Monolithic InAs/InP Quantum Dash Mode-Locked Lasers for Millimeter-Wave-Over-Fiber Mobile Fronthaul Systems

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***Abstract*—Semiconductor monolithic mode-locked lasers (MLLs) are potential solutions for generating high-speed optical pulses in future mobile fronthaul networks in the millimeter-wave (mmW) bands. Our previous studies have investigated using buried heterostructure (BH) quantum dash (QDash) multi-wavelength lasers for photonic mmW applications. Here we present results from monolithic chip-scale ridge waveguide QDash MLLs for generating and transmitting mmW signals. Through optimizing epitaxy growth, waveguide design, and fabrication process, the five-layer ridge waveguide QDash MLL exhibits superior performance with regard to the coherent comb bandwidths, lasing threshold current, output power, and internal quantum efficiency. The generated mmW frequency at 28.36 GHz exhibits excellent frequency stability, with a drift of less than ±50 kHz. For the first time, we have utilized the free-running five-layer ridge waveguide QDash MLL to implement single- and dual-optical carrier modulation schemes in the millimeter-wave-over-fiber (mmWoF) systems. Both modulation schemes have achieved satisfactory performance achieving error vector magnitude (EVM) performance much lower than the 3GPP requirements ($<$12.5%) for future networks. In particular, the single-carrier modulation scheme achieves higher conversion efficiency and improved EVM performance. In contrast, the dual-carrier modulation scheme alleviates the path length matching challenges, offering a low-cost and easy-to-implement solution in different usage scenarios.**

***Index Terms*—Microwave photonics, millimeter-wave, optical heterodyne, radio-over-fiber, quantum dash, mode-locked lasers, mobile fronthaul system.**

I. INTRODUCTION

To ADDRESS the spectrum shortage problem and capacity limitations of the current mobile network and to satisfy the upcoming data rate demands, the utilization of millimeter-wave (mmW) carrier frequencies (30–300 GHz) and beyond is being considered as a solution for providing an unprecedentedly large bandwidth with very high bit rates [1]. In addition, due to the short wavelength, mmW communications facilitate multiple small-sized antenna arrays [2] to be arranged in a restricted area, allowing for highly directional beamforming that enhances link margin and mitigates cell interference [3]. However, for efficient high-speed mobile communication, there are two main challenges in mmW generation and data transmission. First, generating high-frequency mmW carriers in the conventional electronic domain is challenging and less financially attractive. Secondly, mmW suffers substantial signal degradation in free space and has a restricted communication range and coverage [4]. These two main challenges have brought much attention to microwave photonics systems such as radio-over-fiber (RoF) [5], [6]. RoF technology integrates the advantages of radio networks and photonic devices. In photonic mmWoF wireless systems, the RF data modulated signal is produced at the optical transmitter and then transmitted via a fiber link to the wireless transmitter front-end. The wireless transmitter delivers the signal to the mobile end-users at mmW frequency [7]. This integration aids in reducing the complexity of carrier generation and circumvents significant transmission loss in electronic components when operating at mmW frequencies. Furthermore, RoF can seamlessly integrate with the existing

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fiber infrastructure, and it is a promising and reliable approach for access networks (first/last mile) in various scenarios when combined with wavelength division multiplexing (WDM) technology [8].

The photonic generation of mmW signals can be achieved by the optical heterodyne beating of (at least) two optical carriers with channel spacing equivalent to the intended RF beating frequency detected using a photodetector (PD) [9]. The effectiveness of a mmW transmission system is heavily reliant on several factors, such as the stability of the RF beating frequency, the RF linewidth, the spectral purity, and the coherence of the optical sources [10]. Optical sources create intensity and phase noise, which can impact the generated mmW signals when transferred via optical heterodyning [11]. As such, it is preferable to either reduce the noise or establish a strong correlation among the optical carriers to generate mmW carrier signals with excellent spectral purity and phase stability [12].

Recently, optical frequency comb (OFC) sources [13] have gained attention for potential applications as integrated sources for multiple wavelength channels in coherent systems, WDM, and RoF systems. An OFC creates beat notes at the repetition frequency when each comb line beats with any of its two adjacent lines [14]. Among different OFC technologies [13], semiconductor monolithic self-pulsating passively MLL sources have emerged as highly desirable options, particularly for mmWoF communication systems, owing to their ability to mitigate phase noise between correlated optical tones. Such OFC sources do not necessitate an external mode-locking mechanism to partially reduce the phase noise, resulting in a more stable system with cost-effective benefits. Several material systems have been studied for semiconductor monolithic MLLs, such as quantum wells (QWs), quantum dots (QDots), or quantum dashes (QDashes). Among them, semiconductor QDash/QDot lasers are considered a viable solution as a potential OFC source for photonic mmW signals generation and processing [15], [16], [17], [18]. InAs/InP QDash or QDot MLLs provide significant advantages such as wide bandwidths, low threshold current densities and reduced spontaneous emission rates [19]. These characteristics result in lower intrinsic noise levels.

