Deployment of 1610 nm InAs/InP Quantum-dash Laser Diode in 28–50 GHz Hybrid RoF-RoFSO-Wireless Transmission System

M. Z. M. Khan[1,2]

[1]*Optoelectronics Research Laboratory, Electrical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*

[2]*Center for Communication Systems and Sensing, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*

Keywords: Millimeter Waves, Radio-over-fiber, InAs/InP Quantum-dash Laser, L-band Optical Communication.

Abstract: In this paper, we report on our recent demonstrations on deploying mid L-band ~1610 nm quantum-dash (Qdash) laser diode (LD) in millimeter-wave (MMW) applications. 28 and 30 GHz MMW beat-tones are generated using a self-injection-locked (SIL) Qdash LD-based comb source (QDCS) with phase noise of ~-120 dBc/Hz at 1MHz offset frequency. Moreover, we demonstrated transmission of these MMWs over various channels comprising of single-mod-fiber (SMF), generally known as radio-over-fiber (RoF), free-space-optics (FSO), known as radio-over-FSO (RoFSO), and wireless (WL) links, which are attractive solutions for future flexible next-generation access networks (NGANs). In particular, we demonstrated successful transmission of 28 and 30 GHz MMW modulated with analog 2 Gb/s quadrature-phase-shift-keying (QPSK) data over hybrid 20 km SMF – 5 m FSO and 0- 6 m WL channel. Moreover, we also discussed our very recent preliminary results of 50 GHz high-frequency generation and transmission utilizing QDCS. In this case, we showed error-free transmission of 2 Gb/s QPSK data over 50 GHz carrier and 11.6 km SMF – 6 m FSO and 0-1 m WL channel. This rule-changing broad multi-wavelength lasing spectrum from Qdash LD and emission covering S- to U-band has made it a prime contender for NGANs.

1 INTRODUCTION

The unprecedented rise in the network connectivity with smart devices (internet-of-things) and increase in bandwidth-hungry services (high-definition video broadcasting, gaming, etc.) is persistently pressing the existing fiber-optic network infrastructure to explore different last/first-mile access solutions, which are the key bottlenecks in providing high data rate services to the end-users. The so-called NGANs are expected to be flexible, scalable, and possible extendable in terms of wavelength operation and reaching remote areas (Nesset, 2017, Uwaechia, 2020)

In this regard, MMW wireless technology has been identified as a promising candidate for last/first-mile access applications due to its several unregulated MMW frequency spectrum across the world. Furthermore, the MMW optical/wireless integration could also realize seamless wireless integration with the existing high-speed fiber-optic networks. This RoF is a potential technology for distributing MMW signals directly to the user end. In particular, hybrid optical/wireless network infrastructures such as RoF-WL and its integration with FSO communication, *i.e.,* RoFSO has been envisioned as promising hybrid architectures for NGANs (Ragheb, 2021, Uwaechia, 2020).

Moreover, transmitter light sources are expected to play a crucial role in future access networks since their performance, aggregate data rates in particular, relies on the performance of these semiconductor laser diodes. Besides, the proposal of extending the wavelength operation of NGANs beyond the C-band has positioned investigating high-performance laser diodes in S- and L-band regimes to sustain the future needs (Nesset, 2017). In recent years, InAs/InP Qdash nanostructure active region based semiconductor lasers have emerged as the prime contenders as light transmitters, thanks to their rule-changing broad multi-wavelength lasing spectrum and wavelength-tunable broad gain profile covering S- to U-band regions (Reithmaier, 2005). The capability of this energy-efficient optical source in the C-band, and

Khan, M.
Deployment of 1610 nm InAs/InP Quantum-dash Laser Diode in 28–50 GHz Hybrid RoF-RoFSO-Wireless Transmission System.
DOI: 10.5220/0010987400003121
In *Proceedings of the 10th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2022)*, pages 84-88
ISBN: 978-989-758-554-8; ISSN: 2184-4364

