InP-Si_3N_4 Dual-Laser Hybrid Source-Based Wireless Mm-wave Communication Link Using Optical Injection Locking

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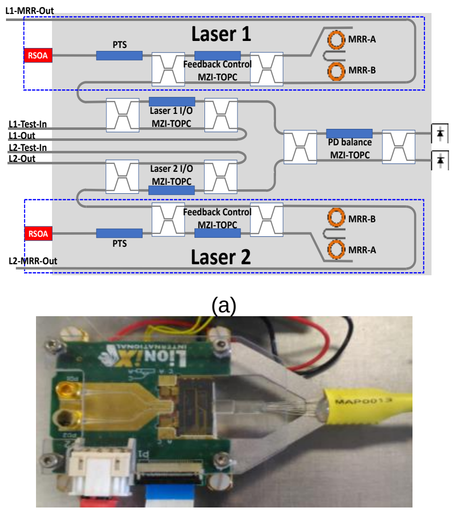
Abstract *This paper presents an InP-Si_3N_4-based dual-laser hybrid optical source stabilized using an optical injection locking for the mm-wave signal generation which provides a carrier frequency at 93 GHz for a wireless communication link. We demonstrate a wireless link with a data rate up to 28 Gbps.*

Introduction

It is expected that networks will utilize frequency bands in the millimeter-wave range (from 30 to 300 GHz) to deliver extreme link capacities with miniaturized transceivers [1]. These are key parameters to enable radio access densification in urban scenarios through wireless backhaul of small cells. Photonic-based RF signal generation techniques, due to their efficiency and maximum reachable frequency, have spearheaded access to the millimeter-wave range **Error! Reference source not found.**. Among the available techniques for continuous-wave (CW) signal generation, optical heterodyning exhibits the widest frequency range, from the microwave (3 GHz to 30 GHz) to the Terahertz (300 GHz to 3 THz) range, with the potential for tuning the carrier radiofrequency (f_{RF}) across these bands. Optical heterodyning is based on beating two optical wavelengths (λ_1, λ_2), spaced by the desired RF frequency, onto a photo mixer (a high-speed photodiode or a photoconductor. In addition to a high maximum frequency and wide tuning range, other key performance indicators are frequency stability, linewidth, and spectral purity [3] which usually required using some stabilization scheme with an optical heterodyne source. In this work, we present for the first time a wireless transmission link operating at a carrier frequency in the millimeter-wave range (93 GHz) based on an injection-locked stabilized hybrid integrated optical heterodyne source using higher-order modulation formats to increase the data rate up to 28 Gbps.

Device structure.

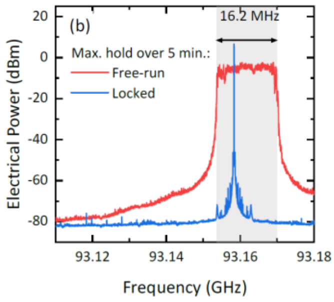
Fig. 1 shows the hybrid integrated optical heterodyne source, which has been previously used for a free-running mm-wave generation [4] and optical transmission [5]. Each laser is formed by an InP quantum-well gain chip (RSOA) and a TriPleX chip where high-Q cavity mirrors are defined using a double Micro Ring Resonator (MRR). Each ring in the MRR structure, MRRA and MRRB, have independent heater-based phase actuators enabling wavelength tuning. An intracavity Mach-Zehnder interferometer (MZI-TOPC) controls the optical power coupled out and a phase tuning section (PTS) allows to fine tune the cavity length [6]. A second MZI outside the cavity controls where the optical power is directed, either to a pair of integrated photodiodes (PDs, which were not used in the experiments reported here) or to the output fiber. A key parameter for optical heterodyne millimeter-wave generation besides the optical linewidth of each wavelength is the long-term drift generated by each laser due to thermal inestabilities in the laser, since this parameter determine the frequency stability of the generated RF signal. Fig. 2 (a) (red line) shows the frequency drift of the generated RF signal when the hybrid laser source is in free-running condition. It exhibits a frequency drift



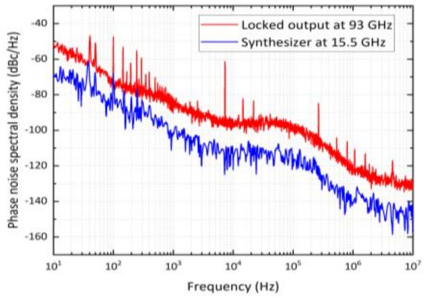
(a)

(b)

Fig. 1: (a) Schematic diagram of the hybrid optical heterodyne photonic integrated circuit (not to scale), and (b) Photograph of the resulting module. RSOA: Reflective Semiconductor Optical Amplifier, PTS: Phase Tuning Section, MZI-TOPC: Mach-Zehnder Interferometer based Thermo-Optic Power Coupler, MRR: Micro-Ring Resonator, PD: Photodiode.



(a)



(b)

Fig. 2: (a) Electrical spectrum of the hybrid laser obtained. (b) Phase noise spectral density of the 93-GHz locked signal and that from the 15.5-synthesizer signal used to drive the Optical Frequency Comb Generator (OFCG)

about 16.2 MHz over 5 minutes using a Maxhold condition. On the other hand, by locking the optical modes of each laser to an external stable optical frequency comb, this frequency drift can be reduced. The Optical Injection Locking (OIL) technique is used to stabilize the wavelength of the hybrid laser reducing the long-term drift due to thermal inestabilities of the laser source in order to comply with the current regulations on frequency stability. Therefore, we can see in Fig. 2 (a) (blue line) , the frequency drift is reduced, less than 1 Hz, so that it depends on the frequency stability of the synthesizer used for this purposed. Fig. 2 (b) shows the phase noise of the 93-GHz signal and also that from the 15.5-GHz synthesizer signal used to drive the Optical Frequency Comb Generator (OFCG). As the multiplication factor was 6 (i.e., 15.5 6 = 93), the theoretically-expected difference between the two curves is 20 log10(6) = 15.6 dB. It is very noticed that, in order to comply with ITU regulations on frequency stability, an ultra-stable RF signal must be generated independently of the type of detector used at the receiver stage.

