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5 Gbps wireless transmission link with an optically pumped uni-traveling carrier photodiode mixer at the receiver

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Abstract: We report the first demonstration of a uni-traveling carrier photodiode (UTC-PD) used as a 5 Gbps wireless receiver. In this experiment, a 35.1 GHz carrier was electrically modulated with 5 Gbps non-return with zero on-off keying (NRZ–OOK) data and transmitted wirelessly over a distance of 1.3 m. At the receiver, a UTC-PD was used as an optically pumped mixer (OPM) to down-convert the received radio frequency (RF) signal to an intermediate frequency (IF) of 11.7 GHz, before it was down-converted to the baseband using an electronic mixer. The recovered data show a clear eye diagram, and a bit error rate (BER) of less than 10^{-8} was measured. The conversion loss of the UTC-PD optoelectronic mixer has been measured at 22 dB. The frequency of the local oscillator (LO) used for the UTC-PD is defined by the frequency spacing between the two optical tones, which can be broadly tuneable offering the frequency agility of this photodiode-based receiver.

OCIS codes: (230.5170) Photodiodes; (130.0250) Optoelectronics; (040.2840) Heterodyne.

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1. Introduction

As the highest demand for mobile services comes from indoor wireless networks [1], millimeter waves (mm-waves) provide an attractive solution in indoor wireless access networks because of the large spectrum availability in the mm-wave range (30 GHz – 300 GHz) [2], which allows for high speed wireless communications even at low spectral efficiency. Moreover, the high propagation loss in the mm-wave range [3] is advantageous in indoor communications since it reduces interference and allows for frequency reuse.

For communications at high carrier frequencies a mixer is needed in the receiver to down-convert the incoming radio frequency (RF) signal to an intermediate frequency (IF) to allow for electronic processing before final down-conversion to the baseband. There are several types of mixers in the mm-wave range [4, 5], including: Schottky diodes mixers [6], superconductor–insulator–superconductor (SIS) mixers [7], hot electron bolometer (HEB) mixers [8] and low temperature grown GaAs (LTG-GaAs) photomixers [9]. However, there are limitations associated with these mixers. For example, most of these mixers are not compatible with the photonic InP technology [10]. Also, SIS and HEB mixers require cooling to very low temperatures, while LTG-GaAs works at 850 nm or shorter wavelength [11] making it less attractive since components and technologies used in optical communications are more available at 1,300 nm and 1,550 nm.

On the other hand, a uni-traveling carrier photodiode (UTC-PD) has a wide range of frequency of operation [12], can be monolithically integrated with lasers and modulators on InP substrates [13] and works at room temperature. Also, unlike Schottky diode mixers, a UTC-PD does not require an electronically generated local oscillator (LO) as it can be generated by the UTC-PD itself through heterodyning two optical signals [10]. Further, it has been shown that UTC-PDs have an IF bandwidth in excess of 10 GHz [10], making them an attractive alternative if successfully demonstrated as receivers.

Previously, it has been shown that a UTC-PD can be used as an optically pumped mixer (OPM) at frequencies up to 600 GHz [14], but these demonstrations were done within a 100 Hz bandwidth [10,15]. In this paper, we demonstrate for the first time an OPM based on a UTC-PD to down-convert a wireless RF signal modulated with 5 Gbps non-return to zero on-off keying (NRZ – OOK) data occupying the bandwidth from 30.1 GHz to 40.1 GHz and centered at 35.1 GHz. Although this proof of concept was done at a carrier frequency of 35.1 GHz, this work is expected to be scalable to higher frequencies since the UTC-PD could operate at hundreds of GHz [14].

The findings of this work show the potential of using the UTC-PD as a transceiver on a single chip such as the one presented in [16]. This work could find interesting applications in future 5G or beyond networks because parts of the (30 GHz – 40 GHz) band are candidates for 5G in a number of countries [17] and future wireless networks using frequencies in the mm-wave and THz range are being investigated for a number of scenarios.

