations of 2 Gbaud QPSK signal at 0 m and 4 m WL link lengths, while the bottom insets are the constellations of 3 Gbaud and 4 Gbaud QPSK signal at 4 m for DS and for 3 Gbaud US 2 m and 4 m WL link lengths, at aforementioned received optical powers.

Moreover, doubling the data rate to 2 Gbaud (8 Gbits/s) displayed a power penalty of $\sim 3.0 \text{ dB}$, as noted from Fig. 9(a), at a fixed 2 m WL link length. Again, this is a direct effect of higher modulation schemes and data rates sensitivity to the system noise, which requires stringent phase noise requirements and higher OSNR and, consequently, higher ENSR to achieved the FEC threshold for successful transmission. This is also shown by the 16-QAM constellations shown in Fig. 9(b) across different WL lengths, as well as optical received powers is evident. Moreover, this could also be inferred from Fig. 9(a), which plots the DS 28 GHz MMW beat-tone transmission of 16-QAM signal over 2 m WL link length. A BER of $7.0 \times 10^{-3}$ is achieved for 1 Gbaud (4 Gbits/s) data rate due to higher phase noise in the DS transmission system. Nevertheless, the performance could be significantly increased by engaging the delay line in the MMWoF-WL system, as discussed above.

Lastly, the relevant literature has been organized in Table 1 along with the present work. From the table, it can be observed that the data rate reported in this work is reasonable compared with the other research optical sources reported in the literature for the unidirectional MMW transmission, besides demonstration bidirectional MMW transmission. Next, comparing the data rate and channel with the commercial optical sources with that of the present work, the former source demonstrated higher data rates and channel distances in general. This is expected since the present study deployed a new class of QD-DML optical source, which is an unoptimized device operating in the challenging L-band. Moreover, the inferior performance of several optical components and equipment at $\sim 1610 \text{ nm}$, restricted the system power budget, which in turn not only affected the sub-link lengths of fiber, fiber-WL but also restricted higher data rates for DS as well as the US.

Nonetheless, with all these constraints, demonstrating simultaneous transmission of 8 Gbits/s data rate serves as a proof of concept for expounding the potential of QD-DML as an alternative
Table 1. Reported MMWoF and MMWoF-WL transmission employing various optical sources.\(^a\)

