60 GHz Wireless Link Implementing an Electronic Mixer Driven by a Photonically Integrated Uni-Traveling Carrier Photodiode at the Receiver

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***Abstract*— We report the first 60 GHz wireless link implementing a uni-traveling carrier photodiode (UTC-PD) at the transmitter and a photonic integrated chip incorporating a UTC-PD at the receiver. In this demonstration, a 64.5 GHz signal carrying 1 Gbps on-off keying (OOK) data was generated by heterodyning two optical tones into the transmitter UTC-PD. The signal was transmitted using a 24 dBi gain parabolic antenna over a wireless distance of three metres before reaching an identical receiver antenna. At the receiver, an electronic mixer was used to down-convert the received signal into an intermediate frequency of 12.5 GHz. The local oscillator to the electronic mixer was provided by heterodyne mixing of two optical tones generated using a UTC-PD that is monolithically integrated with semiconductor lasers. The down-converted signal was acquired by a real-time oscilloscope for offline processing, which showed zero error bits in a 10^5 bit-long transmission.**

Keywords—5G, photodiodes, millimeter waves, mixers.

I. Introduction

The characteristics of the millimeter waves (MMWs) have attracted the interest of many fields, including: communications, radar, spectroscopy, among others [1]. For instance, the large bandwidth available in the MMW range (30 GHz – 300 GHz) allows for high speed communications even at low spectral efficiency. Also, the high path loss [2] at the MMW frequencies makes it more secure and allows for frequency reuse. Further, at such high frequencies, the antenna size becomes smaller, which would facilitate multiple input multiple output (MIMO) systems [3]. Consequently, MMW is considered as an enabling technology for the next generations of mobile communications and future networks. Among the potential MMW bands, the 60 GHz band is particularly interesting for the fifth generation of mobile communications (5G) because it contains 7 GHz of unlicensed spectrum in many countries [4].

MMW communications is a research area that involves two competing technologies: electronics and photonics. Despite the important advances in electronics [5], photonic-based technologies are still considered as a strong alternative because they offer wide tuneability and easy integrability with the existing high-speed fiber networks [6]. In that regards, the uni-traveling carrier photodiode (UTC-PD) is a well-known photonic-based MMW generation technology due to its superior performance in the MMW range in terms of the emitted power and the large bandwidth [7]. However, the UTC-PD exhibits a poor performance as an optoelectronic mixer because of its significant frequency conversion loss; a conversion loss of 32 dB at 100 GHz has been demonstrated using this type of photodiode [8]. On the other hand, Schottky-based electronic mixers have demonstrated less than 5 dB conversion loss at 180 GHz [9]. However, a Schottky-based mixer requires a high frequency electronic local oscillator (LO), which can be expensive and may restrict frequency agility of the receiver, while a UTC-PD mixer is widely tuneable and does not require an electronic LO as the LO is provided optically.

In this work, we present a wireless transmission link that combines the advantages of both electronic and photonic technologies. At the transmitter, a UTC-PD was used to generate 1 Gbps on-off keying (OOK) data signal at 64.5 GHz by means of optical heterodyning. The signal was transmitted using a 24 dBi gain parabolic antenna over a wireless distance of three metres before reaching an identical receiver antenna. The receiver implemented a UTC-PD-driven electronic mixer, where the UTC-PD is used to provide the LO to the electronic mixer, thus, combining the low conversion loss of the electronic mixer and the wide tuneability of the UTC-PD. The receiver UTC-PD is integrated with two distributed feedback (DFB) lasers and several semiconductor optical amplifiers (SOAs) on a single photonic integrated circuit (PIC) [10]. The spacing between the optical tones was 0.43 nm, resulting in a 52 GHz electrical heterodyne signal, which was used to drive the electronic mixer. Consequently, the incoming data signal at 64.5 GHz was down-converted to 12.5 GHz. The down-converted signal was then acquired by the real-time oscilloscope (RTO) for processing. The recovered data showed an open eye diagram, and the number of errors was zero in a 10^5 bit-long transmission.