Pioneering studies have been conducted utilizing InP-based QDash or QDot MLLs for mmWoF systems [20], [21], [22]. For instance, Stohr et al. demonstrated high bandwidth photonic mmW transmission at the 60-GHz frequency range with data rates as high as 27.04 Gbit/s (EVM of 17.6%) using 16QAM OFDM modulation and achieving a bit-error-rate (BER) of 4.2×10^{-3} [20]. In the demonstration, a semiconductor laser chip, comprising a buried structure and an active medium consisting of six layers of InAs QDashes on an InP substrate, was utilized. The RF linewidth was demonstrated to be as narrow as 10 kHz [23]. Afterward, Brendel et al. studied the influence of chromatic dispersion on the transmission of 60 GHz radio signals across a standard single-mode fiber (SSMF) [24]. Recently, Elwan et al. presented a simplified chromatic dispersion model for 60 GHz RoF transmission based on a QDash MLL [11]. They investigated how dispersion affects the power of the signal and noise on the heterodyne carriers. Moreover, they investigated how the higher-order terms of the fiber's propagation constant affect the mode partition noise of mmW heterodyne carriers. Their experimental results revealed that the laser mode partition noise symmetry was transformed to an asymmetric deformation on the beating carrier [25]. More recently, Delmade et al. demonstrated several techniques that specifically target the performance limitations of the mmW signal. Of these techniques, the use of optical heterodyne with QDash MLL OFC provides a more practical solution for generating and transmitting mmW signals [21]. In the demonstration, the optical linewidth of the QDash MLL used is around 6 MHz. Without an optical feedback scheme, the RF linewidth is ∼10 kHz, and the measured EVM is 13%. However, utilizing an optical feedback scheme, the RF linewidth is down to ∼2 kHz, and the EVM performance is improved to 6% [21].

Over the past few decades, we have reported various InAs/InP QDash/QDot Fabry-Perot (F-P) MLLs with channel spacing ranging from tens of GHz up to THz [26], [27], [28]. In our preliminary work, we developed and experimentally demonstrated a BH waveguide InAs QDash MLL with a repetition rate of 25 GHz for mmWoF systems [22]. The BH configuration incorporated additional material growth processes, including *p-n-p* blocking and ballast layers, to enhance mode symmetry, output power and achieve a lower divergence angle that improves coupling efficiency. However, the BH waveguide's lower divergence angle resulted in a larger RF frequency drift (±150 kHz) due to its higher susceptibility to optical feedback. In this study, we focus on the performance of free-running InAs/InP *ridge* waveguide QDash MLLs with 5, 8, and 12 stacked QDash layers. The ridge waveguide has a smaller active area compared to the BH structure, resulting in higher intracavity intensity, improved mode confinement, broader lasing bandwidth, and potential mode-locking. Through the optimization of epitaxy growth, waveguide design, and fabrication process, the five-layer ridge waveguide QDash MLL exhibits superior performance with regard to the coherent comb bandwidths, lasing threshold current, output power, and internal quantum efficiency. Using the five-layer ridge waveguide QDash MLL, we have achieved the optical heterodyne mmW frequency of 28.36 GHz with excellent stability, exhibiting a drift of below ±50 kHz over a free-running period of 4.5 hours. Thus the generated mmW frequency fluctuation falls well within IEEE's frequency tolerance (less than ±20 ppm, corresponding to a frequency of ±567 kHz) [29]. The measured RF beat-note 3-dB linewidth of the QDash MLL is down to 2.4 kHz without using any optical feedback scheme. The selected modes exhibit an average integrated relative intensity noise (RIN) of −132.1 dB/Hz and an optical linewidth of 1.9 MHz. This guarantees the transmission and distribution of mmW signals with high-level stability. For the first time, we have used the ridge waveguide QDash MLL to implement and experimentally demonstrate single- and dual-optical carrier modulation schemes in mmWoF fronthaul configurations. Both modulation schemes have achieved satisfactory performance. The single optical carrier modulation scheme notably offers higher conversion efficiency and improved EVM performance. In contrast, the dual-carrier modulation scheme has low complexity in the transmitter part, providing a low-cost and easy-to-implement solution in different usage scenarios.

