Flexible V-band mmWave Analog-RoF Transmission of 5G and WiGig signals using a InP-SiN Integrated Laser Module

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***Abstract*—In this paper, we have demonstrated analog radio-over-fiber (A-RoF) transmission of 5G (256/512-QAM) and WiGig (64-QAM) signals in the millimeter-wave (mm-Wave) frequency range from 55 GHz - 65 GHz in a system with 10 km fiber and 1 m wireless channels. The system employs a hybrid integrated InP-Si_3N_4 dual laser module for flexible heterodyne operation in the V-band and a simplified system setup, with respect to our prior demonstrations. The experimental results show excellent performance with bit error ratio (BER) values as low as of 8.46×10^{-6} and 1.11×10^{-4}, and lowest error vector magnitudes (EVMs) of 2.4 % and 6.1%, achieved for the 5G and WiGig signals, respectively.**

Keywords—5G, WiGig, mmWave, ARoF, SiN, V-band, Envelope detector, Hybrid Integration

I. INTRODUCTION

The advent of data hungry applications such as virtual reality (VR), live ultra-high definition (UHD) video streaming, and autonomous driving has fuelled much interest in mm-wave (26 – 300 GHz) frequency carriers for mobile wireless communication systems. The 5th generation new radio (5G NR) mobile systems will use carriers in the 26 to 52.4 GHz frequency range [1], while the 60 GHz unlicensed frequency band continues to grow in popularity for short distance wireless systems like Wi-Fi [2]. Such systems require efficient and scalable mm-wave carrier generation techniques. Higher wireless propagation losses for mm-wave carriers necessitate an ultra-dense deployment of the antenna sites – placing an onus on the development of efficient and flexible fronthaul for centralized radio access networks (C-RAN) [3]. In this C-RAN configuration, the fronthaul link connects the centralized baseband unit (C-BBU) to various antenna site remote radio heads (RRH).

Optical heterodyning provides an effective solution for the generation of high frequency carriers, by beating two optical CW signals with the desired mm-wave carrier frequency spacing [4] - [6]. When combined with heterodyne operation, the spectrally efficient A-RoF fronthaul scheme can facilitate the distribution of mm-wave carrier and data signals to multiple simplified remote RRH antenna sites through the same fiber [7]. In such optical heterodyne A-RoF links, the frequency offset (FO) and phase noise (PN) of the free-running lasers employed will limit system performance. This has been shown to be a major hindrance for the transmission of multi-carrier A-RoF signals with relatively low subcarrier spacing and higher order modulation [6]. Multiple techniques such as the use of optical injection locking [5], optical phase-locked loops [8], digital signal processing [9] and optical frequency combs [6] have been proposed over the past years to mitigate the effect of laser FO and PN in such systems. These techniques either increase the hardware or digital complexity of the optical heterodyne A-RoF system, or can limit the achievable mm-wave tuning range.

In this paper, we demonstrate an optical heterodyne A-RoF system with a dual tunable hybrid integrated InP-SiN laser module and simplified system architecture incorporating a single ended modulator, a single optical amplifier and an envelope detector. Based on the use of integrated micro-ring resonators (MRRs) the dual laser module has been shown to be tunable over the entire C band [10] and can be fine-tuned to achieve desired carrier frequency spacings – offering continuous RF carrier tuning from 5 GHz to 150 GHz when used in a heterodyne configuration [11]. More details of the laser module and system are discussed in section II. The use of an envelope detector in the system mitigates the effect of laser frequency and phase fluctuations and allows RF local oscillator (LO) free signal detection. A previous system demonstration [12] uses a similar envelope detector-based approach, but the requirement for a wavelength-locked colorless laser diode and pre-emphasis increases its complexity. A similar concept is demonstrated in [13] albeit with the use of an active mode-locked laser and transmission of NRZ – OOK data for which the effects of laser FO and PN are minimal. In this work, we demonstrate the successful transmission of ~195 MHz bandwidth 5G NR compatible (subcarrier spacing of 244.4 kHz with 256-QAM and 512-QAM data modulated subcarriers) and 1.6 GHz IEEE 802.11ad Wi-Fi standard (64-QAM) compatible orthogonal frequency division multiplexing (OFDM) signals, over 10 km of single-mode fiber and a 1 m wireless distance. Results show the near uniform performance as the centralized laser module was tuned to enable remote generation of various mm-wave carrier frequencies available in the 60 GHz unlicensed band of the mm-wave spectrum.

