Flexible Optical and Millimeter-Wave Analog-RoF Transmission with a Silicon-based Integrated Dual Laser Module

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Abstract *A hybrid integrated InP-Si_3N_4 dual tunable laser module is deployed as a highly flexible source for converged optical/mm-wave fronthaul. Experimental results show the wavelength flexible delivery of 5G signals over analog radio-over-fiber, incorporating wireless transmission at 60 GHz, with received EVMs as low as 5%.*

Introduction

The recent inclusion of millimeter-wave (mm-wave) frequencies in 5G specifications has paved the way for the widespread commercialization and deployment of mobile communications systems initially utilizing carrier frequencies between 25 and 39 GHz. The enormous bandwidth demands envisioned for future applications such as autonomous vehicles (AV) and virtual reality (VR), coupled with the continued proliferation of small cell antenna sites, means that the expansion to higher mm-wave, and even terahertz (THz), frequencies is inevitable as we transition to the next generation of mobile communications[1].

For many years, photonic solutions have been recognised as an effective means to generate electronic carriers at such high frequencies. More recently, research has focused on how these methods may be integrated with existing optical infrastructure (e.g. optical access networks) for mm-wave generation and distribution – a concept known as 'convergence'[2,3]. Indeed, our previous works have explored how a pair of optical carriers with a mm-wave frequency difference may be distributed over an analog radio-over-fiber (A-RoF) fronthaul link from a central office (CO) to a remote radio head (RRH) for heterodyne detection; directly producing a mm-wave mobile signal after the photo-detection stage[4,5]. Although the A-RoF (i.e. multi-carrier modulation) transmission approach introduces stringent linearity, phase noise and frequency offset requirements[4], it holds a distinct advantage over current digital (i.e single carrier) approaches in terms of both spectral efficiency and the potential for network scaling[6].

Increasingly, flexible optical technologies such as tunable lasers, optical switch fabrics and active remote nodes are being proposed as a means to incorporate high bandwidth and low latency wavelength division multiplexing (WDM) networking in the access domain[7-10]. From the perspective of a converged network operating in such a dynamic environment, the ability to assign pairs of optical carriers in a flexible manner across a wide wavelength range for remote mm-wave carrier generation would be highly advantageous.

A discrete approach to optical heterodyning involves the use of two independent tunable lasers whose wavelengths are separated by the desired mm-wave frequency. This method can provide a high level of tunability – but such operation typically requires the use of bulky and expensive sources as well as phase locking. Comb based solutions such as gain-switched optical frequency combs (GS-OFCs)[11] and mode locked lasers (MLLs)[4] can provide pairs of coherent carriers for heterodyning but lack a high degree of tunability in operational wavelength and carrier frequency spacing, respectively. Integrated dual laser solutions providing higher levels of tunability have also been proposed using two distributed Bragg reflector (DBR) lasers[12,13] with Carpintero et al.[12] showing flexible THz operation on a hybrid InP-polymer platform. The advantages of silicon photonics (SiP) are exploited by Hulme et al.[14] who demonstrate mm-wave carrier generation from 1-112 GHz with a wavelength tuning range of 42 nm using a dual external cavity laser (ECL) integrated SiP circuit.

In this work, a tunable InP-Si_3N_4 based hybrid integrated dual laser module is successfully deployed for the first time in a heterodyne A-RoF fronthaul link, incorporating both 10 km fiber and 60 GHz wireless transmission over up to 2 m. The dual laser device, which offers ultra wide wavelength tuning (up to 70 nm for each laser[15]) and relative carrier frequency differences incorporating mm-wave and THz frequency ranges[16], is combined in the fronthaul system with a phase noise cancelling (PNC) receiver which eradicates the need for a receiver local oscillator (LO)[17]. The resultant system supports wavelength flexible 60 GHz A-RoF delivery, with transmission of 5G 64-QAM orthogonal frequency division multiplexing (OFDM) exhibiting error vector magnitudes (EVM) as low

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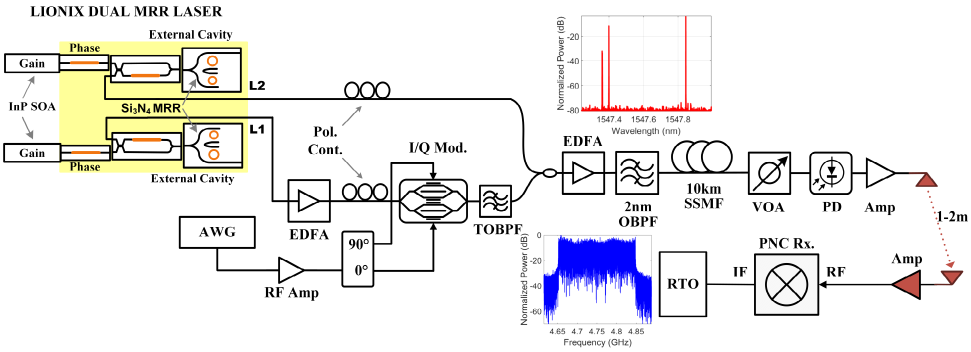