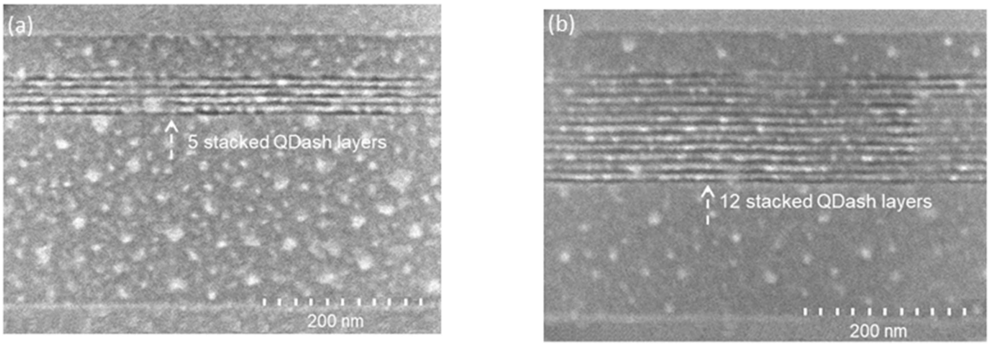

Fig. 1. (a) and (b) cross-section scanning electron microscopy of the five and twelve stacked InAs QDash layers (200 nm scale bar).

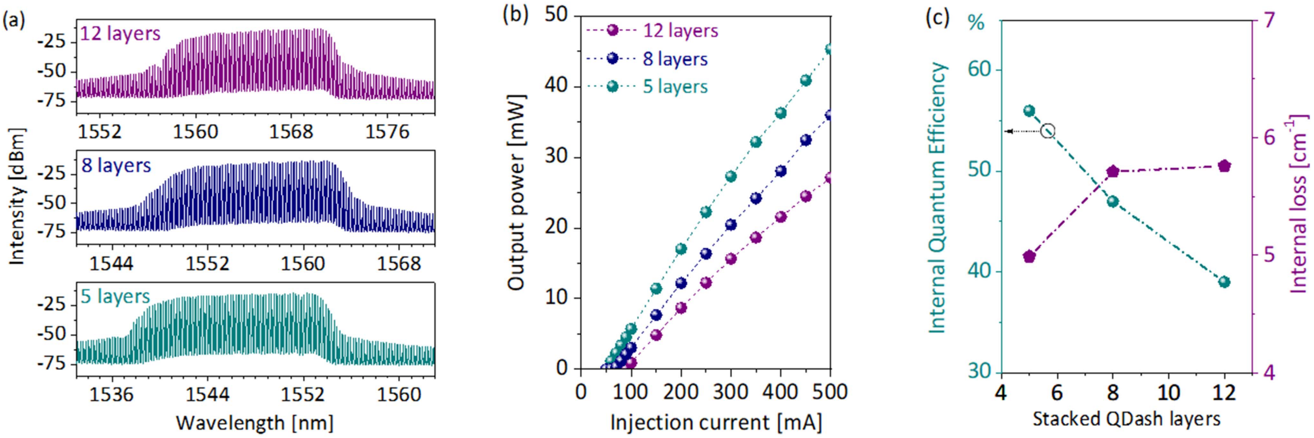

Fig. 2. (a) Measured optical spectra from QDash lasers with five, eight, and twelve stacked InAs QDash layers, at 421 mA and 18 °C. (b) Output power-current characteristics from QDash lasers with five, eight, and twelve stacked InAs QDash layers, measured at 18 °C. (c) Calculated typical internal quantum efficiency and internal losses of the QDash lasers with five, eight, and twelve stacked InAs QDash layers.

II. QUANTUM DASH MLL DESIGN, FABRICATION, AND CHARACTERIZATION

The study utilizes InAs/InP QDash MLLs with identical designs. The experimental outcomes rely on consistent features observed across multiple batches, indicating that the findings can be replicated and are not restricted to a single device. Fig. S1(a) and S1(b) in the supplementary material contain a representative schematic diagram and a corresponding scanning electron microscopy (SEM) that shows the facet of the devices after fabrication.

The gain region consisted of a 350 nm InGaAsP waveguide core with *five*, *eight*, or *twelve* stacked InAs QDashes layers and lattice-matched In$_{0.816}$Ga$_{0.184}$As$_{0.392}$P$_{0.608}$ (1.15Q) barriers. The SEM cross sections of the 5 and 12 QDash layer cores are shown in Fig. 1(a) and (b). More detailed material growth and device characterization can be accessed in our previous publication [30]. Fig. 2(a) depicts typical optical spectra from the QDash MLLs with 5, 8, and 12 stacked layers, with corresponding center wavelengths of 1547.1 nm, 1556.6 nm, and 1566.0 nm, respectively. With 6-dB bandwidths of 12.5 nm, 12.1 nm, and 10.2 nm, the lasers offer 56, 54, and 44 channels, respectively. Fig. 2(b) illustrates the relationship between output power and current injection. Throughout the entire range investigated (300 mA to 500 mA), the curves exhibit no evidence of power saturation. Clear thresholds have been identified: the lowest is at 51.9 mA for the five-layer devices, the middle is at 70.1 mA for the eight-layer devices, and the highest is at 94.5 mA for the twelve-layer devices. The five-layer QDash devices have 67.1% higher output power than the twelve-layer QDash devices, e.g., 45.3 mW vs. 27.1 mW at 500 mA. The five-layer QDash devices exhibit the highest internal quantum efficiency of 55% with the lowest internal loss (5.0 cm^{-1}). In comparison, the twelve-layer QDash devices (eight-layer QDash devices) lasers have not only lower efficiency of 39% (47%) but also a higher internal loss of 5.8 cm^{-1} (5.7 cm^{-1}) because of increasing absorption [Fig. 2(c)].