II. LASER MODULE AND SIMPLIFIED ANALOG RECEIVER

The hybrid integrated dual laser module consists of two on-chip lasers (L1 and L2), each having a InP semiconductor optical amplifier (SOA) hybrid coupled to Si_3N_4 feedback circuit as shown in Fig. 1. The feedback circuit is composed of a phase section, coupler and Si_3N_4 micro-ring resonators (MRR) in a Vernier configuration. The gain, phase, coupler and MRR sections can be thermo-optically controlled to

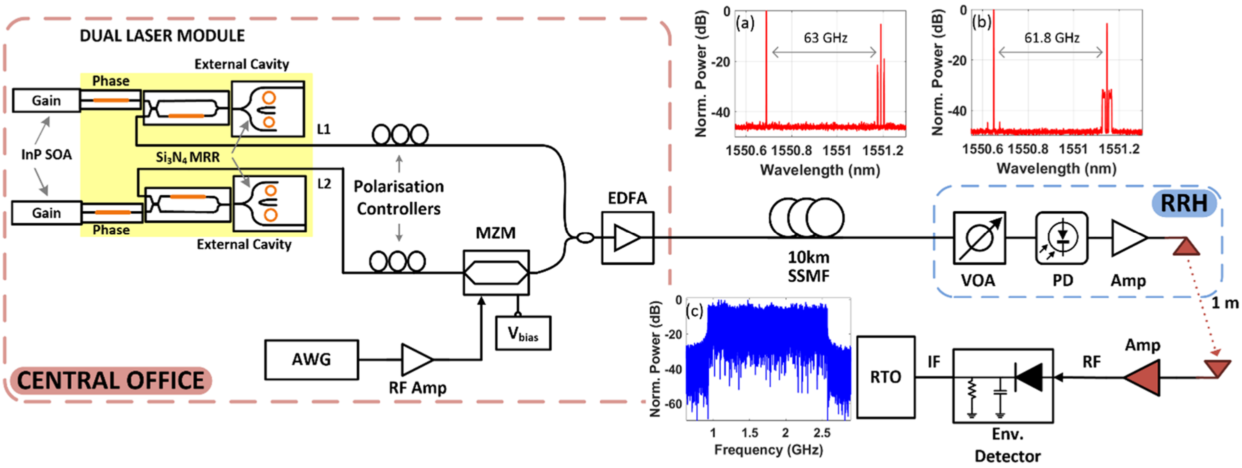

Fig. 1. Graphically representation of integrated dual laser module with experimental setup. Wireless transmission components are highlighted in red. Inset (a) , (b) shows optical spectrum of 5G NR and WiGig signal respectively received at PD and (c) shows received IF WiGig signal for $F_C = 61.8$ GHz

enable tunable (both in terms of power and wavelength) single mode operation. A detailed analysis of the laser module [10] shows that the laser module supports a 70 nm tuning range and a side mode suppression ratio (SMSR) of > 50 dB. In this work, each of the on-chip lasers are controlled (primarily through the MRRs) such that the output carriers (maintained in the C band between 1547-1552 nm) have a frequency separation (F_c) between them which can be varied within the 55-65 GHz range of the V-band (this range limit is dictated only by the mm-wave amplifiers used). The output powers of L1 and L2 were kept approximately at -5 dBm and +1.8 dBm respectively, with small variations observed throughout the experiments due to tuning conditions used.

A. *Tunability, Frequecy Offset and Phase Noise Considerations*

In our previous work we have demonstrated the use of the hybrid integrated laser module in a 60 GHz heterodyne A-RoF fronthaul link using a range of wavelengths across the C-Band [14]. Since the gain sections (SOAs) of L1 and L2 are independent, the optical carriers emitted are non-coherent, giving rise to PN and FO on the produced beat-tone. To alleviate these issues, while still maintaining the wavelength tunability afforded by two independent lasers, we previously implemented a phase noise cancelling (PNC) receiver which eliminates PN and FO arising from the non-coherent optical sources [15]. The trade-off with this implementation is the additional cost and complexity added to the receiver and the use of an IQ modulator at the transmitter. To simplify the design we have deployed a simple and low cost analog receiver employing an envelope detector, which then facilitates the use of a single ended Mach-Zehnder modulator (MZM) for amplitude modulation at the transmitter and just a single booster optical amplifier. Of course this simplified system architecture comes at the cost of reduced spectral efficiency compared to [15] and a reduction in receiver sensitivity. Nevertheless excellent performance is achieved.

