Quantum-Dash Laser-Based Tunable 50/75 GHz mmW Transport System for Future L-Band Networks

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***Abstract*— Tunable 50/75 GHz millimeter wave (mmW) transmission system has been demonstrated employing self-injection locked quantum-dash laser diode comb source (SIL QDCS) in the challenging 1610 nm region. The generated 50/75 GHz mmW beat-tones exhibited low phase noise of −64 dB/Hz at 1 kHz offset and narrow radio-frequency (RF) linewidths of ∼1 kHz at the transmitter end. A 4 GBd (8 Gb/s) quadrature phase-shift keying (QPSK) data stream is successfully transmitted over both mmW carriers and across various channels *viz.* 2 m wireless (WL) link, 11.6 km single-mode-fiber (SMF) – 2 m WL link, and 11.6 km SMF – 6 m free-space-optics (FSO) – 2 m WL link, thus affirming the potential of quantum-dash laser diode (QDLD) in high-frequency mmW applications. This work is a potential step towards realizing next-generation high-frequency tunable mmW optical-RF convergent hybrid networks operation in L-band, and one such possible proposal with a single QDCS is presented.**

***Index Terms*— Quantum-dash laser, self-injection locking, comb source, millimeter wave transmission, L-band.**

I. Introduction

THE rising demand in connecting high-definition video and audio applications, internet-of-everything, bid-data, and cloud-based services, are resulting in massive data volume being transported across networks. This trend affects all segments of existing network technologies, mainly first/last mile access networks, with challenges related to high data rates, low latency, energy efficiency, reliability, flexibility, connectivity, etc. Hence, optical systems and networks demand substantial advancements in this regard, and with this viewpoint, next-generation access networks (NGANs) have been set forth to achieve these goals [1]–[3]. Moreover, hybrid access networks with radio frequency (RF) and optical convergence, in the form of radio-over-fiber (RoF) and radio-over-FSO (RoFSO) with wireless (WL), have been identified as a promising front-end solution for 5G and beyond networks, while exploiting the unexplored mmWs frequency bands thus meeting NGANs requirements [2]–[5]. Specifically, millimeter waves (mmWs) from 50 GHz onwards, covering E- to D-bands (∼70-180 GHz), have garnered recent attention, thanks to their generally unregulated frequency spectrums across the globe, which have been planned to engage in network densification [6], [7].

Evolution in optical sources, quantum confined nanostructure-based semiconductor laser diodes, in particular, have played a crucial role in advancing hybrid optical-RF convergence access networks. Thanks to the self-heterodyning technique for geinerating quality high-frequency mmW signals, which is challenging via electronic means. Notably, the recent penetration of the new-class of InAs/InP quantum-dash (QD) laser diode (LD) (QDLD) in RoF–RoFSO–WL convergence domain concentrating on the new-wave of mmW communication is garnering attention [2]–[4]. The rule-changing tunable ultra-broadband lasing emission from these QDLDs, covering C to U (∼1550-1650 nm) wavelength bands, and demonstrating inherent mode-locking characteristics at 1550 nm, has taken center stage in the last few years [7]–[11]. Furthermore, integrating 1610 nm QDLDs with optical injection locking, since intrinsic mode-locking has not been observed yet on L-band LDs, both wavelength LDs have shown substantial advancements in optical as well as mmW RF-optical convergent networks, thus corroborating them as a promising candidate optical source for NGANs.

In recent years, extensive works on 60 GHz mmWs, to exploit this un-regulated frequency band and <50 GHz mmW region have been reported on InAs/InP QDLD based transmission systems [2], [4]. Moreover, there has been an apparent paradigm shift to deploy this optical source in high-frequency mmW applications, particularly in the challenging L-band region. This stems from the fact that extendable wavelength operations covering L-bands are under consideration for NGANs. Therefore, investigation of QDLDs in the 1600-1625 nm region is paramount for further asserting this promising source in NGANs, thereby possibly contributing towards a smooth transition into extended wavelength operations.