Fig. 1: Dual laser module schematic and experimental setup. Elements in red indicate components added to the system for wireless transmission. Insets show transmitted optical spectrum (red) and a received IF OFDM signal (blue).

as 5 % over the full link.

MRR based Dual Tunable Laser Module

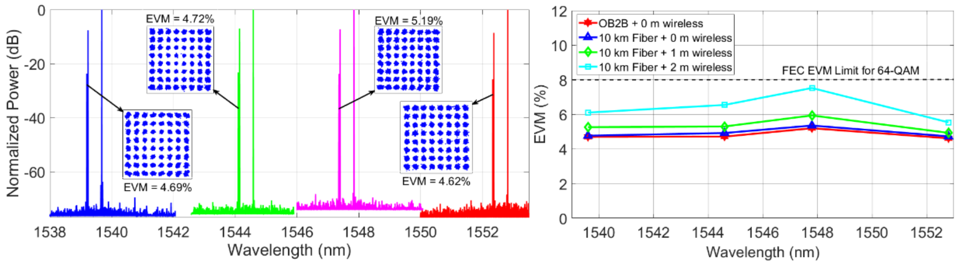
The InP-Si_3N_4 hybrid integrated dual laser module comprises two on-chip lasers, each with their own output fiber, and is graphically represented in Fig.1. Each laser consists of an independent InP semiconductor optical amplifier (SOA) hybrid coupled to Si_3N_4 feedback circuit which incorporates two micro-ring resonators (MRRs) in a Vernier configuration. Both lasers have associated phase and Mach-Zehnder interferometer-based tunable coupler sections which, along with the MRRs, can be thermo-optically controlled to vary the lasers' wavelength and output power. A detailed device description and characterization is given in our previous work [15], and shows laser tuning ranges of 70 nm each and high side mode suppression ratio (SMSR) of > 50 dB. In this work, fine thermo-optic tuning of each lasers' associated sections was undertaken such that a relative carrier frequency difference of 56 GHz was exhibited at four separate central wavelengths within the C-band.

Experimental Setup

The heterodyne A-RoF experimental setup is shown in Fig. 1. The output from laser 1 (L1) is set to -3 dBm and is then amplified to overcome the losses introduced by the modulation arm of the transmitter. The output of laser 2 (L2) is set to +1dBm and assigned as the unmodulated optical carrier. An electrical 64-QAM OFDM signal (800 data subcarriers, 195 MHz bandwidth, 244 kHz subcarrier spacing and data rate of 1.17 Gb/s) at an intermediate frequency (IF) of 4.75 GHz, was produced by the arbitrary waveform generator (AWG) operating at 20 GSa/s. The signal was amplified and fed to a 90° hybrid coupler and I/Q Mach-Zehnder Modulator (MZM) biased close to the null point to perform optical single sideband (O-SSB) modulation on the optical carrier (L1). Complete suppression of the upper sideband was achieved using an optical band pass filter (OBPF) following modulation - considering the 20 dB modulator extinction. The modulated and the unmodulated optical carriers, which are 56 GHz apart, are coupled using a 50:50 coupler and the combined output is amplified by the Erbium doped fiber amplifier (EDFA) to a total power of +3 dBm before it enters the 10 km fiber. A 2 nm OBPF is used for filtering out the out-of-band amplified spontaneous emission (ASE) noise. The two optical carriers beat together at the 70 GHz PIN photodetector and produce a mm-wave carrier at 56 GHz and OFDM sideband at 60.75 GHz (56 GHz + 4.75 GHz). The composite mm-wave signal (carrier and data signal are amplified and then transmitted over a wireless link of 1 - 2 m using a set of 20 dB gain directional horn antennae. The transmission of the mm-wave data signal alongside a phase noise correlated carrier, enables phase noise and frequency offset cancellation using an analog electrical PNC receiver structure which is described in detail in[5, 17]. Mixing of the mm-wave carrier and data sideband terms at the PNC stage produces a clean IF OFDM signal which is then captured by a real time oscilloscope (RTO) at 50 GSa/s before offline processing consisting of synchronization, channel estimation and equalisation and EVM measurement was performed.

