Quantum Dash Passively Mode Locked Laser for Optical Heterodyne Millimeter-Wave Analog Radio-over-Fiber Fronthaul Systems

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Abstract: In mm-wave systems, carrier phase noise limits the performance of analog multicarrier signal transmission. Experimental results show the successful use of a passively mode-locked laser with optical feedback in a 60GHz A-RoF heterodyne 25km system.

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1. Introduction

A combination of technologies such as advanced modulation, wide channel bandwidth (BW), multiple-input multiple-output (MIMO) and ultra-dense antenna deployment, in conjunction with a centralized radio access network (C-RAN) architecture, will be deployed to achieve enhanced mobile broadband targeted high data rates for 5G wireless systems [1]. In order to achieve higher channel BW (~200 MHz), millimeter-wave (mm-wave) frequency (26-300 GHz) carriers are proposed for use in wireless transmission systems. Higher wireless propagation loss associated with mm-wave frequencies will result in smaller radio cell sizes and ultra-dense (UD) antenna deployment. This places an onus on the development of spectrally efficient and cost-efficient X-haul (front/back/cross-haul) links. An optical link between centralized baseband unit (C-BBU) and remote radio heads (RRH) – known as *fronthaul* –facilitates the increased network speeds with reduced CAPEX and OPEX [2]. An analog radio-over-fiber (A-RoF) approach retains the inherent bandwidth efficiency of the wireless signals over the fronthaul link and simplifies the RRH site architecture (compared to the digital radio-over-fiber (D-RoF) approach) by avoiding the use of expensive analog-to-digital and digital-to-analog converters at the RRH [2].

Optical heterodyning, wherein two optical carriers with a spacing equal to the desired mm-wave carrier frequency beat on a high-speed photodetector, has been studied extensively for high-frequency carrier generation [3, 4]. It also facilitates the distribution of mm-wave carriers to the RRH sites through compatible A-RoF optical fronthaul networks. Complexities resulting from the lasing frequency fluctuations and phase noise of two free-running lasers, in an optical heterodyne mm-wave A-RoF system, can be mitigated by replacing them with correlated optical sources, such as an optical frequency comb (OFC) source [4]. Previous works have proposed heterodyne solutions with OFCs [4, 5] produced using either a gain switching technique or external modulators. The necessity for a relatively high powered RF synthesizer in both of these cases adds a degree of complexity to the transmitter side. Considering optical heterodyning with *analog* RoF transmission, previous work has shown how the coherence length of relatively high linewidth, correlated optical tones, coupled with effective path length difference in the system, can result in decorrelation at the receiver – producing mm-wave carriers with relatively high levels of phase noise. This essentially places fundamental limits on both the optical linewidth and correlation of OFC's for use in mm-wave A-RoF systems [4]. Hence RF synthesizer free, cost-efficient low linewidth OFC sources are required in order to meet the laser specifications and cost-effectiveness for wide deployment in optical/mm-wave fronthaul systems.

In this work, we demonstrate the use of a quantum dash passive mode-locked laser (MLL) based C-band OFC source with free space optical feedback in an optical heterodyne mm-wave A-RoF fronthaul system operating at ~60 GHz. Previous work, in [6], on mm-wave optical heterodyne systems with MLL has demonstrated the transmission of ~100 Mbaud single carrier signals, for which the impact of phase noise is minimal. Here, we demonstrate the transmission of a 5G envisioned multi-carrier signal over 25 km standard single mode fiber (SSMF) based heterodyne system, using subcarrier baud rates/spacing suitable for practical 5G systems. 195 MHz BW orthogonal frequency division multiplexing (OFDM) signals, with subcarrier baud rates of 250 kbaud and higher were successfully transmitted, with received error vector magnitudes (EVM) below the 7% overhead Forward Error Correction (FEC) limit (8% for 64-QAM data), when external feedback is applied to the laser for optical linewidth reduction.

2. Quantum Dash Passively Mode Locked Laser Device

A single section MLL with the gain medium made of a few layers of InAs quantum dash (QD) was used. A buried ridge structure guides a single transverse mode inside the Fabry-Pérot cavity. The complete description of the device can be found in [7, 8]. The laser mirrors were made with cleaved facet and the length of the cavity was chosen to have 32.5 GHz repetition rate. At 20°C, the threshold current was under 25 mA, and the fiber coupled power was ~9 dBm at 300mA. The OFC generated by the MLL laser has a 3 dB bandwidth of 11.8 nm resulting in ~45 flat comb lines (spectrum in Inset (i) of Fig.1). The optical linewidth of the comb lines is around 4 MHz and its respective RF linewidth of the beat signal between comb lines is several 10's kHz, depending on operating conditions.