The results presented in this work demonstrate the feasibility of hybrid integration of electronic and photonic technologies in MMW wireless receivers as an alternative solution to purely electronic or photonic -based receivers.

The rest of the paper is organized as follows. In Section II, we present the characterization of the PIC-mixer subsystem in terms of its conversion loss, followed by its implementation in the receiver of a wireless link, as described in Section III. The experimental results are presented in Section IV, and, finally, we conclude this work in Section V.

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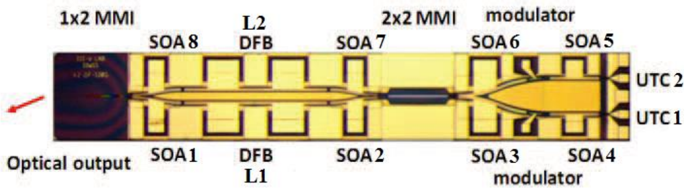

Fig. 1. Micrograph of the photonic integrated circuit [10].

II. Receiver Characterization

In this section, we present the characterization procedure of the receiver. First, the MMW generation capability of the PIC was investigated to ensure that it can generate an electrical LO signal with enough power at the required frequency. Then, the specifications of the electronic mixer were presented. Finally, the PIC-mixer subsystem was characterized in terms of its conversion loss.

A. PIC Characterization

As shown in Fig. 1, the PIC used in this work [10] comprises two UTC-PDs, two DFB lasers to provide the optical heterodyne, several SOAs to amplify the optical signals, multimode interference (MMI) couplers, and electro-absorption modulators (EAMs). Moreover, this PIC has an optical monitoring output.

First, the lower laser (L1) output was characterized by applying a DC current to its gain section. The current bias was gradually increased from zero up to 340 mA, while the optical output was monitored on the optical spectrum analyzer (OSA), as shown in Fig. 2. We observed that L1 started single mode lasing at a current bias of 43 mA. It maintained its single mode operation up to a bias of 76 mA, where it started dual-mode operation. In this regime, the spacing between the two modes was around 80 GHz, and it was found tuneable by few GHz as the current bias increased. The laser continued its dual-mode operation up to a current bias of 300 mA, after which, a third optical tone was observed. In this regime, the spacing between the two main tones was 52 GHz. Given that this PIC is to be incorporated in a 60 GHz wireless receiver, and given the frequency limitation of receiver mixer to 67 GHz, as will be shown next, the three-mode regime was decided as more suitable for the transmission experiment.

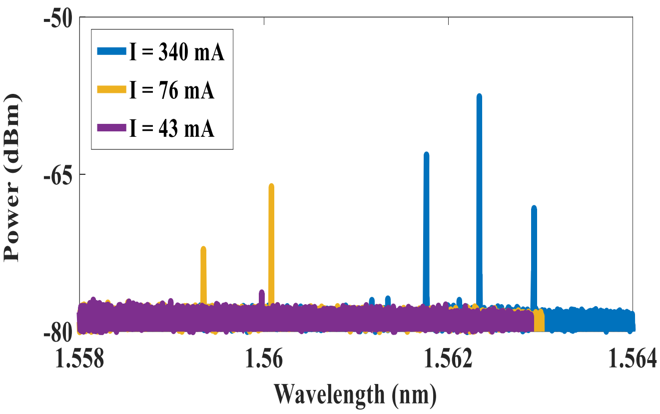

Fig. 2. Optical spectra of L1 operation at different DC currents.

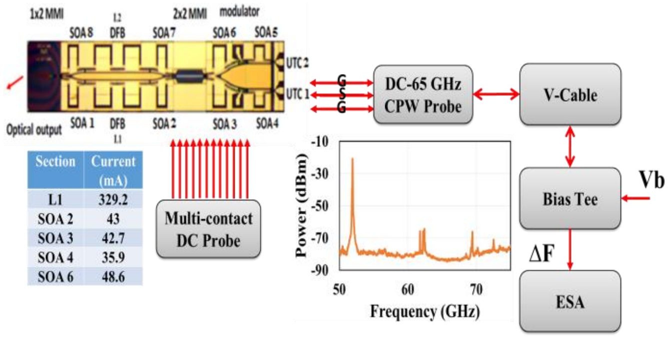

Fig. 3. Block diagram of the optical heterodyning setup.