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2. UTC-PD optoelectronic mixer characterization

In this work, we used a 7x15 um^2 UTC-PD that has coplanar waveguides with epitaxy structure similar to the one described in [18]. We have characterized the UTC-PD in terms of its photocurrent versus the bias voltage for different levels of injected optical power, as shown in Fig. 1. The frequency response of the UTC-PD was characterized using the heterodyne system shown in Fig. 2, which gave a 3dB bandwidth of 33 GHz at –4 V voltage bias and 18 dBm of optical power, as shown in Fig. 3.

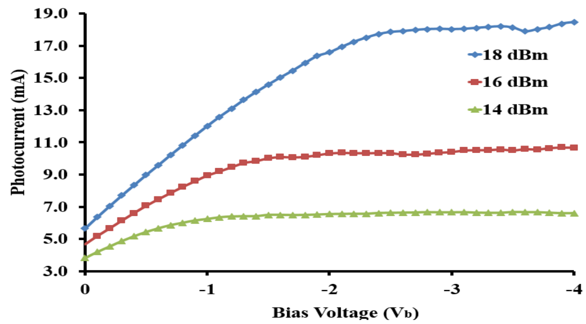

Fig. 1. I-V characteristic curve of the UTC-PD.

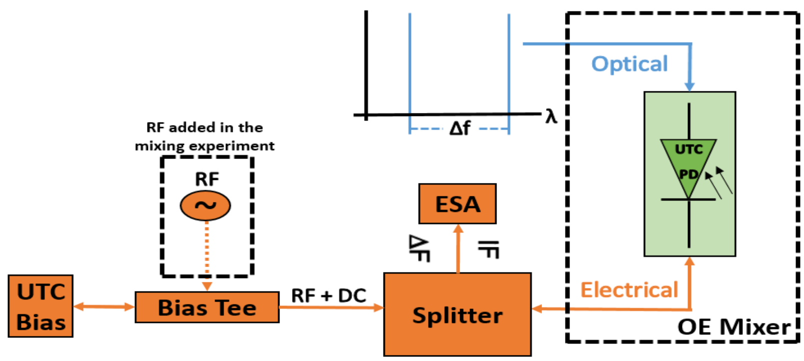

Fig. 2. Setup for optical heterodyning (without RF) and optoelectronic mixing (with RF) in UTC-PD.

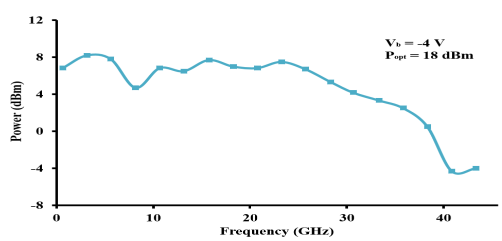

Fig. 3. UTC-PD bandwidth measurement.

Using the same experimental system with optical tones spaced by ΔF = 9.7 GHz at –4 V bias and 18 dBm optical power, we observed that the UTC-PD generates higher order harmonics of the heterodyne signal (ΔF). Signals at 9.7 GHz, 19.4 GHz, 29.1 GHz and 38.8 GHz are clearly observed in the spectrum in Fig. 4, corresponding to ΔF, 2ΔF, 3ΔF, 4ΔF, respectively. This indicates a strong enough nonlinear behaviour for mixing purposes.

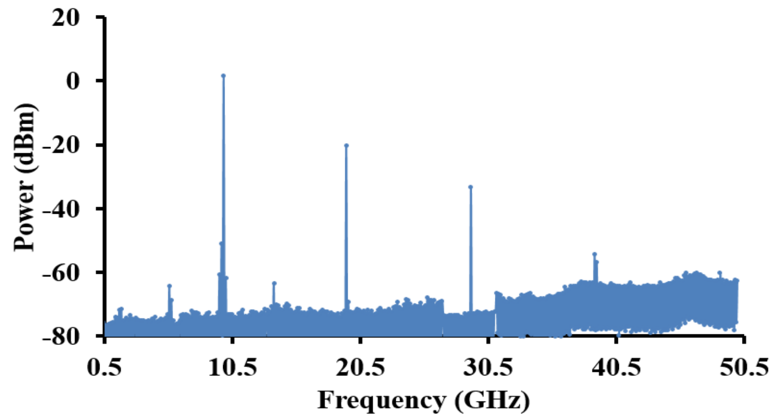

Fig. 4. UTC-PD's heterodyne and higher order harmonics at 18 dBm optical power and −4 V bias (RBW = 300 kHz, VBW = 30 kHz).