An external free space cavity of approximately 30 cm length is used to reduce the phase noise of both the optical lines and RF beating signal. It consists of a collimating lens, a free space attenuator and a mirror. The phase of the optical feedback loop is controlled by tuning the position of the mirror with a piezo controller. The level of optical and RF beat signal linewidth reduction achieved depends on the strength and phase of the feedback [9].

3. Experimental Setup

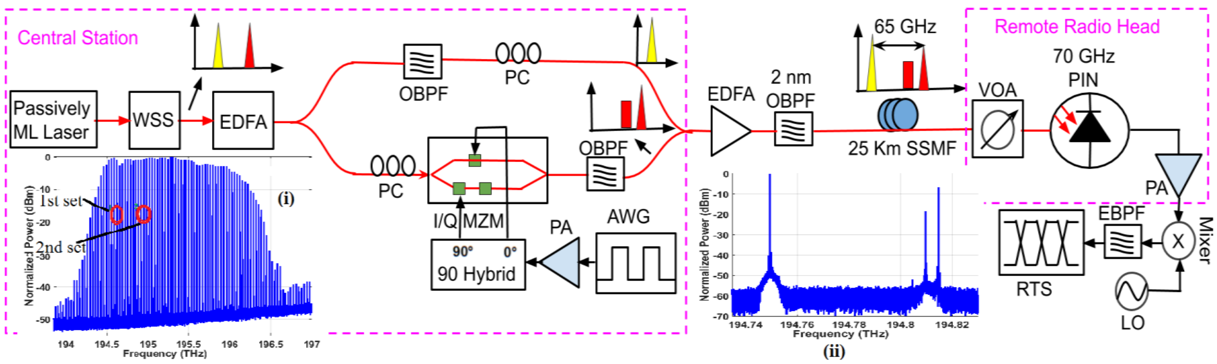

Fig. 1: Optical heterodyne mm-wave transmission system setup with insets showing (i) the optical spectrum of the QD MLL OFC and (iii) the optical spectrum at the input to the fiber.

The schematic of the QD MLL based optical heterodyne mm-wave A-RoF experimental setup with figurative spectra along the transmission path is shown in Fig. 1. An external free space cavity with phase tuning capabilities, as described in section 2, was used for linewidth reduction. The collimating lens and mirror were removed for non-feedback operation. A wavelength selective switch (WSS) was used to select two optical tones spaced close to the required mm-wave frequency, in this case 65 GHz (twice the FSR of the OFC). Two different sets of optical tones with operating frequencies of 194.556 & 194.621 THz (first set) and 194.916 & 194.981 THz (second set), were selected, to show the flexibility in the choice of the tones. An erbium doped fiber amplifier (EDFA) was used to boost the power of the optical carriers before the optical path is split in two using a 50:50 coupler. One carrier (red in Fig. 1) was optical single sideband (O-SSB) modulated, with an OFDM signal, at an intermediate frequency (IF) of 5 GHz, generated by an arbitrary waveform generator (AWG). O-SSB was achieved using an electrical 90^{o} hybrid coupler and I/Q Mach Zehnder Modulator (MZM). Optical band pass filters (OBPF) were used in both paths to filter out residual optical components. The OSSB modulated carrier was combined with the un-modulated carrier (yellow in Fig. 1) and transmitted through 25 km SSMF after amplification by an EDFA. The WSS was programmed to pre-equalize the power difference between two optical paths resulted from I/Q MZM insertion and OSSB modulation loss.

At the receiver RRH side, the beating of the unmodulated carrier and the OFDM data bands, on the 70 GHz PIN PD, produced a copy of the data signal at 60 GHz. This mm-wave data was captured using a real-time oscilloscope (RTS) after mixing it back to an IF stage with an external local oscillator (LO). Offline processing including re-sampling, channel estimation/equalization as well as bit error rate (BER) and EVM calculations were performed using Matlab. 195 MHz BW OFDM signals with variable subcarrier spacing values of 2 MHz, 1 MHz, 500 kHz, 250 kHz, 125 kHz and 62.5 kHz were generated and frequency converted to the IF with Matlab and then loaded into the AWG at the transmitter, to investigate performance with different subcarrier baud rates. In order to keep the OFDM signal bandwidth constant, the IFFT size and number of data subcarriers were changed by a factor of two with respect to previous subcarrier spacing signal.