As summarized in Table. I, in literature, most of the current developments in high ≥50 GHz frequency mmW generation and transmission have been demonstrated on C-band mode-locked QDLD. mmW beat-tones in the range of 50-100 GHz have been generated and transmitted over 10s of km of SMF, including FSO and with/without WL sub-links employing multi-wavelength Fabry-Perot (FP) LDs [3,4,7-12]. Data rates in the range of 1-10 Gb/s with high order quadrature amplitude (QAM) modulation scheme in tandem with orthogonal frequency division multiplexing (OFDM) have been reported. For instance, 1.12 Gb/s 64-QAM-OFDM signal over 25 km SMF have been successfully demonstrated [3].

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TABLE I
ADVANCEMENTS IN InAs/InP QDLD BASED HIGH FREQUENCY (≥50 GHz) mmW GENERATION AND TRANSMISSION

QDLD Source	λ [nm]	mmW Beat Frequency	Δf [kHz]	Modulation Scheme	Channel Link	Data Rate [Gb/s]	Ref.
MLL	1550	60 GHz	18	OOK	25 m **WL***	5	[8]
SIL+MLL	1550	80 GHz	–	16QAM-OFDM	25 km SMF-20 m **WL***	10	[9]
SIL+MLL	1550	100 GHz	16	OOK	50 km SMF-10 m **WL***	10	[10]
DFB	1550	146 GHz	700	OOK	2.5 cm BtB **WL***	1	[7]
SIL	**1610#**	50/75 GHz	1	QPSK	11.6 km SMF-6 m FSO-2 m **WL***	8	This Work
SIL+MLL	1550	50 GHz	16	OOK	50 km SMF	10	[10]
MLL	1550	60 GHz	10	QPSK-OFDM	50 m SMF BtB	3	[11]
SIL+MLL	1550	60 GHz	50	64QAM-OFDM	25 km SMF	1.12	[3]
SIL+EIL	1550	60 GHz	–	32QAM-OFDM	50 km SMF-100 m FSO	6.5	[12]

*Channels with WL sub-links, #Mid L-band operation, λ: Wavelength operation, *Δf* : RF 3-dB linewidth

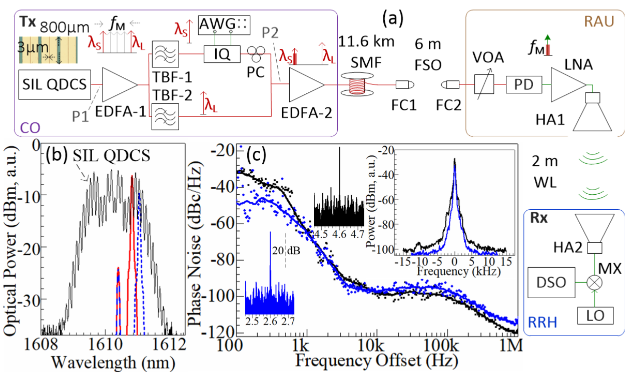

Fig. 1. (a) The experimental block diagram of the SIL QDCS source-based 50/75 GHz mmW transport system with insets depicting the schematic spectrums at selected locations. (b) Emission spectrum of SIL QDCS at location P1 and the filtered 50 (red) 75 (blue) GHz mmW beat tones at location P2. (c) 50 (black) and 75(blue) GHz mmW signals measured phase noise. Insets in (c) show the RF linewidths of 50 and 75 GHz mmW signals and respective coarse electrical spectrum at IFs in GHz.

Noticeably, a 146 GHz mmW generation and 1 Gb/s on-off keying (OOK) transmission over 2.5 cm WL link has also been demonstrated but on monolithically integrated dual distributive feedback (DFB) 1550 nm QDLD [7]. Therefore, the realization of QDLD based >50 GHz mmW systems in the L-band region is scarce, thus urging more investigations.