Mixing in UTC-PD can be exploited in receivers by down-converting the incoming RF signal to a lower intermediate frequency (IF) as illustrated in Fig. 2, where an optical signal with two tones spaced by ΔF is coupled into the UTC-PD via a lensed fiber, while an RF signal and a DC voltage bias are supplied to the UTC-PD via a coplanar probe. The frequency of the down-converted signal (IF) is equal to the difference between the incoming RF signal and the heterodyne signal (ΔF).

The mixing properties of the UTC-PD used as an OPM depend on the bias voltage and the injected optical power [15], hence, both should be optimized. In that regard, the conversion loss as a function of bias voltage should be plotted for different levels of optical power (Fig. 5). Here, conversion loss is defined as the ratio between the power of the incoming unmodulated RF signal (measured at input of the coplanar probe that is connected to the waveguides of the UTC-PD), and the generated IF signal power.

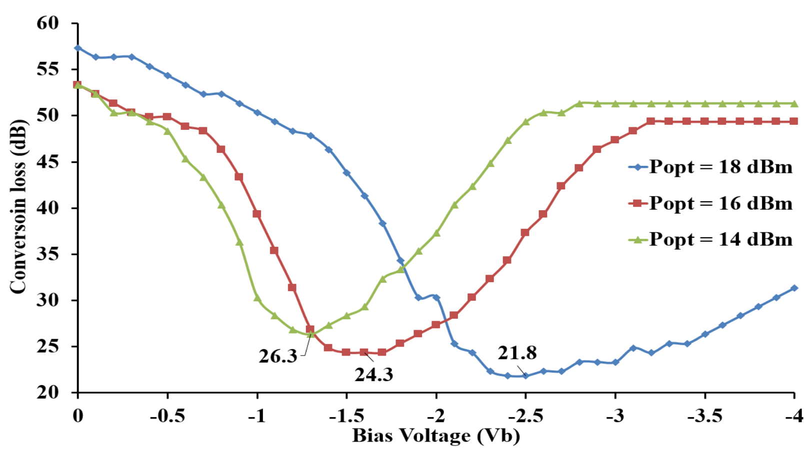

Fig. 5. UTC-PD's conversion loss versus bias voltage for different levels of optical power.

In that configuration, it's observed that lower conversion losses are achievable at higher optical powers; a minimum conversion loss of 21.8 dB was obtained at −2.5 V and 18 dBm optical power, which is the maximum optical power deliverable by the experimental setup. A plot of the conversion loss as a function of optical LO power, in Fig. 6, shows an inverse relation between the two; conversion loss decreases with increasing optical power.

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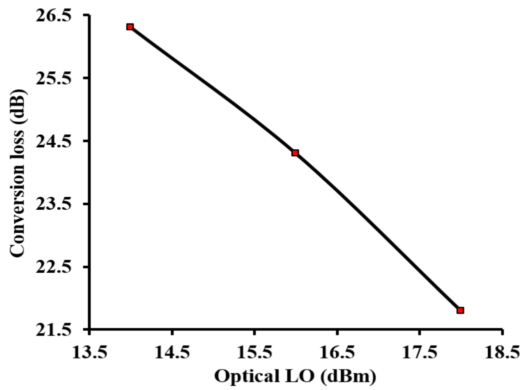

Fig. 6. UTC-PD's conversion loss versus optical power.

We observed other mixing products due to the mixing of RF and 2ΔF, as seen in Fig. 7. Subsequently, when down-converting a modulated RF signal, one should choose ΔF and RF carefully to avoid interference between multiple versions of the down-converted RF signal. Another constraint was the frequency of operation of components used in the experiment, such as amplifiers and antennas, which are limited to 40 GHz. Taking all that into account, RF was chosen to be 35.1 GHz while ΔF was set to 23.4 GHz resulting in 2ΔF = 46.8 GHz. This configuration resulted in two mixing products at the same frequency, IF_1 and IF_2 at 11.7 GHz. Figure 7 shows the electrical spectrum of the RF signal, heterodyne signals and their mixing products.