Communication Experiments

In this section, a wireless transmission link with a 93 GHz carrier signal is carried out with the hybrid integrated heterodyne source under optical injection locking and its results are reported. Regarding the transmitter stage, in order to transmit a high data rate, high modulation formats are used, thus, a DSP-aided transmission of 7-GBd 16-quadrature amplitude modulation (QAM) signals is performed in this experiment. On the other hand, at the receiver stage, an Envelope Detector (ED) is used in this experiment. A key feature of the EDs is that they are insensitive to the phase noise of the transmitted data signal and, thus, can be used to recover jittery signals (which may have either real symbols or complex ones as shown in [7]).

For this experiment, a gain current of around 180 mA was used in both lasers, each of them generating an output power of 12.5 dBm. The SMSR obtained from each independent laser is about 40 dB The experimental arrangement for real-time transmission is shown in Fig. 3 (a). The output of the OFCG was split in a 50/50 coupler and sent to the module containing the two-hybrid lasers via two circulators. After the optical Optical Injection Locking (OIL) of both lasers, a Mach-Zehnder modulator (MZM) placed at the laser 2 output for optical modulation of the digital signal was used. The modulated signal (whose spectrum is shown in Fig. 3 (b)) was then amplified by an EDFA to overcome and compensate for the optical losses introduced by the MZM and its output combined with the laser 1 output using and optical combiner. The optical combiner output is then injected into an F-band waveguide-coupled uni-traveling carrier photodiode (NTT IOD-PMF-13001). The 93-GHz signal was then launched into free space with a horn antenna and collimated with a Teflon lens. At the receiver side, another identical Teflon lens focused the 93 GHz signal into an envelope detector (ED) [8]. This ED has a Si lens for light coupling. The ED was a waveguide-coupled ED from VDI (WR10ZBD-F). After the ED a low-noise

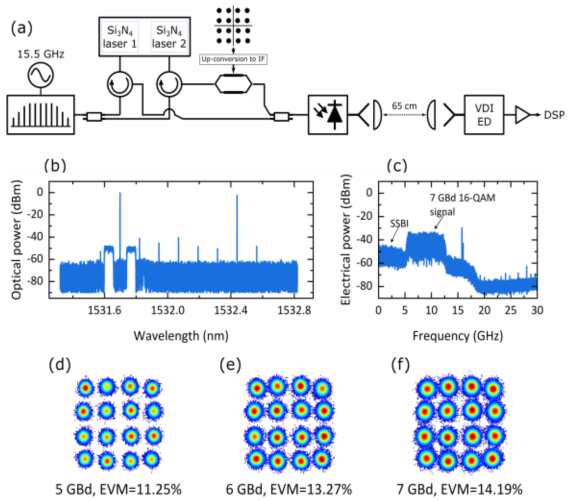


Fig. 3: (a) Experimental arrangement for real-time transmission at 93 GHz; optical spectrum after Mach-Zehnder modulator (MZM) for (b) free-running and (c) locked signals; and (d) bit error rate (BER) curves of the free-running and locked signals

amplifier was used before sending the received signal to the Digital Signal Processing (DSP), where constellation analysis and bit error counting were carried out.

It is important to realize that, when the source is operated in locked mode, the unwanted OFCG tones that are not totally suppressed by the OIL-based filter leak into the PD. In [9], where a similar experiment is reported with two polymer lasers locked to an external comb, these spurious tones are cited as the main reason limiting the data speed of the system.

Digital-to-analog and analog-to-digital conversion were performed with a Keysight arbitrary waveform generator (M8195A) and oscilloscope (UXR0334A), respectively. A conventional DSP routine was used for data generation and reception with the only difference that no frequency offset or phase noise compensation algorithms were required at the receiver due to the high purity of the transmitted signal. A guard-band between the optical carrier and data-carrying signal was intentionally set (as can be seen from Fig. 3 (b)) to reduce the signal-signal beat interference (SSBI). Fig. 3 (c) shows the spectrum of the signal digitized by the oscilloscope. The peak at 15.5 GHz is caused by the spurious tones from the OFCG adjacent to the data-carrying signals. Fig. 3 (d), (e), and (f) show the 16-QAM constellation diagrams for symbol rates of 5, 6, and 7 GBd, respectively. A data speed of up to 28 Gbit/s (corresponding to the symbol rate of 7 GBd) was successfully transmitted over the wireless link. The main limitations of the current system are two: the bandwidth of the low-noise receiver amplifier - up to 12 GHz - and the dynamic range of the MZM driver amplifier. The limited bandwidth of the LNA, together with the need for a guard band to combat the SSBI made it difficult to transmit at speeds faster than 7 GBd. On the other hand, the MZM driver amplifier introduced non-linear distortions for relatively low AWG output powers. Because of this, the modulator was driven with a peak-to-peak voltage substantially lower than half of its π voltage (from Fig. 3 (b) one can see that the modulation index was rather low).

Conclusions

Successful carrier generation at 93 GHz is demonstrated by locking two integrated hybrid InP- Si_3N_4 lasers to an optical frequency comb achieving an ultra-stable ITU-compliant signal. DSP-aided data transmission is achieved at this frequency with a data rate of up to 28 Gbit/s.

Acknowledgments

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