In this letter, we aim to uphold the potential of 1610 nm further L-band InAs/InP QDLDs by (i) demonstrating the efficient generation of tunable 50/75 GHz beat-tone in 1610 nm region employing self-injection locked QDLD based comb source (SIL QDCS) exhibiting ~1.0 kHz RF linewidths and low phase noise of -64 dBc/Hz at 1 kHz offset frequency. (ii) Establishing successful transmission of 4 GBd quadrature-phase-shift keying (QPSK) data stream over tunable 50/75 GHz mmW and under various hybrid channels comprising of 11.6 km SMF-1.5-2 m WL link (H_1) and 11.6 km SMF-6 m-FSO-1.5-2 m WL link (H_2). (iii) Proposing a possibly RoF-RoFSO-WL hybrid access network employing a *single* L-band SIL QDLD-based comb source (SIL QDCS). This is the first report of 50/75 GHz mmW generation and transmission employing L-band QDLD to the author's knowledge.

II. Experimental Setup

The schematic block diagram of the tunable mmW transmission system is illustrated in Fig. 1. The SIL QDCS, generating multiple phase and frequency locked modes with 12.5 GHz spacing, is amplified by an L-band erbium-doped fiber amplifier (EDFA-1, Amonics AEDFAL-EX2-B-FA) before power splitting into two parts using a 3-dB coupler. Tunable optical bandpass filters (TBF-1, EXFO XTM-50, and TBF-2, Santec OTF-350) are utilized in each arm to select appropriate comb lines exhibiting the desired mmW frequency beat-tone. It is noteworthy to mention here that the TBFs may be replaced by a customized tunable fiber Bragg grating (FBG) to simplify the system significantly. The filtered short-wavelength mode λ_S from the upper arm is employed for externally modulating a 4 GBd QPSK drive signal in an inphase-quadrature (IQ) modulator (Fujitsu FTM7977HQA). Using an arbitrary waveform generator (AWG, Keysight M8195A), the drive signal is generated via 2^{11}-1 pseudo-random bit-sequence length under MATLAB environment [2]. The modulated optical tone is then passed through a polarization controller (PC) before re-combining with the longer wavelength λ_L unmodulated optical carrier from the lower arm by another 3-dB coupler, thus realizing the required single sideband (SSB) modulated mmW beat-tone signal. The signal is then transmitted via 11.6 km SMF after amplifying again via another L-band EDFA (EDFA-2, Amonics AEDFAL-EX2-B-FA). Furthermore, it is worth mentioning that both optical tones are phase decorrelated due to transmission along different short-length SMF between the two arms of the 3-dB coupler pair, in addition to exhibiting the different amount of power loss (*i.e.* displaying appreciable peak power difference), as shown in Fig. 1(b), thus rendering this work's transmission investigation challenging. Next, the output end of the SMF is then connected to an indoor 6 m FSO system comprised of two fiber collimators (FCs, Thorlabs F810APC-1550nm) serving as the transmitter (FC-1) and receiver (FC-2) with a 3.6 mm beam diameter. The FSO system exhibited an insertion loss of ~6 dB due to manual 2-axis alignment stages. The output from the FSO system is then passed through the variable optical attenuator (VOA, Agilent N7764A) for system analysis before reaching the high-speed 70 GHz photodiode (PD, Finisar XPDV3120R). The beating of the dual-optical carriers in the PD generates the desired mmW frequency modulated 4 GBd QPSK mmW signal in the electrical domain, which is amplified by a low-noise amplifier (LNA, QuinStar QLW-50754530) before re-transmitting wirelessly using a pair of horn antennas (HAs, QuinStar QWH-VPRR00 50-75 GHz), thus integrating the SMF-FSO with the RF system. This optical-to-electrical conversion is performed at the network's remote access unit (RAU).