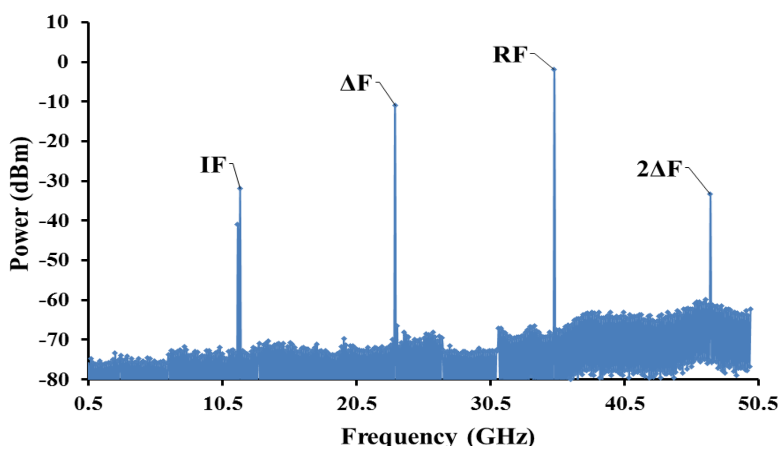

Fig. 7. Electrical spectrum showing RF, heterodyne, and IF signals (RBW = 300 kHz, VBW = 30 kHz).

3. Wireless transmission experiment implementing a UTC-PD-based receiver

We conducted a wireless transmission experiment to demonstrate the optoelectronic mixing capabilities of the UTC-PD, and how they can be useful at the receiver, by photonically down-converting the incoming mm-wave signals into a lower IF.

A block diagram of the experimental system is shown in Fig. 8. A single wavelength laser at 1550 nm followed by an intensity modulator generated three optical tones that are spaced by 23.4 GHz. They were followed by a reconfigurable optical filter (WaveShaper^{TM}) to select only two adjacent optical tones (suppression ratio of more than 40 dB). These optical tones are coherent since they originate from an externally modulated laser, and they were used to generate the heterodyne signal on the UTC-PD. Two erbium-doped fiber amplifiers (EDFAs) were used to amplify the optical signal followed by a 1 nm-bandwidth optical bandpass filter

(OBPF) to reduce the ASE noise. The total power of the optical signal measured at the output of the OBPF was 18 dBm, which gives the lowest conversion loss as shown in Fig. 5.

At the transmitter, a NRZ – OOK 5 Gbps pseudo random bit sequence (PRBS) data with a length of $2^{11} - 1$ was generated at the baseband, then, up-converted to 35.1 GHz using an electronic mixer. After that, it was amplified (Gain of 25 dB, Noise Figure (NF) of 3 dB) and fed into a 20 dBi horn antenna. The total power of the modulated signal at the transmitter was 11.8 dBm. The signal was transmitted over a wireless distance of 1.3 m before reaching the receiver 20 dBi horn antenna. Then, the signal was amplified (Gain of 35 dB, NF of 4 dB) and passed to a bias tee, where it is coupled with the DC bias, then, to a splitter, and finally, to a coplanar probe that is connected to the coplanar waveguides of the UTC-PD.

The RF signal was opto-electronically mixed with the optical heterodyned LO signal at the UTC-PD resulting in an IF signal at 11.7 GHz. The splitter was used in order to allow for the simultaneous supply of RF and the extraction of IF signals. The extracted IF signal was amplified (Gain of 35 dB, NF of 4 dB), then, fed into an electronic mixer to down-convert it to the baseband. The locking of the transmitter and the receiver was ensured by connecting the 10 MHz REF ports of the receiver synthesizers to that of the transmitter synthesizer. The final baseband signal was filtered and displayed on the oscilloscope. An open eye diagram of the received signal was obtained, as shown in the inset of Fig. 9, and a bit error rate (BER) of less than 10^{-8} was measured.