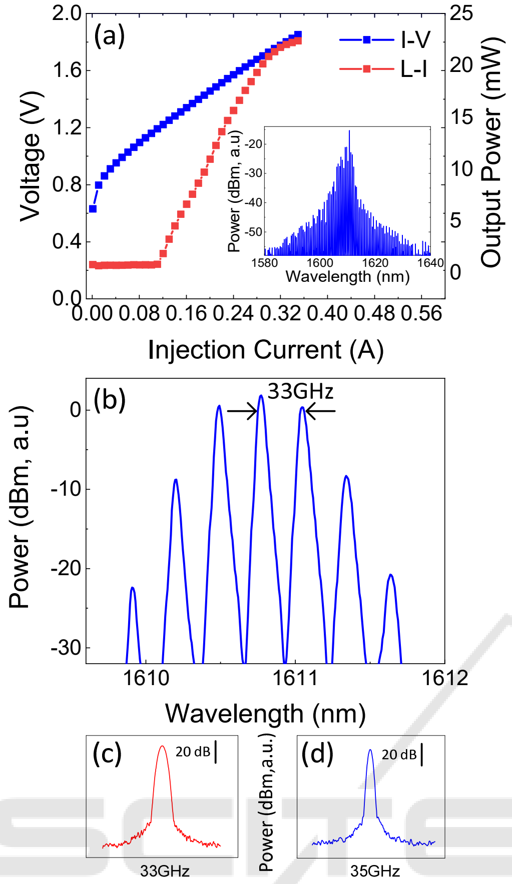

Figure 1: (a) L-I-V charactersitics of InAs/InP Qdash LD with inset showing the free-running lasing spectrum. (b) InAs/InP Qdash comb source (QDCS) with 33 GHz FSR. (c) 33 GHz and (d) 35 GHz unmodulated MMWs obtained by filtering two modes of (b) with 3and 35G Hz mode spacing, respectively.

very recently, in the L-band (1600 nm) challenging window by our group, in achieving green optical and fifth-generation (5G) wireless communication and beyond, has been underlined in literature (Delmade, 2020, Ragheb, 2021).

This paper provides an overview of our work in deploying mid L-band InAs/InP Qdash LD in MMW applications. In particular, we generated MMW beat-tones at ~1610 nm exploiting injection-locked Qdash LD-based comb source (QDCS) (Ragheb, 2021). High-quality 33 and 35 GHz MMWs exhibiting low phase noise of -120 dBc/Hz at 1 MHz offset frequency, and radio frequency (RF) linewidths in a few kHz range, have been realized. Moreover, 1.0 Gbaud (2 Gb/s) analog QPSK double-side-band (DSB) modulated signal at 5 GHz intermediate frequency (IF) has been successfully transmitted over various hybrid channels comprised of WL, RoFSO, and RoF sub-links. For instance, transmission over 28 GHz MMW carrier on hybrid 20 km SMF–6 m WL and over 30 GHz MMW on 20 km SMF – 5 m FSO–6 m WL channel demonstrated an error-free transmission with receiver sensitivities ~3.3 and ~-3.0 dBm, respectively (Ragheb, 2021). In addition, our very recent preliminary results of 50 GHz MMW beat-tone generation at ~1610 nm using QDCS displayed RF linewidth of 1.0 kHz and phase noise -64 dBc/Hz at 1.0 kHz offset. Transmission of 1 Gbaud single-sideband (SSB) modulated QPSK over 11.6 km SMF–6 m FSO–1 m WL channel with ~-2.0 dBm receiver sensitivity further affirm quality beat-tone generation and transmission of high-frequency MMWs at ≥ 50 GHz from this new-class of laser device, thus substantiating itself as a candidate light source in NGANs.