To maximize spectral efficiency, five-layer QDash devices with the best static characteristics are selected for further investigation of the system's performance. The cavity length is 1500 µm. The QDash MLLs are prone to timing instabilities due to various environmental noise sources, including laser injection currents, temperature fluctuations, and unwanted optical feedback [31]. To assess the stability, the RF peak frequency and its free-running drift are measured at 421 mA and 18 °C. Fig. 3(a) presents the RF performance, indicating a beating frequency of

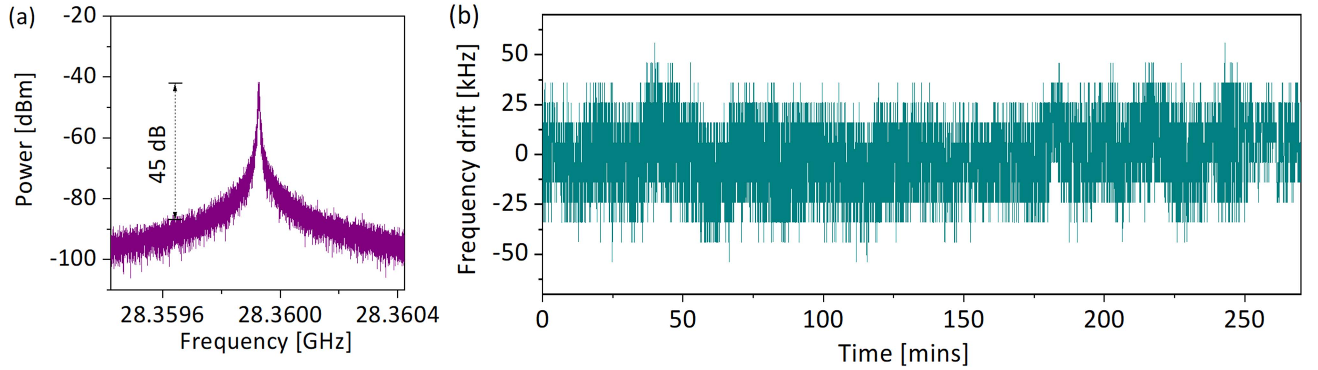

Fig. 3. (a) RF beating frequency and (b) RF peak frequency drift measurement at 421 mA and 18 °C (RBW:1 kHz).