In order to assess the performance of the PIC as an LO generator, we conducted the heterodyning experiment illustrated in Fig. 3 on the lower UTC-PD (UTC1). The optical heterodyne was generated by L1 in the multi-mode operation regime. The monitoring SOA (SOA1) was not biased to minimize reflections. The bias current values applied to the other sections are presented in the table in Fig. 3. The bias currents were applied by a multi-contact DC probe, while the generated electrical heterodyne signal was extracted by a DC–65 GHz coplanar waveguide (CPW) probe. A bias-tee was used to couple a DC bias of -2.1 V to the UTC-PD. A 1 m-long DC – 60 GHz cable was used to connect the probe to the electrical spectrum analyzer (ESA). As shown in the inset of Fig. 3, the generated electrical heterodyne signal has a peak power of -21 dBm at 51.9 GHz. Taking the cable and the bias-tee losses into account gives a peak heterodyne power of -10.7 dBm at the input of the probe. The other tones seen in the same plot are heterodyne products of other optical tones generated by the same laser.

B. Electronic Mixer Specifications

The mixer used in this experiment is a double balanced electronic mixer from Marki Microwave^{TM} (part no. MM1-2567LS) [11], which operates from 25 GHz to 67 GHz at the LO/RF ports, and from DC to 25 GHz at the IF port.

C. PIC-Mixer Characterization

Fig. 4 shows the block diagram of a mixing experiment that was conducted to characterize the PIC-mixer combination in terms of its conversion loss.

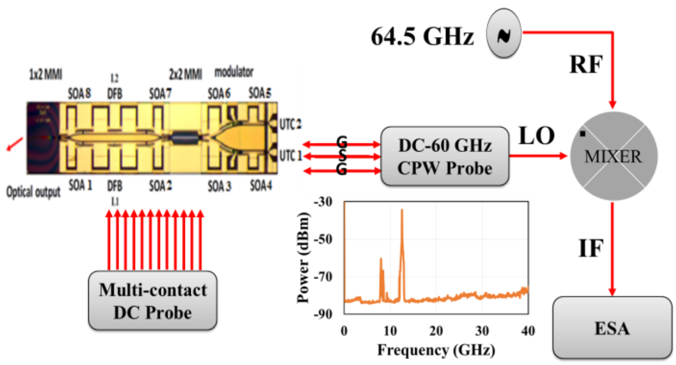

Fig. 4. Block diagram of the mixing experiment using the PIC-mixer combination.

The conversion loss is defined as the difference in dB between the power of the RF signal at the input port of the mixer and the power of the IF signal at the IF port of the mixer. A 10 dBm RF signal was generated at 64.5 GHz by a signal generator and applied to the RF port of the mixer via a 1 m-long V-cable, while the electrical heterodyne signal from the PIC, generated at 52 GHz, was applied to the LO port of the mixer. The generated IF signal was, then, measured on the ESA, as shown in the inset of Fig. 4. The measured IF signal at 12.5 GHz has a peak power of -34.3 dBm. Taking the cables losses in the RF and IF paths (16 dB and 5.3 dB, respectively), gives a conversion loss of 23 dB for the PIC-driven electronic mixer.

III. 60 GHz Wireless Transmission Experiment

Having characterized the PIC-mixer subsystem, we now show how it can be utilized in wireless communications systems by implementing it in the receiver of a 64.5 GHz wireless link.

A. *Transmitter Setup*

At the transmitter, a 1 Gbps OOK data signal was generated at 64.5 GHz by heterodyning two optical tones originating from two external cavity lasers (ECLs) into a 3x10 μm^2 UTC-PD with an epitaxial structure similar to the one described in [12].