2 QUANTUM DASH LASERS

In this work, the employed InAs/InP Qdash LD operates in the mid L-band challenging window emitting at ~610 nm. The bare unbonded and unmounted chip typical L-I-V characteristics are shown in Figure 1(a), exhibiting a threshold current of ~100 mA. The emission bandwidth comprised several Fabry-Perot (FP) modes within a 3-dB bandwidth of ~8-10 nm. Unfortunately, the optical linewidth of these modes displayed value in tens of MHz, hence rendering their usage in coherent optical communication. This is unlike the C-band InAs/InP Qdash LD counterpart, where inherent passive mode-locking has enabled phase locking of all FP modes with a significant reduction in linewidths, in few tens to hundreds of kHz (Delmade, 2020, Rahim, 2019). Unfortunately, mode-locking in L-band Qdash LD has not been observed yet due possibly to the unoptimized device design and growth process. Hence, we deployed the optical injection locking technique, particularly self-injection locking (SIL), to realize a single-mode emission spectrum from the Qdash LD with high spectral purity, exhibiting optical linewidth ~45 kHz (Ragheb, 2021). Hence, to demonstrate the possibility of employing Qdash LD in MMW applications, we generated a comb using the single locked mode by generating its harmonics by phase modulating it with an RF source frequency equal to the FSR of the comb source. In our initial work, we utilized 33 and 35 GHz RF sources to realize Qdash LD-based comb source (QDCS), whose spectrum is shown in Figure 1(b), exhibiting seven comb lines (Ragheb, 2021). Two modes are filtered using an optical tunable bandpass filter (OBPF), thus realizing a MMW beat-tone of desired frequency (33 or 35 GHz). Figures 1(c) and (d) show the electrical spectrum of the unmodulated MMW carriers after beating the two tones in a high-speed photodiode. Both carriers exhibited low phase noise (not shown here) of -120 dBc/Hz at 1 MHz offset frequency and RF linewidths in a few kHz range (Ragheb, 2021).

In our very recent preliminary work, we successfully generated a 50 GHz beat-tone via a 12.5 GHz FSR comb source where we selected the central mode and the fourth mode along with a longer wavelength, thus exhibiting a mode spacing of 50 GHz. It is worth mentioning that a low-frequency RF source would be sufficient to generate high frequency and good quality MMW carriers with this technique. Moreover, it is to be noted that once mode-locking in mid L-band Qdash LD is observed, then appropriate mode-locked FP modes from the multi-wavelength spectrum could be extracted to generate MMW beat-tone, as has been the typical case in C-band Qdash mode-locked lasers (MLLs). In this case, the LD cavity length would dictate the mode spacing of the locked emission spectrum or the FSR and essentially controls the generated MMW carrier frequency, which could be multiples of FSR. Furthermore, Qdash MLL could also serve as energy-efficient light sources since a single device could provide several sub-carriers for MMW-WDM systems.

3 28 GHZ MMW TRANSMISSION

For the MMW transmission, the extracted dual-modes of the QDCS, which is essentially the desired MMW beat-tones (33/35 GHz), are then intensity-modulated (with DSB modulation) via a Mach Zehnder modulator (MZM). The modulating signal was 2 Gb/s analog QPSK over an IF 5.0 GHz. Hence, the output of the modulator includes the two optical carriers, each exhibiting DSB modulating signal and 5.0 GHz apart from the carrier. Thus, the desired 28/30 GHz MMW carrier was achieved by beating one of the unmodulated optical carrier with the sideband.

This optical MMW beat-tone is transmitted over 20 km SMF and then 5 FSO channels, which was established with two fiber collimators, before reaching the variable optical attenuator (VOA) for performance analysis, and high-speed photodiode to convert the MMW beat-tone into an electrical signal. The electrical MMW carrier is then transmitted over a transmitting horn antenna, which is then received at the receiver horn antenna. The distance between the horn antennas constitutes the WL link length. The received MMW is the amplified, frequency down-