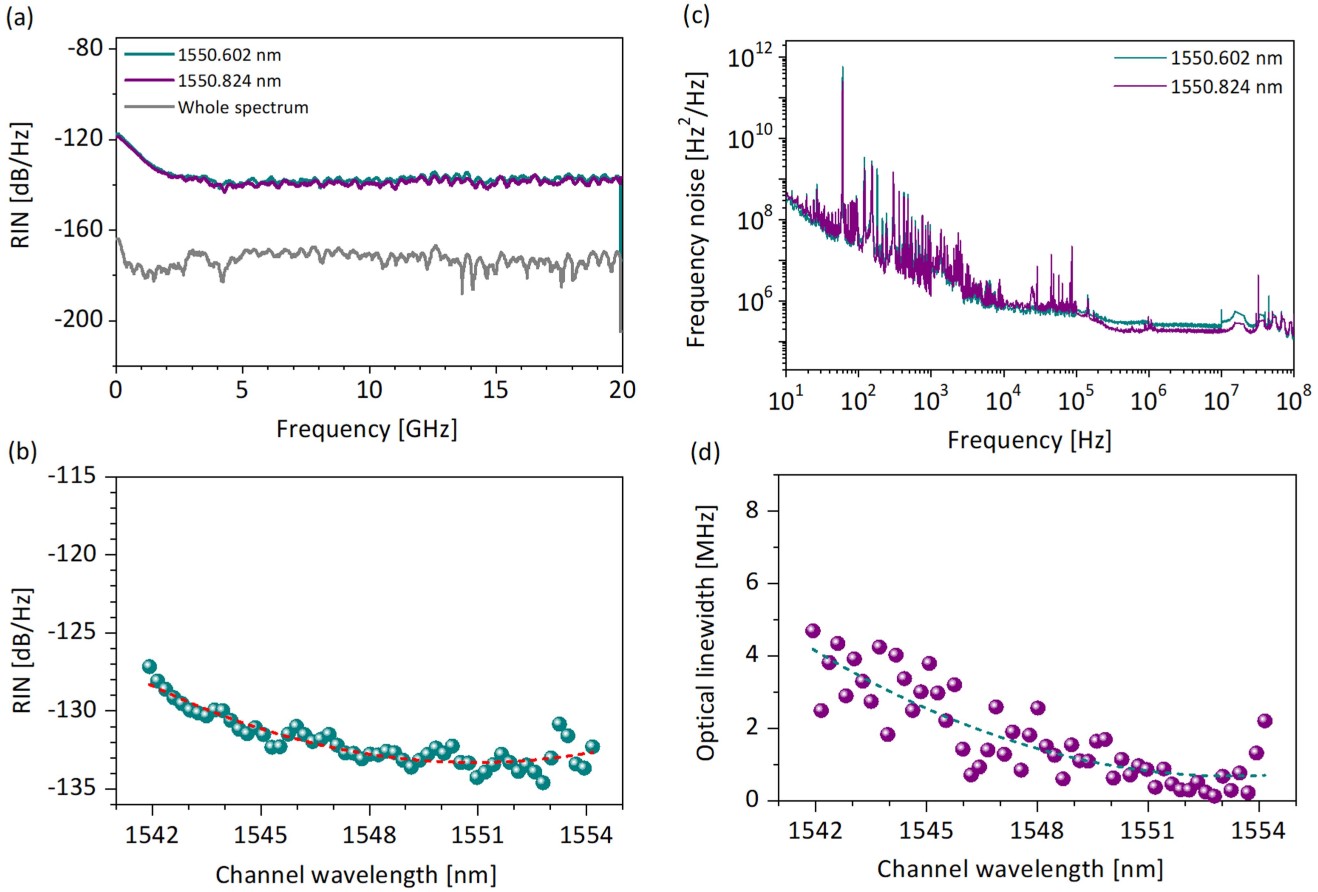

Fig. 4. (a) Measured RIN spectra; (b) integrated RIN from QDash lasers individual modes at 421 mA and 18 °C. (c) measured frequency noise spectra at 421 mA and 18 °C; and (d) optical linewidth from QDash lasers individual modes at 421 mA and 18 °C.

28.36 GHz and signal-to-noise ratio (SNR) that exceeds 45 dB. The frequency fluctuation is measured at a sweep interval of 20 ms for 4.5 hours to assess the frequency drift on this time scale. The result shows a free-running drift of less than ±50 kHz [Fig. 3(b)]. The frequency instability of the mmW carrier signal is low and thus falls well within IEEE's frequency tolerance [29].

The laser mode-locking characteristics are also investigated. The RF spectra evolving with current injection are illustrated in Fig. S2(a) in the supplementary material. Clear single peak frequencies at approximately 28.36 GHz demonstrate effective mode-locking over an extensive range of current injection. To determine the RF linewidths, we apply Lorentzian fitting on the RF beating-notes. The measured RF beat-note 3-dB linewidth is