| Ref. | Source | Type | Mode | Freq. Channel | Data Rate | Modulation Format | Technical Remarks |
|------|--------|------|------|---------------|-----------|-------------------|-------------------|
| [8]  | DFB LD | C    | B    | 28 G          | 25 km DS SMF+600 m FSO+4 m WL | 10 G DS 16-QAM OFDM | EIL and VCSEL based wavelength selector in C-band |
| [10] | FP LD  | R    | U    | 28 G          | 25 km SMF+1.6 m WL | 16 G 16-QAM OFDM | EIL and simultaneous optical BB bidirectional transmission in C-band |
| [11] | ECL    | C    | B    | 73 G          | 40 km DS SMF+2 m WL | 10 G 16-QAM OFDM | Full-duplex in C-band |
| [12] | ECL    | C    | B    | 81 G          | 36 km DS SMF+2 m WL | 16 G 16-QAM OFDM | Separate DS and US SMFs in C-band |
| [13] | FP LD  | R    | U    | 60 G          | 25 km DS SMF | 12.5 G 16-QAM | Comb generation using gain-switched FP LD and EIL by ECL in C-band |
| [14] | FP LD  | R    | B    | 61 G          | 12 km DS SMF | 0.89 G 64-QAM OFDM | C-band gain-switched FP LD and EIL with remote US down conversion and DS wavelength reuse |
| [15] | BLS    | C    | U    | 100 G         | 40 km DS SMF+10 m WL | 25 G OOK | MZM optoelectronic oscillator based BLS with the optical bidirectional transmission in C-band |
| [16] | TL     | C    | B    | 18 G          | 1 km DS SMF | 0.2 G 16-QAM | Centralized light source in full-duplex and wavelength reuse in C-band |
| [17] | FP LD  | C    | U    | 60 G          | 40 km DS SMF+3 m WL | 10 G 16-QAM | EIL by DFB LD with the optical bidirectional transmission in C-band |
| [19] | TL     | C    | U    | 60 G          | 23 km DS SMF | 1.25 G OOK | Simultaneous MMW and bidirectional optical transmission in C-band |
| [21] | QD-LD  | R    | U    | 146 G         | 2.5 cm DS SMF | 1 G OOK | Dual QD DFB LDs in C-band |
| [22] | QD-LD  | R    | U    | 46 G          | < 10 m DS SMF | 2 G PAM-4 | Dual QD DFB LDs in C-band |
| [23] | QD-LD  | R    | U    | 80 G          | 50 km DS SMF+20 m WL | 10 G OFDM | SIL based QD BLS in C-band |
| [24] | QD-MLL | R    | U    | 25 G          | 25.2 km DS SMF+2 m WL | 16 G 16-QAM | Passive QD-LD MLL in C-band |
| [25] | QD-LD  | R    | U    | 28 G          | 20 km DS SMF+6 m WL | 2 G QPSK | Dual-mode QD-LD with SIL in L-band |
| [29] | QD-MLL | R    | U    | 60 G          | 25 cm DS SMF | 1.58 G QPSK | Passive QD-LD MLL in C-band |
| This work | QD-LD | R    | B    | 28 G          | 10 km DS SMF+4 m WL | 25 cm 8 G 16-QAM | Centralized dual-mode QD-LD with SIL and wavelength reuse in mid L-band |

\(^a\)B: Bidirectional, U: Unidirectional, C: Commercial, R: Research, VCSEL: Vertical Cavity Surface Emitting Laser, MLL: Mode Locked Laser, BLS: Broadband Light Source, Freq. in Hz and Data Rate in bits/s
Fig. 9. (a) BER versus the received optical power of DS and US 16-QAM data signals, at different data rates and 10 km SMF 0 - 4 m WL link lengths, for the bidirectional MMWoF-WL convergence system. (b) QAM constellations shown for 1 Gbaud and 2 Gbaud at aforementioned received optical powers and WL link lengths.

single centralized source which can significantly reduce capital and operating expenditure without trading off data rate, for 5G and beyond RoF MMW applications. Utilization of an optimized passively mode-locked QD-LD similar to [24] can result in a simple, efficient, and cost-effective MMWoF and MMWoF-WL simultaneous bidirectional convergence system in both C and L-band wavelength region, which would be a step towards energy-efficient next-generation flexible heterogeneous optical networks by reducing carbon footprint.

4. Conclusion

In conclusion, we have proposed a single InAs/InP QD-DML optical source-based MMWoF and MMWoF-WL bidirectional convergence system and demonstrated in the demanding 1610 nm L-band rather than standard C-band wavelength window, thus supporting the proposal of expanding the wavelength operation in next-generation optical networks. The 28 GHz FSR dual modes of the QD-DML are exploited to demonstrate DS transmission while using wavelength reuse to achieve US 25 GHz transmission over 10 km SMF – 4 m WL MMWoF-WL convergence system. Successful 4 Gbaud (8 Gbits/s) DS QPSK transmission and 2 Gbaud (8 Gbits/s) US 16-QAM transmission is achieved simultaneously on this hybrid system, thus reinforcing this single cost-effective optical source-based system solution and potentially extendable to MMWoF-WDM network infrastructures. The corresponding exhibited receiver sensitivities are −2.0 and −4.0 dBm for 4 m WL link distance. In general, the $S_{\phi}$ characterization of these MMW beat-tones highlights a higher quality US 25 GHz carrier than DS 28 GHz counterpart, which is also reflected from the transmission experiments.

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