The receiver end of Fig. 1 is typically the remote-radio-head (RRH) of the network, which receives the modulated mmW signal from the HA2 and is then downconverted to an intermediate frequency (IF) by passing through a mixer (MX, WR15SHM), which is provided by an appropriate local oscillator (LO) RF signal. The downconverted IF signal is then received by a digital storage oscilloscope (DSO, Keysight DSOX 932048) that performs the demodulation and post-signal processing to recover the modulating signal. For optical and electrical characterization, an electrical signal analyzer (ESA, Keysight N9010B) and optical spectrum analyzer (OSA, Agilent 86142B with 60 pm resolution) are employed at appropriate places in Fig. 1 to measure the RF linewidth and phase noise of the generated mmW signals, and their respective beat-tone optical spectrums.

III. SIL QDCS-Based 50/75 GHz mmW Generation

The bare FP InAs/InP QDLD of dimension 3 × 800 μm^2 is utilized in this experiment, as shown in the inset of Fig. 1(a) consisting of four layers on InAs QD in InGaAlAs quantum-well with varying thickness InGaAlAs barriers [2]. The unbonded and unmounted device is SIL to improve a single locked mode's noise and optical linewidth characteristics before realizing a comb source by generating its harmonics via external phase modulating with a 12.5 GHz RF signal. The SIL QDCS exhibited >14 lines in its flat-top emission section with 10 lines exhibiting ±1.0 dB flatness and a free spectral range (FSR) of 12.5 GHz, as depicted in Fig. 1(b), measured before EDFA-1. Next, the two filtered and unmodulated modes of 50 and 75 GHz beat-tones are displayed in Fig. 1(b), taken before EDFA-2. The first optical tone at $\lambda_S = 1610.40$ nm is fixed and serves as a common optical carrier for modulation purposes. Whereas λ_L is tuned to select the desired mode spacing, thus realizing a tunable mmW frequency system. In this work, $\lambda_L = 1610.840$ (1611.057) nm is selected for $f_M = 50(75)$ GHz beat-tones. It is worth mentioning that the other way around would be more attractive in multi-frequency mmW SMF-FSO-RF convergent networks where a common unmodulated optical tone could be combined with various other modulated optical tones of SIL QDCS to serve multiple mmW frequency environments. In general, the optical tones displayed an OSNR of >30 dB. It is to be noted that a mode-locked QDLD could replace SIL QDCS once this phenomenon is observed on L-band devices as it is well established in C-band LDs. Inset of Fig. 1(c) depicts the generated 50 and 75 GHz unmodulated mmW signals in back-to-back (BtB) configuration (*i.e.,* when the output of EDFA-2 and LNA is directly connected to VOA and MX, respectively) and analyzed on ESA after frequency down-conversion with MX to the IF of 4.6 and 2.6 GHz using LO frequencies 22.7 and 38.8 GHz, respectively. Both RF linewidths measured 3-dB bandwidth of ∼1.0 kHz and similar phase noise characteristics as shown in Fig. 1(c). For instance, phase noise values of −35 (−44), −48 (−55) and −64 (−64) dBc/Hz, at 0.2, 0.5 and 1.0 kHz frequency offset are noted for 50 (75) GHz mmW signals.

IV. 50/75 GHz mmW SMF-FSO-WL Transmission

The transmission results of 50/75 GHz mmW are evaluated in terms of error-vector-magnitude (EVM) and signal-to-noise-ratio (SNR), and a successful transmission is assured with corresponding values of 37 % and 8.5 dB, respectively, thus reaching forward-error-correction (FEC) bit-error-rate (BER) criteria of 3.8 × 10^{-3} [2]–[4]. At first, the modulated 4 GBd QPSK 50 GHz mmW beat-tone carrier is transmitted in BtB configuration, and the results of measured EVM and BER are shown in Fig. 2(a), where a minimum required optical power of ∼0.5 dBm guaranteed error-free transmission. Next, the performance is evaluated on the WL channel only by removing the SMF and FSO sub-links from Fig. 1(a), and the obtained results are also plotted in Fig. 2(a). A receiver sensitivity of ∼3.0 and ∼5.3 dBm is noted for the 1 and 2 m WL distances, which is attributed to the free-space path loss of mmWs, thus displaying an average ∼2.5 dB/m channel loss with a 50 GHz mmW signal.