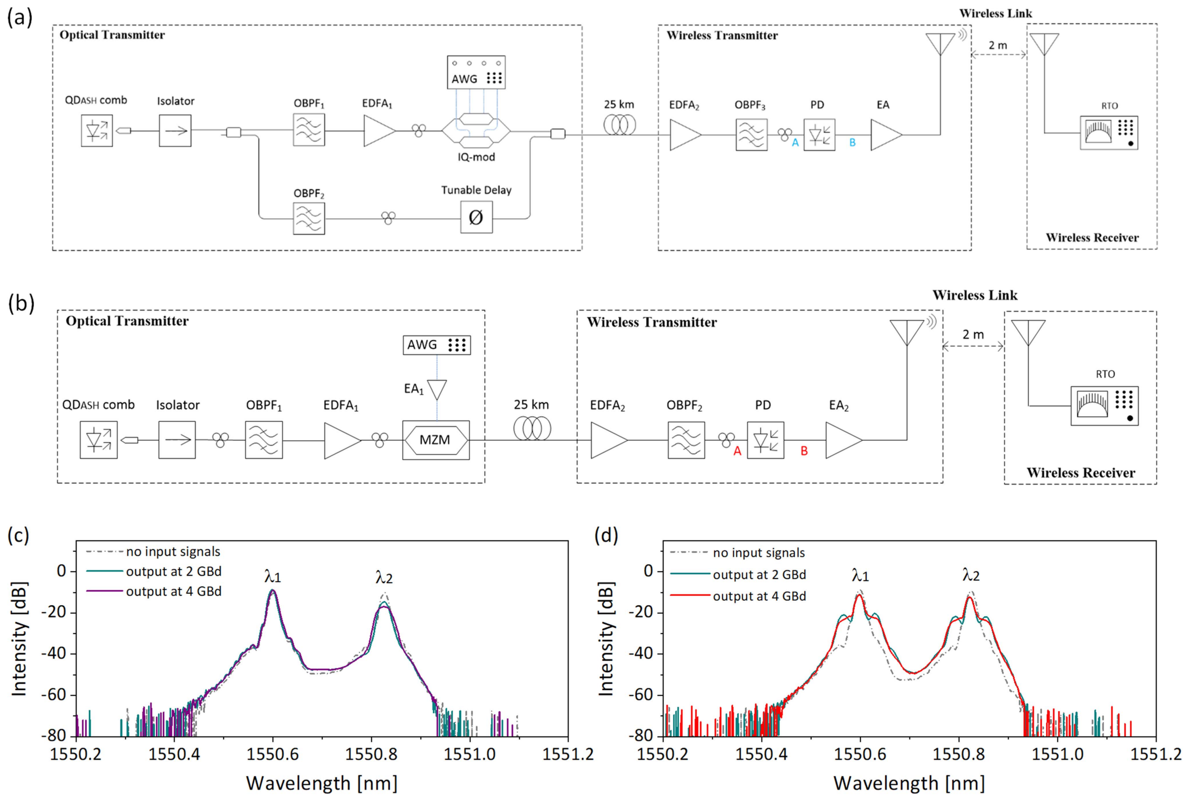

Fig. 5. Experimental setup for (a) single-carrier modulation and (b) dual-carrier modulation on a seamless fiber-mmWoF system. Measured optical spectra for (c) single-carrier modulation and (d) dual-carrier modulation of the selected two channels at the wireless transmitter before the PD (at point A).

down to 2.4 kHz without using any optical feedback scheme [Fig. S2(b) in the supplementary material]. The noise characteristics are also investigated, as they have a substantial influence when the MLL device is utilized for generating photonic mmW signals and transmitting data. Fig. 4(a) and (b) show the RIN spectra. These MLLs have a low collective RIN of −171.8 dB/Hz in their overall spectral emission, with an average integrated RIN value of −132.1 dB/Hz across all selected modes. Fig. 4(c) and (d) depict the frequency noise spectra and optical linewidth, respectively. An average optical linewidth of 1.9 MHz across all modes demonstrates excellent noise performance. Thus, these QDash MLLs are appealing options for multi-wavelength sources in mmWoF systems. To reduce frequency noise in individual laser sources, researchers have employed various techniques, such as optical/electrical injection locking [32], [33], dispersion engineering, optical-phase-locked-loop [34], or integrated external cavity [35], [36], [37]. In particular, Tran et al. [35] have extensively discussed techniques to significantly reduce the linewidth of lasers, including the use of hybrid/external cavity lasers and the heterogeneously integrated of silicon with III-V materials for narrow linewidth lasers. A comprehensive discussion on this topic will be presented in a forthcoming publication.

III. SYSTEM IMPLEMENTATION, RESULTS, AND DISCUSSION

To exploit the ridge waveguide QDash MLLs in the converged optical/mmWoF fronthaul system, two types of experimental configurations are implemented. The system mainly includes five parts: optical transmitter, fiber link, wireless transmitter for optical-to-RF conversion, wireless link, and wireless receiver. In our experiment, the lengths of the fiber link and wireless link are 25 km and 2 m, respectively. The main difference between both setups lies in the optical transmitter, while the receiver and subsequent signal processing and conversion steps are identical.

A. Single Optical Carrier Modulation

A schematic illustrating the experimental setup for the optical single-carrier modulation is shown in Fig. 5(a). At the optical transmitter side, the output light from the QDash-MLL is collected using an antireflection-coated fiber focuser. The QDash-MLL optical tones are separated into two paths using a 90/10 polarization maintaining optical coupler, transmitting through two tunable optical bandpass filters (OBPFs). OBPF$_1$ and OBPF$_2$ separate two optical modes, providing flexibility in wavelength tunability and RF frequency generation. For example, in Fig. 5(c), a repetition frequency of 28.36 GHz was obtained in channel 1 (1550.602 nm) and channel 2 (1550.824 nm). Channel 1 serves as an un-modulated optical local oscillator (LO) for optical heterodyne beating. In contrast, channel 2 is the optically modulated data channel with an I/Q lithium niobate ($LiNbO_3$) Mach-Zehnder modulator (Model SHF 46215B DP-QAM, 23 GHz bandwidth, 14.0 dB insertion loss). Baseband 16QAM data signals are used to modulate channel 2 at symbol rates of 2-GBd or 4-GBd, utilizing a 65 GSa/s