As illustrated in the block diagram of Fig. 5, the two optical tones were generated by free-running lasers with 0.52 nm spacing (corresponding to a 64.5 GHz). A Mach Zehnder Modulator (MZM), biased at the quadrature point (V_b = 7 V), was used to modulate one of the optical signals with a 1 Gbps data signal from a pattern generator. Then, the two optical tones were coupled using a 3-dB optical coupler, and amplified by an erbium doped fiber amplifier (EDFA). The EDFA was followed by a 1 nm-wide optical filter to reduce the amplified spontaneous emission (ASE) noise. The polarization controllers (PCs) shown in Fig. 5 were used to match the polarization of two optical tones to that of the UTC-PD waveguide to maximize light coupling from the lensed fiber to the UTC-PD.

The total power of the optical signal at the input of the lensed fiber was measured by a power meter at 14.3 dBm, while the optical spectrum of the signals at this stage was measured using an optical spectrum analyzer (OSA), as shown in Fig. 5-a.

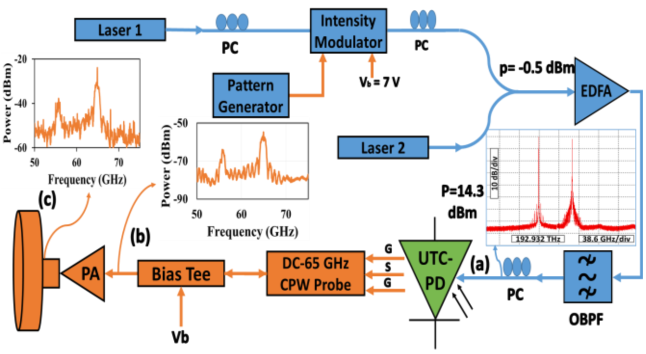

Fig. 5. Block diagram of the optical transmitter.

The UTC-PD voltage bias was supplied from a Keithley source/meter at -2.1 V using a bias-tee, while the generated photocurrent was measured at -3.5 mA. A DC-65 GHz CPW probe was used to extract the generated electrical heterodyne signal from the waveguides of the UTC-PD. The extracted electrical heterodyne signal, shown in Fig. 5-b, was then amplified with a power amplifier (PA) (gain = 37.9 dB, noise figure (NF) = 4 dB). A W-band (50 GHz - 75 GHz) variable attenuator was placed after the PA to control the transmitted signal power. The signal was transmitted using a 24 dBi gain parabolic antenna over a wireless distance of 3 m before reaching an identical antenna at the receiver. The attenuator was set to attenuate the signal by 3 dB, which corresponds to 1.4-fold increase in distance (d_{new} = 4 m).

B. *Receiver Setup*

The block diagram of the receiver is illustrated in Fig. 6. It shows the 64.5 GHz 1 Gbps data signal after detection by a 24 dBi gain parabolic antenna (Fig. 6-a), after which, it was amplified by a low noise amplifier (LNA) (gain = 31.3 dB, NF = 5.8 dB) as shown in Fig. 6-b. An LO at 52 GHz was supplied to the mixer from the PIC, as shown in Fig. 6-c. The PIC-mixer subsystem successfully down-converted the carrier frequency of the received signal into an IF of 12.5 GHz, after which, it has been captured by a real-time oscilloscope (RTO), as shown in Fig. 7, for offline processing.

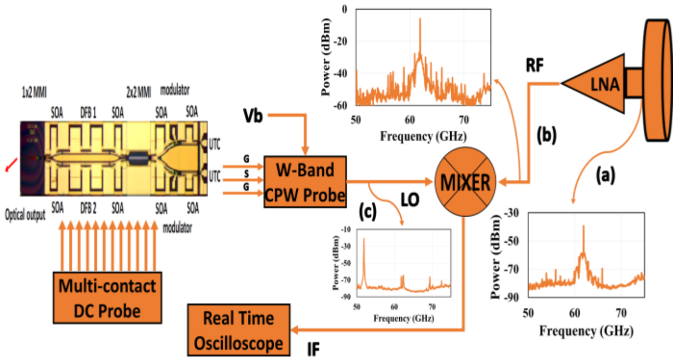

Fig. 6. Block diagram of the receiver, which implements a PIC and an electronic mixer.