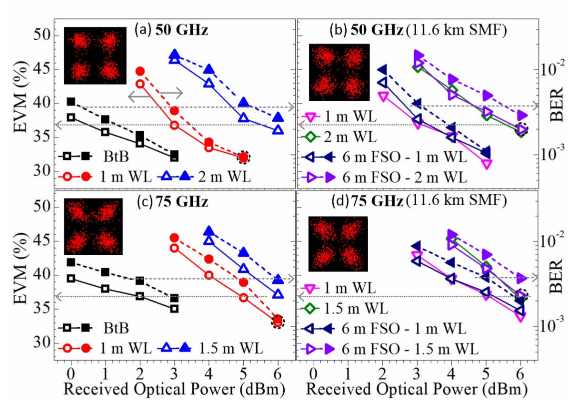

Fig. 2. Transmission results of 50 GHz [(a) and (b)] and 75 GHz [(c) and (d)] system utilizing SIL QDCS over various channel links in terms of EVM and BER versus the received optical power. (a) and (c) corresponds to WL only channel along with BtB configuration, and (b) and (d) represents hybrid channels incorporating 11.6 km SMF. Insets show the received 4 GBd QPSK constellations at the respective indicated received optical power shown by the black dashed circle. The two grey dashed lines represent the FEC limit.

Thereafter, the transmission performance is evaluated on two-hybrid channels to emulate flexible hybrid access optical-RF networks transporting information via mmWs from CO to the premises. The EVM results for both channels are summarized in Fig. 2(b), where the $H_1(H_2)$ channel exhibited receiver sensitivities of ∼3.1 (∼3.2) and ∼5.4 (∼5.6) dBm for 1 m and 2 m WL sub-links, respectively, suggesting a minor effect of adding SMF and FSO sub-links in the system. In other words, the SMF chromatic dispersion induced phase decorrelation between the two optical tones of the 50 GHz signal, and the power fading effects are negligible. Thanks to the narrow RF linewidth mmW beat-tones and deployment of SSB modulation in the system. Again, an average channel loss of ∼2.5 dB/m is noted from both hybrid systems and is in good agreement with the previous WL-only channel results.

Next, the transmission results of modulated 75 GHz beat-tone with 4 GBd QPSK data stream after downconversion, demodulation, and post-signal processing is shown in Fig 2(c) for the BtB and WL only case and over hybrid channels in Fig. 2(d). As noted here, a minimum received optical power of ∼1.7 dBm is required for successful BtB transmission, which is higher than the 50 GHz counterpart despite exhibiting similar phase noise and RF linewidth characteristics. This may be ascribed to the frequency-dependent performance of the PD and LNA, thereby decreasing their efficiency while working at extreme 75 GHz frequency. This translates to an increased optical power required to achieve error-free

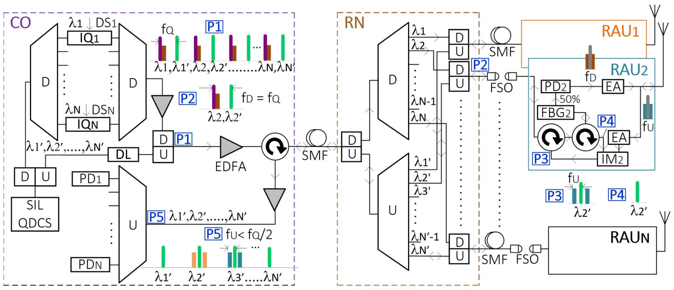

Fig. 3. Proposed RoF-RoFSO-WL hybrid network employing a single SIL QDCS with wavelength reuse feature. Inset shows the optical/electrical spectrums at various locations, with half of the SIL QDCS spectrum dedicated for DS and a half for US transmission. D/U multiplexer, D/U interleaver, DL: delay line. f_Q: FSR of SIL QDCS, f_D (f_U): DS (US) mmW carrier frequency.

transmission under the BtB case. Fig. 2(c) also shows the results of WL transmission only with the measured receiver sensitivity needed to reach the FEC limit of 37% EVM as ∼5.0 and ∼6.0 dBm for 1 m and 1.5 m WL link distances, respectively. This increase in receiver sensitivity on extending the WL distance is consistent with the 50 GHz system, and the exact reason of free-space path loss holds. An average channel loss of ∼2.7 dB/m is measured with this 75 GHz signal case.