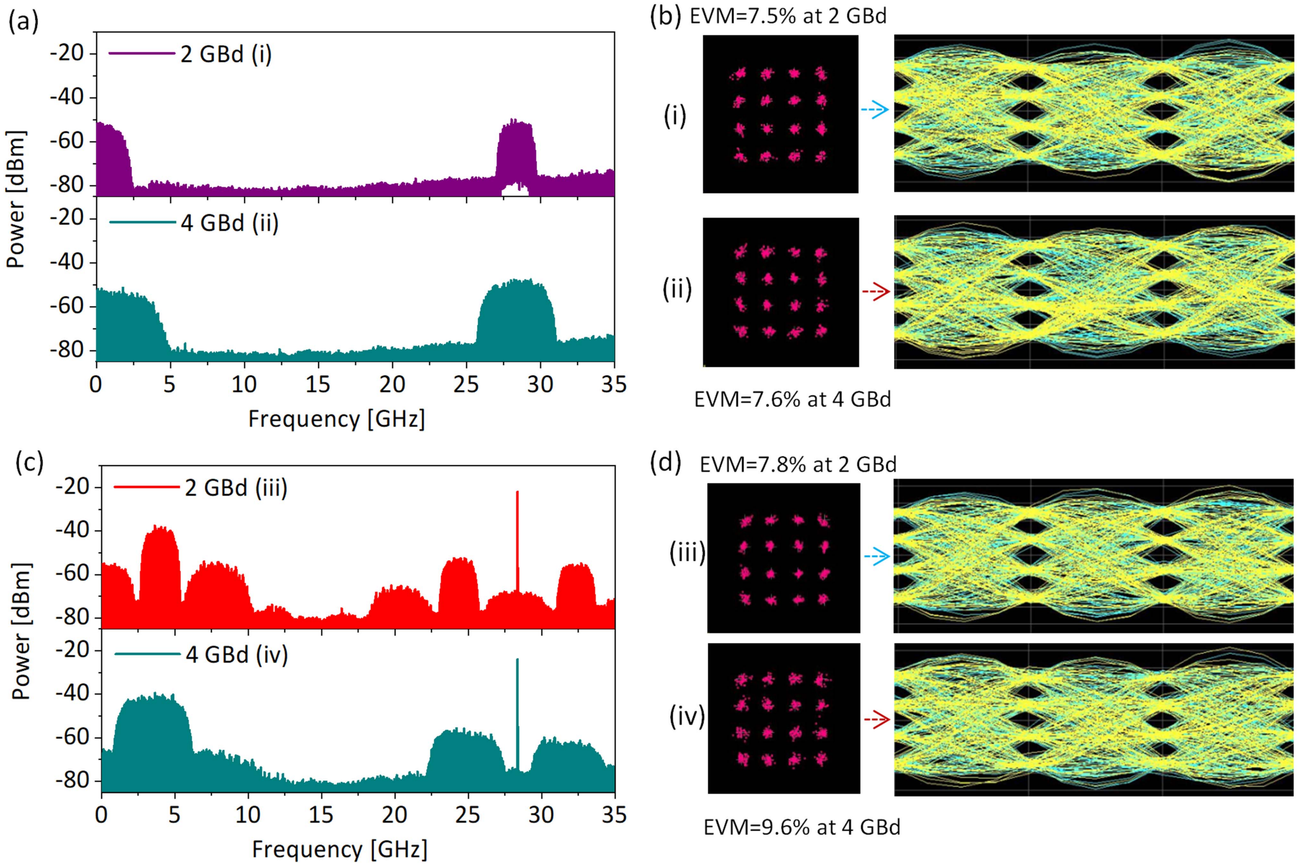

Fig. 6. Measured electrical spectra for (a) single-carrier modulation and (c) dual-carrier modulation at the wireless transmitter after the PD (at point B); Performance of the ridge waveguide QDash MLL in photonics-assisted (b) single-carrier modulation and (d) dual-carrier modulation at 8 Gbit/s (2-GBd × 16QAM) and 16 Gbit/s (4-GBd × 16QAM) mmWoF systems ((i)(iii) 2-GBd and (ii)(iv) 4-GBd 16QAM constellations with measured EVM and their corresponding eye diagrams).