Results and Discussion

In order to assess the suitability of the photonic integrated dual laser source for mm-wave distribution in a flexible network, the performance of the outlined mm-wave A-RoF system is analyzed using four different sets of wavelengths (attained through appropriate biasing of the device’s sections) across the C-band.. Four different transmission scenarios are then evaluated for each wavelength pair while maintaining a constant relative carrier difference of 56 GHz. Fig. 2(i) shows normalized optical spectra for these four sets of wavelengths along with a modulated 5G NR compatible OFDM data signal. The four insets in Fig. 2(i) show the corresponding 64-QAM constellations of the demodulated 60.75 GHz mm-wave signal at these wavelengths after optical back-to-back



(i) (ii)

Fig. 2: (i) Superimposed spectra of wavelengths after 2 nm OBPF with respective constellations of the demodulated 60.75 GHz mm-wave signal and EVM values, (ii) EVM performance of the received signal with respect to the wavelength.

(OB2B) transmission – which does not include wireless transmission. The excellent performances across the C-band (which are also shown by the red curve in Fig 2(ii)) of between 4.6 and 5.2% EVM highlight the wavelength tuning capabilities of the device, as well as the ability of the PNC receiver to mitigate the effects of phase noise (PN) and frequency offset which can arise from the independent nature of the lasers' on-chip gain sections. A small degradation in the performance at the 1547.8 nm wavelength pair is attributed to a reduction in the combined EDFA gain response at that wavelength, as evidenced by the corresponding normalized spectrum (pink) in Fig. 2(i). Consequently, a slightly elevated EVM value is obtained for all transmission results obtained at this wavelength (see Fig. 2(ii)). Fig. 2(ii) also shows that the addition of transmission over 10 km of fiber has a negligible effect on system performance compared to the OB2B case for all four wavelength pairs - the received optical power (ROP) is set at -2 dBm in these cases.

Wireless mm-wave transmission is experimentally undertaken by adding two horn antennae each with a pass band of 55-65 GHz and an additional receiver side electrical amplifier required to boost the input power to the PNC receiver. The line of sight wireless link was manually adjusted to maximise the received power for transmission distances of 1 and 2 m's. Fig. 2 (ii) shows that the addition of a 1 m wireless link following 10 km fronthaul transmission (green curve) results in a small (~0.5%) degradation in EVM across all tested wavelength pairs. This is attributed to the reduced electrical signal-to-noise ratio (SNR) at the receiver due to signal attenuation over the wireless link. Nevertheless, excellent performance below 6% was achieved in all cases over the full fiber-wireless link.

Increasing the wireless distance to 2 m results in a further 1 - 1.5 % degradation in EVM across the range, and this is due to the combined effects of marginally elevated PD nonlinearity (as the ROP in this case was increased to 0.5 dBm in order to obtain a reasonable signal level at the PNC receiver), as well as additional signal attenuation over the increased wireless link distance. Again, good performance, below the forward error correction (FEC) limit, of between 6 and 7.8% EVM can be observed for the received 1.17 Gb/s OFDM signal. It should be noted that a more advanced wireless mm-wave link design, such as beam-forming operation using a phase array antenna (PAA) for example, could greatly increase the achievable wireless transmission distance for the presented system [18].

Conclusion

The experimental results presented in this work demonstrate the ability of a hybrid integrated InP-Si_3N_4 dual tunable laser module to provide flexible carrier assignment, across a range of wavelengths in the C-band, for remote mm-wave generation. When implemented in tandem with an analog PNC receiver circuit, excellent performances of ~5% EVM are achieved on all test wavelengths over the full fibre fronthaul link and a 1 m wireless distance, with negligible degradation compared to the back-to-back cases. The results demonstrate, for the first time, how an integrated dual MRR-based laser module can provide a highly re-configurable silicon-based platform for the successful delivery of 5G A-RoF mm-wave services – in this case delivering a raw mobile data rate of 1.17 Gb/s at 60.75 GHz.

Compared to InP-based solutions, the used silicon nitride approach provides the potential for smaller form-factor, greater cost efficiency and a higher yield device fabrication, as well as ease of integration with surrounding optical and electronic components; ultimately paving the way for a fully integrated optical/mm-wave transmitter.

Overall, the work shows that wide tunability afforded by the integrated dual laser module in combination with advanced system design is a highly promising approach enabling photonic mm-wave networking over an optical access infrastructure. This holds particular relevance for future converged optical networks exploiting flexibility in the wavelength domain.

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