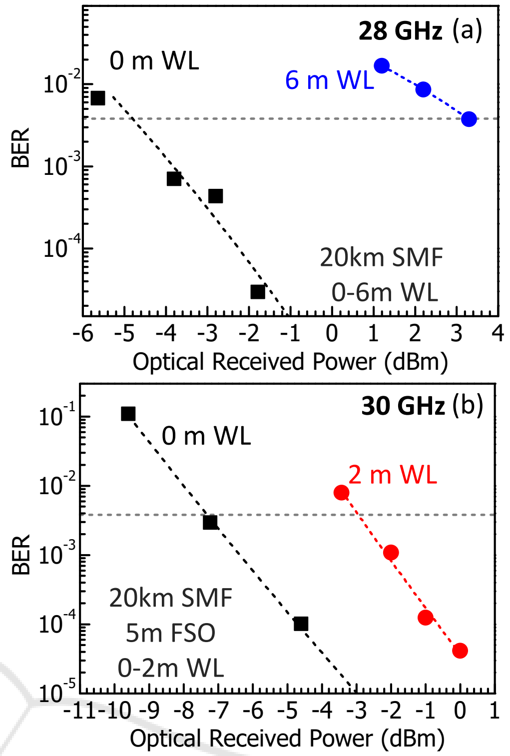

Figure 2: Performance of DSB modulated 2 Gb/s analog QPSK at 5 GHz intermediate frequeny over (a) 28 GHz and (b) 30 GHz MMW carier signals employing QDCS. The transmission channels are: (a) hybrid 20-km SMF – 0-6m WL link and (b) 20 km SMF-5m FSO-0-2m WL link.

converted, and then demodulated in a Keysight digitizer. More details of the experimental setup can be found elsewhere (Ragheb, 2021). Figure 2(a) shows the transmission performance of 28 GHz MMW carrier over the hybrid 20 km SMF – 6 m WL. The back-to-back (BtB) configuration, with 20 km SMF – 0 m WL link length, is also shown for comparison purposes. An error-free transmission with both channels reaching forward-error-correction (FEC) bit-error-rate (BER) limit of 3.8 $\times 10^{-3}$ at receiver sensitivity of ~-5.1 dBm and ~3.3 dBm is noted between the BtB and the hybrid channel with 6 m WL link case. This corresponds to ~ 8 dB loss through the 6 m WL link and is attributed to the fee-space path loss (Ragheb, 2021).

For the 30 GHz MMW transmission configuration, the hybrid channel comprises a 20 km SMF – 5 m FSO – 2 m WL link, while identical 2 Gb/s analog QPSK over 5 GHz IF modulating signal have been utilized. As seen in Figure 2(b), a successful transmission is again achieved with receiver sensitivities ~-7.3 dBm for the BtB case (i.e., with 0 m WL sub-link) and ~-3 dBm for the hybrid channel, translating to ~3.7 dB loss over 2 m WL

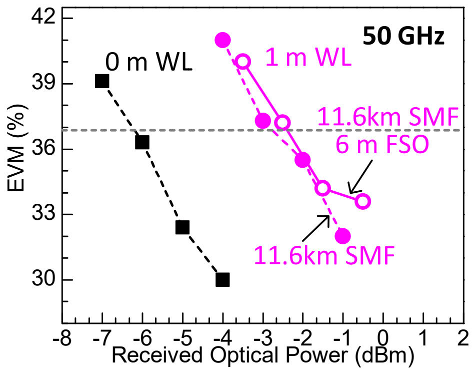

Figure 3: Performance of SSB modulated 2 Gb/s digital QPSK over 50 GHz MMW carier signal employing QDCS with 12.5 GHz FSR. The transmission channels are hybrid 11.6-km SMF – 0-1m WL link and 11.6 km SMF-6m FSO-0-1m WL link.

distance. Again, free-space path loss has been attributed to this received power loss when increasing the WL link distance. It is to be noted that 28 GHz and 30 GHz experiments were performed on different days and hence the difference in their receiver sensitivities under BtB configuration is reasonable (Ragheb, 2021).