III. EXPERIMENTAL SETUP

The mm-wave A-RoF experimental setup is depicted in Fig. 1. The lasers are individually thermo-optically tuned to produce the optical carriers with the desired wavelength and mm-wave frequency carrier separation. The output from L2 is amplitude modulated at an intermediate frequency (IF) of 1.75 GHz by a single-ended LiNbO$_3$ MZM. The power of L2 is set at a higher power than the output from L1 to partially compensate for the losses introduced by the MZM. We have transmitted two types of IF OFDM signals that resemble the 5G NR and Wifi Gigahertz (WiGig) [2] standards. The two IF signals, whose properties are given in Table I., were generated by the Tektronix arbitrary waveform generator (AWG) 70002A operating at 20 GSa/s and amplified before being used to drive the MZM biased at quadrature for double sideband modulation. The modulated and unmodulated carriers are combined by a coupler and the composite signal (see example optical spectra for the 5G and WiGig signals in Fig 1. (a) and (b) respectively) is amplified using an Erbium doped fiber amplifier (EDFA) with the input power to the 10 km optical fiber reel set at +7 dBm. After transmission, remote heterodyne detection is enabled by a 70 GHz PIN photodetector. The produced mm-wave signal with two data sidebands is first amplified before being transmitted and received by a set of 20 dB gain directional horn antennae over a 1 m wireless link distance. The received mm-wave signal is fed to a 50-75 GHz envelope detector with 3 GHz IF bandwidth. The envelope detector retrieves the amplitude modulated information to generate an IF OFDM signal (see example IF WiGig spectra in Fig.1 (c)) which is captured by a real time oscilloscope (RTO) at 50 GSa/s. The captured signal goes through offline time synchronization, channel estimation and equalization and BER and EVM calculation.

TABLE I. INTERMEDIATE FREQUENCY PROPERTIES

Properties	5G NR	WiGig
QAM order	256, 512	64
FFT size	2048	512
No. of Subcarriers	800	336
Subcarrier Spacing	244.14 kHz	4.88 MHz
Bandwidth	195.31 MHz	1.64 GHz
Datarate	1.56, 1.76 Gbps[a]	9.84 Gbps

[a] Values for QAM-256 and QAM-512 respectively.

IV. RESULTS AND DISCUSSION

The mm-Wave A-RoF system performance is initially analyzed in terms of BER with respect to the received optical power (ROP) for two frequencies in the V-band modulated with both the 5G NR and WiGig signals. The results presented

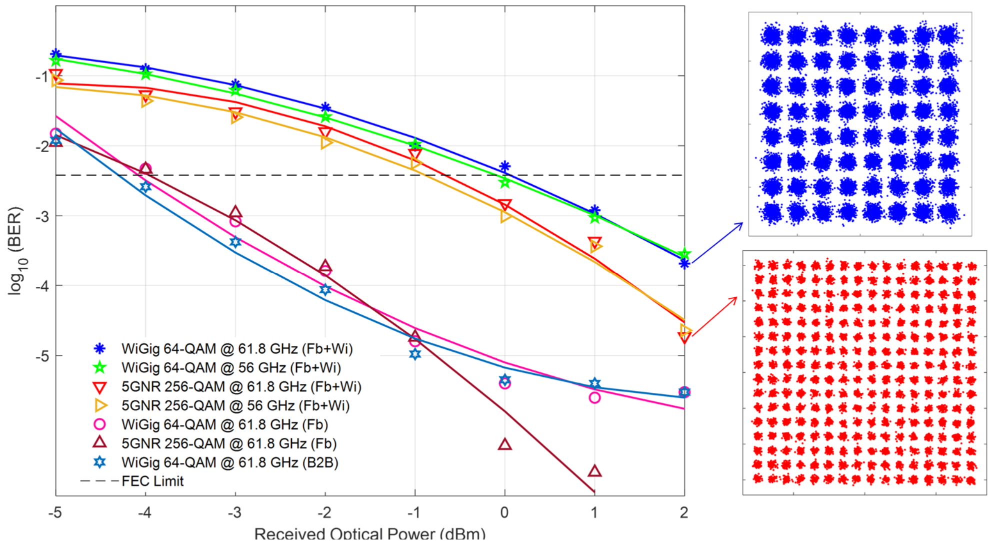

Fig. 2. BER versus ROP over both fiber and wireless, only fiber and back-to-back links. The right insets show the constellation of demodulated 61.8 GHz mm-Wave 64-QAM WiGig (blue) and 256-QAM 5G NR (red) signals, respectively, at +2 dBm ROP.