arbitrary waveform generator that employs a pseudo-random binary sequence pattern of 2^{15}-1 bits. An erbium-doped fiber amplifier (EDFA$_1$) is utilized to amplify the data channel prior to modulation. A tunable optical delay line (around 40-m) on the un-modulated path is inserted to pre-compensate the effective difference in path length. This establishes a strong level of phase coherence between optical tones resulting in the mitigation of RF phase noise when the optical signals beat at the high-speed PD. Optical polarization controllers are placed on both the un-modulated and modulated paths and are adjusted manually to ensure that the polarization states of both paths match. Subsequently, the modulated 16QAM optical signal is recombined with the unmodulated optical tone at a 50/50 optical coupler. After being transmitted over the 25-km SSMF, the optical signal received at the wireless transmitter is amplified using EDFA$_2$, and then passes through OBPF$_3$. The optical and electrical spectra of the received carriers before and after the PD are depicted in Figs. 5(c) and 6(a), respectively. After photo-mixing the two optical signals using a PD, the resulting output is amplified by an RF power amplifier with a typical small signal gain of 43 dB, before being fed into a 20-dBi horn antenna. After transmission over the wireless link, the mmW signal is received using another antenna. Finally, the signal is sent to a real-time oscilloscope for further processing at the wireless receiver. More detailed system characterization can be accessed in our previous publication [18]. The evaluation of optical-to-millimeter-wave conversion efficiency is a critical metric for assessing the effectiveness of optical mmW signals as it determines the minimum amount of optical power required by the receiver to generate sufficient mmW power. This efficiency of the conversion process is typically expressed as a power ratio of the output mmW signal to the input signal. In this study, we performed measurements to determine the conversion efficiency of the single-carrier modulation, which yielded a value of -17.4 dB. The mmW radio signals are transmitted over the end-to-end system, and their performance is evaluated using the EVM parameter. Fig. 6(b) depicts the EVM performance for 2-GBd and 4-GBd 16QAM signals, which are 7.5% and 7.6%, respectively. This corresponds to data transmission with bit rates of 8 Gbit/s and 16 Gbit/s, respectively. The study includes additional experimentation to investigate transmission rates beyond the previously tested 4-GBd. Specifically, 6-GBd, 8-GBd, and 10-GBd are examined. This corresponds to data transmission with bit rates of 24 Gbit/s 32 Gbit/s, and 40 Gbit/s, respectively. The measured EVM and their corresponding eye diagrams have been provided in the supplementary material.

B. Dual Optical Carrier Modulation

The dual-carrier modulation mmWoF transmission system is illustrated in Fig. 5(b). In this system, both adjacent optical carriers, randomly selected from the 56 comb lines, are modulated by the radio signals at intermediate frequencies (IF) of 4/3.5 GHz. To create the modulated optical signal, a 40 GHz linearly biased $LiNbO_3$ Mach-Zehnder intensity modulator (MZM, Thorlab LNA6112, 4.0 dB insertion loss) with an electrical amplifier is utilized. The inclusion of intensity modulation leads to a reduction in modulator insertion loss and helps to simplify the system in comparison to the single-carrier modulation scheme. Both channels are modulated with IF 16QAM data signals with a symbol rate of 2-GBd (IF = 4 GHz) or 4-GBd (IF = 3.5 GHz). After the 25-km optical fiber link, the received optical signal is amplified using $EDFA_2$ and filtered with $OBPF_3$. For both modulation schemes, the optical signal injected into the PD is maintained at approximately the same level (−0.5 dBm). This power level is sufficient to reach the wireless receiver through an RF power amplifier without causing saturation in the PD. Figs. 5(d) and 6(c) exhibit the spectra of the received carriers before and after the PD, respectively. The conversion efficiency of the dual-carrier modulation is −22.8 dB. Fig. 6(d) shows the EVM performance for 2-GBd and 4-GBd 16QAM signals, which are 7.8% and 9.6%, respectively. The EVM performance for all signals falls below the requirement of 12.5% set by the third-generation partnership project (3GPP) standards. Clear constellation diagrams indicate successful recognition of the 2-GBd and 4-GBd 16QAM mmW signals. This is further demonstrated in the eye patterns of the wirelessly received 2-GBd and 4-GBd 16QAM signals shown in Fig. 6(d). Therefore, both modulation schemes have achieved satisfactory performance. In particular, the single-carrier modulation scheme achieves higher conversion efficiency and improved EVM performance. This improvement can be attributed to the reduction of intermodulation distortion [29], [38], making this scheme more robust to in-band beating noise and chromatic dispersion. On the other hand, the dual-carrier modulation approach mitigated the path length matching challenges since the optical carrier and modulated signal traverse a single optical path. Furthermore, the inclusion of intensity modulation leads to a reduction in modulator insertion loss. Thus the dual-carrier modulation scheme provides an uncomplicated and inexpensive solution in different usage scenarios.

IV. CONCLUSION

Optical heterodyning RoF fronthaul provides an effective method of generating and transmitting mmW data signals for wireless systems. To achieve successful implementation of fiber-wireless systems, it is crucial to develop techniques that reduce restrictions on RF frequency drift and noise properties between optical carriers while keeping additional complexity to a minimum. This article demonstrates the suitability of a monolithic ridge waveguide QDash passively MLL-based optical frequency comb for use in mobile fronthaul systems in the mmW bands. The OFC-based systems using single- and dual-optical carrier modulation methods are evaluated and compared. Satisfactory performance is obtained for both modulation schemes. Thus, for the QDash MLL OFC-based fronthaul systems, the single optical carrier modulation scheme provides higher conversion efficiency and improved EVM performance. In contrast, the dual optical carrier modulation approach offers an uncomplicated and economically viable option for radio access networks in different usage scenarios.

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