4 50 GHZ MMW TRANSMISSION

This section presents our very recent preliminary results of a 50 GHz MMW carrier transmission system. As mentioned in section 2, in this case, 50 GHz beat-tone was obtained by appropriately selecting two comb lines from the 12.5 GHz QDCS. Moreover, we separated the two modes with the help of a 3-dB coupler and two OBPFs where only one mode was SSB digitally modulated with 1Gbaud QPSK data stream using MZM and then recombined with the unmodulated optical carrier with the help of another 3-dB coupler. The optical signal is then transmitted over 11.6 km SMF, 6 m FSO channel and then received by VOA for performance analysis and then high-speed photodiode. The output of the PD is a modulated 50 GHz MMW carrier, which is then passed through the WL channel consisting of two horn antennas. After receiving the electrical signal from the horn antenna, it is amplified with a low-noise amplifier, down-converted to an IF of 4.6 GHz, which is then passed to the digital storage oscilloscope (DSO) for demodulation and post-signal processing. It is noteworthy to mention that this type of MMW transmission system is challenging since the two optical tones are now decorrelated due to passing through different length fibers, thus increasing the phase noise of the generated MMW. Figure 3 shows the BER versus the received optical power, measured before the PD. Again, transmission over BtB channel configuration is also performed, which shows receiver sensitivity of ~6.1 dBm. On the other hand, the received sensitivity measured after passing through the hybrid SMF-WL and SMF-FSO-WL channels is noted to be ~-3.0 and ~-2.5 dBm, respectively. This corresponds to a power loss of ~3 dB when the signal propagates over the 1 m WL distance. More experimental work is in progress to increase the QPSK data rate and WL link length while pushing the generation and transmission of MMWs beyond 50 GHz.

5 SUMMARY

We have summarized our recent progress of deploying mid L-band Qdash LD in MMW applications. In particular, we successfully generated and transmitted 28 and 30 GHz MMW carriers overs various hybrid channels, viz. 20 km SMF – 6 m WL and 20 km SMF – 5m FSO – 2 m WL, with 2 Gb/s QPSK data. Moreover, we also highlighted our very recent preliminary results of pushing the generated MMW frequency to 50 GHz employing a system with increased phase noise. Nevertheless, a successful transmission for 2 Gb/s QPSK data is achieved over 11.6 km SMF – 6 m FSO – 1 m WL channel.

ACKNOWLEDGEMENTS

This work was supported by Deanship of Research Oversight and Coordination, via Center for Communication Systems and Sensing, King Fahd University of Petroleum and Minerals, grant no. INCS2103.

REFERENCES

Nesset, D. (2017). PON roadmap. *Journal of Optical Communications and Networking*, 9(1), A71-A76.

Uwaechia, A. N., and Mahyuddin, N. M. (2020). A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges. *IEEE Access*, v8, p. 62367-62414.

Rahim, M., Zeb, K., Lu, Z., Pakulski, G., Liu, J., Poole, P., Song, C., Barrios, P., Jiang, W. and Zhang. (2019). Monolithic InAs/InP quantum dash dual-wavelength DFB laser with ultra-low noise common cavity modes for millimeter-wave applications. *Optics Express*, 27(24), 35368-35375.

Delmade, A., Browning, C., Verolet, T., Poette, J., Farhang, A., Elwan, H.H., Koilpillai, R.D., Aubin, G., Lelarge, F., Ramdane, A. and Venkitesh, D. (2020). Optical Heterodyne Analog Radio-Over-Fiber Link for Millimeter-Wave Wireless Systems. Journal of Lightwave Technology, 39(2), pp.465-474.

Ragheb, A. M., Tareq, Q., Alkhazraji, E., Esmail, M. A., Alshebeili, S., & Khan, M. Z. M. (2021). Extended L-Band InAs/InP Quantum-Dash Laser in Millimeter-Wave Applications. *Photonics*, 8(5), p. 167.

Reithmaier, J.P., Somers, A., Deubert, S., Schwertberger, R., Kaiser, W., Forchel, A., Calligaro, M., Resneau, P., Parillaud, O., Bansropun, S. and Krakowski, M. (2005). InP based lasers and optical amplifiers with wire-/dot-like active regions. Journal of Physics D: Applied Physics, 38(13), p.2088.