Furthermore, the generated 75 GHz mmW beat-tone is also investigated under hybrid channels with a WL distance of 1.5 m, similar to that of the 50 GHz system, and the results are summarized in Fig. 2(d). A minimum received optical powers of ∼5 (∼5.2) and ∼6 (∼6) dBm are measured to reach the FEC limit for the 1.0 and 1.5 m WL sub-link lengths for H_1(H_2) channels, respectively. This is relatively consistent compared with the WL channel-only case, thus exhibiting a mean channel loss of ∼2.8 dB/m, slightly larger (∼0.25 dB) than the 50 GHz system. In general, the higher free-space path loss is expected from the 75 GHz high frequency mmW system compared to the 50 GHz lower frequency counterpart [4]; however, this has not been apparent in the present work due to small WL link lengths that may have obscured this observation. Nevertheless, this work demonstrated a proof-of-concept of quality generation of high-frequency mmWs employing 1610 nm QDLDs over hybrid channels, a promising versatile light source for next-generation hybrid access networks.

Lastly, a possible hybrid wavelength division multiplexed RoF-RoFSO-WL access network is proposed in Fig. 3, employing a single $f_Q = 50$ GHz (FSR) SIL QDCS. The network is based on $f_D = 50$ ($f_U < 25$) GHz mmW for downstream, DS (upstream, US) bi-directional transmission. As shown in the inset of Fig. 3, half of the comb lines serve for the US and the other half for DS purposes while exploiting the wavelength reuse feature. In other words, the US unmodulated optical carrier and the modulated DS optical carrier serve as the DS $f_D = 50$ GHz beat-tone signal, which is transmitted via SMF (or FSO or SMF-FSO) after multiplexing with other 50 GHz beat-tones DS signals. These 50 GHz beat-tones are separated at the remote node (RN) and then transmitted to the RAU via FSO/SMF/hybrid channels where optical-to-electrical conversation occurs. Moreover, a customized FBG is employed in RAU to reflect 50% of the unmodulated US optical carrier, which is then intensity-modulated (IM) with the incoming US signal over $f_U < 25$ GHz mmW carrier from RRH. This constraint on the f_U mmW carrier avoids any crosstalk between the multiplexed US and DS signals. Next, the US signal exploits the same hybrid channel to be received at the CO via a demultiplexer. It is worth mentioning here that the FSR (f_Q) of the SIL QDCS in Fig. 3 is identical to f_D; however, f_Q could be varied to obtain desired DS mmW optical tones, for instance, resembling Fig. 1(a), which are selected at RN and routed to RAU-RRH for realizing high-frequency mmW-optical transport system.

V. Conclusion

We proposed and demonstrated the feasibility of utilizing a mid-L-band QDLD in the form of 12.5 GHz FSR SIL QDCS to establish a tunable 50/75 GHz high-frequency mmW transport system. Successful transmission of 8 Gb/s QPSK data over various hybrid channels, specifically, 11.6 km SMF – 6 m FSO – 2 m WL link was demonstrated with exhibited receiver sensitivities of ∼5.5 (2 m WL) and ∼6 dBm (1.5 m WL) from 50 and 75 GHz system, respectively. In principle, any mmW frequency between 25 to 112 GHz could be realized from this 1610 nm SIL QDCS based transmission system, which could be replaced by a mode-locked QDLD counterpart in the near future, thus further affirming its potential in NGANs.

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