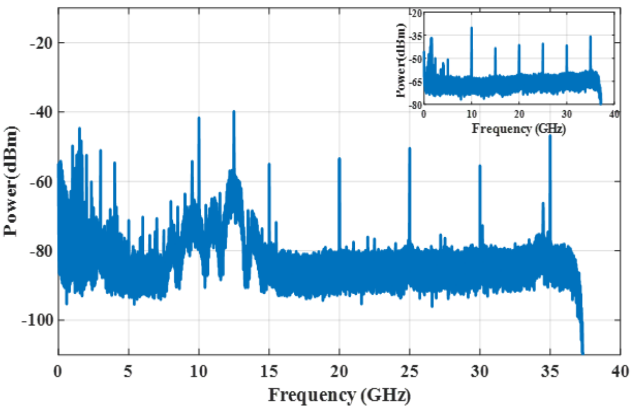

Fig. 7. Electrical spectrum of the down-converted IF signal. The inset shows the spectrum of the RTO only, without connecting any signal at its input.

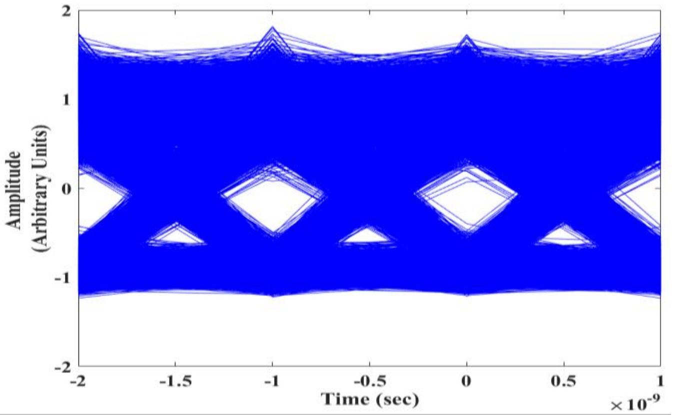

Fig. 8. Eye diagram of the recovered signal (showing 10^5 bits).

IV. Experimental Results

The RTO that captured the signal has a bandwidth of 36 GHz and sampling rate of 80 Gsamples/second. The length of the acquired waveform was 100 µs, which corresponds to 10^5 bits.

In Fig. 7, the lines that appear in the spectrum at multiples of 5 GHz are not part of the down-converted spectrum but are due to the clock signals generated from the RTO. The inset in the Fig. 7 shows the FFT spectrum of the RTO without any input signal.

A low-power data signal is observed at 9 GHz in the spectrum of Fig. 7. This is attributed to another mixing product from a second heterodyne signal since the laser was operating in a three-mode regime. This mixing product did not affect data recovery at 12.5 GHz as it was filtered out digitally.

The offline digital signal processing (DSP) that was applied to the acquired signal includes the following steps: signal filtering, digital down-conversion to the baseband, channel equalization using constant modulus algorithm (CMA), and envelope detection [13].

The number of errors in the received bit stream was calculated by comparing the transmitted and the received bits, and was found to be zero in 10^5 transmitted bits. Also, the recovered data show a relatively open eye diagram as shown in Fig. 8. The eye diagram is not smooth because the CMA equalization algorithm produces only one sample per symbol.

V. Conculsion

We successfully demonstrated a 1 Gbps OOK transmission link at 64.5 GHz with a wireless distance of three metres implementing photonic based system at the transmitter and the photonically driven electronic mixer at the receiver. The UTC-PD at the receiver is monolithically integrated with two DFB lasers and SOAs on a single PIC and was used to provide an electrical LO to drive an electronic mixer.

Transmission distance can be increased to 4 m by removing the 3-dB attenuation at transmitter. The attenuator was introduced due to the laboratory size confinement.

This work shows the viability of hybrid integration of electronics and photonics as an alternative solution to purely electronic or photonic integration. The hybrid receiver presented here combined the advantages of the low conversion losses of electronic mixers and the wide tuneability and integrability of the photonic components with the high-speed fiber networks.

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