4. Results

Initially, the heterodyne system outlined was tested for two different sets of operating frequencies from the comb source (marked by red circles in inset (ii) of Fig. 1) for a 195 MHz BW OFDM signal with a subcarrier baud rate of 2 Mbaud, resulting in a 64-QAM data transmission at the rate of ~1.17 Gb/s. Figs. 2(i) and 2(ii) show the constellation diagrams of the received signal for both sets of operating frequencies when the MLL was operated with free space optical feedback. In both cases an EVM of 6% and a measured BER of around 1.82×10^{-4} was obtained, with no penalty due to fiber transmission at a received optical power of 0 dBm.

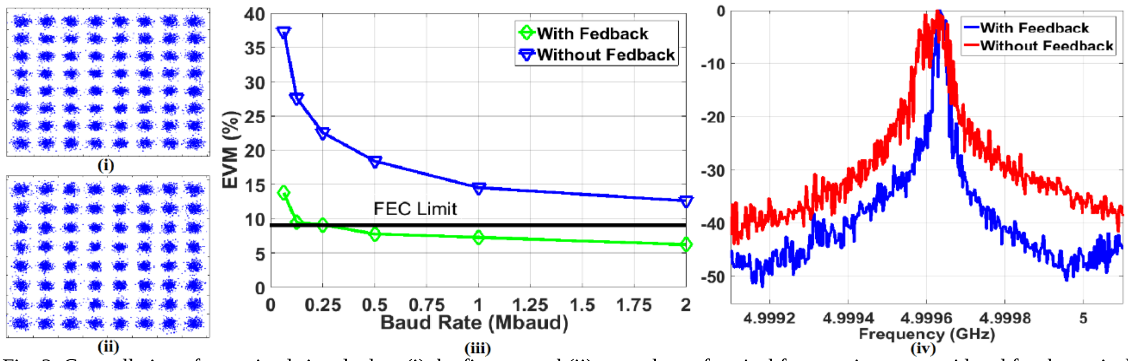

Fig. 2: Constellation of a received signal when (i) the first set and (ii) second set of optical frequencies are considered for the optical heterodyning, (iii) EVM versus subcarrier baud rate performance for OFDM signal and (iv) RF spectra of a frequency down-converted mm-wave carrier for QD-MLL based mm-wave A-RoF fronthaul link

OFDM signals, each with a different subcarrier baud rate/spacing, were generated and transmitted through the 25 km SSMF mm-wave A-RoF system and performance was analyzed for the two different laser conditions - with and without optical feedback. Fig. 2(iii) shows the received EVM of the OFDM signals with differing subcarrier baud rates, at the received optical powers of 0 dBm, for these two cases. The figure shows that for the implemented system, performance degrades as the subcarrier baud rate reduces for both cases, with and without feedback. This is due to the requirement for reduced mm-wave signal linewidth at lower subcarrier baud rates. The EVM reduction under feedback was due to the reduction in the mm-wave carrier linewidth, from ~10 kHz without feedback to ~2 kHz with feedback, as seen from the frequency down converted mm-wave carrier spectrum in Fig 2(iv). EVMs of all the OFDM subcarrier baud rate values were measured to be above the FEC limit of 8% when no feedback was applied, while the signals with subcarrier baud rates of 250 kbaud and higher were successfully transmitted when the feedback was applied to the laser for linewidth reduction. As shown in Fig. 2(iv) subcarrier baud rates of 125 kbaud could not be supported when feedback is applied – a limitation imposed by the produced beat tone linewidth in this case.

Using the QD MLL in the mm-wave system described here results in similar performance to that of our previous demonstrations using a gain switched OFC [4], while also negating the requirement for an RF synthesizer at the transmitter. Also, any mm-wave carrier signal, within the BW of QD MLL OFC (32GHz to 1.2 THz), can be generated by this process by selecting two lines with the desired frequency spacing for optical heterodyning. This highlights the potential for the deployment of the passively mode-locked lasers in future mm-wave systems required to provision multi-carrier A-RoF signals with baud rates compatible with future mobile services.

5. Conclusion

Mm-wave A-RoF optical heterodyne systems employing low linewidth, compact and mass-producible OFC sources can be a promising cost-efficient solution for the fronthauling of the future generations of wireless signals. The results presented here demonstrate the use of a passively mode-locked laser under optical feedback for the generation and transmission of a 60 GHz OFDM signals. The QD MLL enabled heterodyne system is shown to support A-RoF signals with OFDM subcarrier baud rates down to 250 kbaud, over a 25 km fiber. The successful implementation of such an RF synthesizer free OFC in this analog optical/mm-wave system is significant as it highlights the potential for the development of this laser for generation of signals at frequencies upto 1 THz.

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