in Fig. 2 are observed for the system with 10 km fiber and 1 m wireless channel (Fb+Wi), 10 km fiber only (Fb) and back-to-back (B2B) configuration. Line of sight wireless transmission is performed in this experiment using two horn antennae and the additional signal booster amplifier (shown in red in Fig. 1) deployed before the signal is fed to the envelope detector. The figure shows that very similar performances are achieved for operation at both 56 GHz and 61.8 GHz carrier frequencies in all Fb+Wi cases evaluated. Comparing the 5G NR (256-QAM) and WiGig (64-QAM) signals in the Fb+Wi cases, a 1 dB penalty in optical receiver sensitivity is observed at the 7% overhead (OH) FEC limit (3.8×10^{-3}). This observed penalty is attributed to the relative degradation, in terms of signal-to-noise ratio (SNR), of the larger bandwidth WiGig signal as it is transmitted through electrical and optical gain stages as well as the difference in QAM formats between the two mobile signal types transmitted. Removing the wireless link components (Fb cases) results in similar performances for both 5G NR and WiGig signals, with both hitting the FEC threshold at a ROP of -4 dBm. We attribute this convergence of performances to the fact that operation at this ROP results in a relative increase in photodetector (thermal) noise (compared to the Fb+Wi scenarios) and reduced electrical signal input power to the envelope detector. This result indicates an optical receiver sensitivity penalty of 3 - 4 dB due to the additional noise introduced by the RF amplifier required for wireless transmission. Observing the Fb and B2B cases for the WiGig signal at 61.8 GHz indicates that little to no penalty is introduced due to fiber transmission. At higher ROPs in the Fb transmission scenarios an error floor emerges in the case of the WiGig signal at 61.8 GHz, but is not evident for the 5G NR signal at the same frequency (B2B). Again, we attribute this effect to the relative impact of the wider bandwidth signal on system performance.

In Figure 3, the EVM is shown as a function of the transmitted mm-wave carrier frequency (mm-Wave F_c) for a ROP of +2 dBm. The mm-Wave F_c is varied from 55 GHz to 64.3 GHz for the Fb+Wi scenario. At all frequencies across the band the WiGig signal exhibited EVMs in the range of 6.1 - 6.7%; well below the 64-QAM EVM limit of 8%. Even better uniformity in performance across the frequency span is exhibited where the 5G NR signal is transmitted through the flexible mm-wave fronthaul link. Performances below the 3.5% EVM limit for this 256-QAM signal are achieved in all cases; with operation on the 64.3 GHz frequency channel providing an EVM as low as 2.4%. Small variations observed in EVM performance are attributed to slight changes in the carrier power ratio emitted by the dual laser module for various tuning settings. Additional results at 58.3 GHz and 64.3 GHz in Fig. 3 also show that the transmission of a 5G NR-like signal with 512-QAM modulated subcarriers (see inset received constellation) is also feasible in the Fb+Wi system scenario, with measured EVMs of 2.5% and 2.4% (BER = 2.93×10^{-4}), respectively.

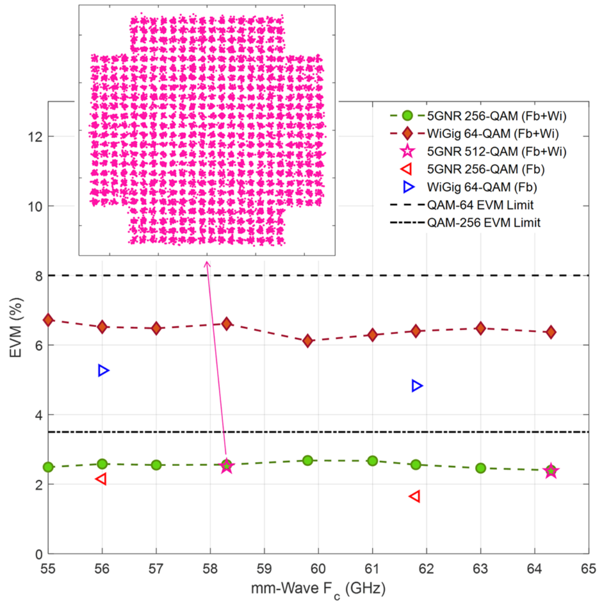

Fig. 3. EVM as a function of mm-Wave F_c is set at 2 dBm ROP. The insets shows an example received constellation for the 512-QAM 5G signal at 58.3 GHz

V. CONCLUSION

In this work, we have demonstrated the flexible remote generation of a range of mm-wave frequencies in the V-band with a hybrid integrated InP-Si_3N_4 dual tunable laser module. The deployment of an envelope detector based receiver simplifies the A-RoF transmission system by eliminating the need for frequency offset and phase noise correction, and in the context of this centralized optical/mm-wave fronthaul platform, enabling the design of an RF LO-free system with just a single optical amplification stage. The system performs exceptionally well, with all recorded EVMs below 3% and 7% for the transmission of 256-QAM 5G and 64-QAM WiGig signals, respectively, and exhibits excellent uniformity in EVM performance with both signals exhibiting a variance of less than 1% across the frequency range. Although, the double sideband nature of the signal transmission here limits achievable spectral efficiency, the results show that this can be somewhat offset by the successful transmission of OFDM signals with higher order QAM, up to 512 levels. Overall, the key features of the of hybrid In-SiN dual laser - ultra-flexible wavelength tuning and compatibility with photonic integration platforms - in combination with the simplicity of the system design, makes the proposed system a cost effective and highly reconfigurable solution for converged optical access networking supporting future mm-wave mobile services.

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