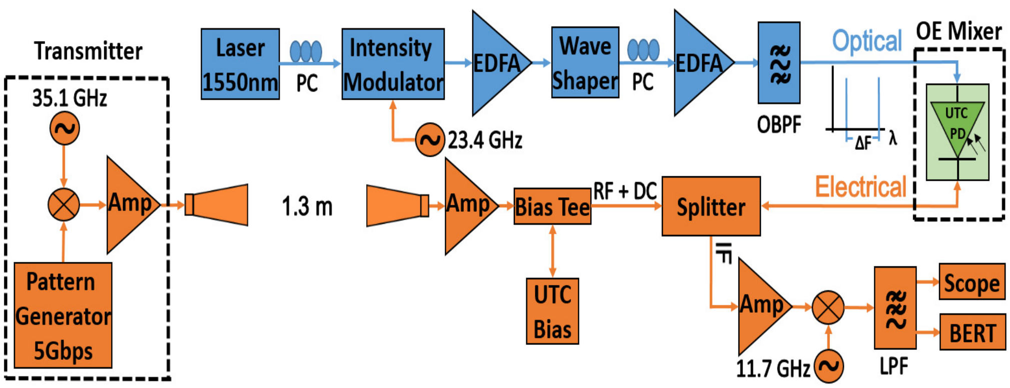

Fig. 8. Block diagram of the wireless transmission experiment.

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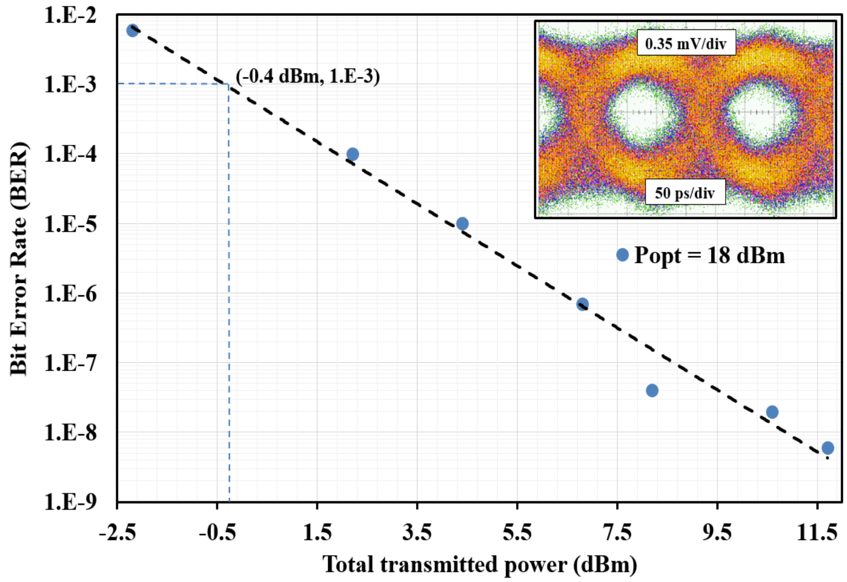

Fig. 9. BER performance of the system as a function of transmitted signal power. The inset shows the eye diagram of the received signal after down-conversion to the baseband.

The effect of transmitted signal power on the BER performance for the same wireless distance, d = 1.3 m, was then investigated, while keeping the optical power and bias voltage at their optimum levels (−2.5 V and 18 dBm). A plot of the BER versus transmitted power is shown in Fig. 9. A BER of $6x10^{-9}$ was achieved for 11.8 dBm transmitted power. The figure shows that the minimum transmitted power required to satisfy the forward error correction (FEC) limit is about −0.4 dBm. This gives more than 12 dB allowance in losses if we are to work at the FEC limit, which corresponds to four-fold increase in transmission distance. Combining this with high gain antennas (G = 42 dBi) would allow for transmission distances of hundreds of meters.

4. Conclusion

In this work, we demonstrated an optically pumped UTC-PD used in the wireless receiver. The best conversion loss obtained with this mixer was 22 dB, which, while lower than previously reported values is high relative to conventional electronic mixers. However, the advantage of using the UTC-PD as a mixer becomes more significant at higher frequencies where electronic mixers are less attractive as they require expensive electronic LO.

This experiment successfully demonstrated wireless transmission of a 5 Gbps signal occupying a 10 GHz bandwidth centered at a carrier frequency of 35.1 GHz using the UTC-PD as an optoelectronic mixer at the receiver. The transmission distance is 1.3 m, limited by the available antenna gain. As the capabilities of UTC-PD as an mm-wave transmitter has been already demonstrated [19], there is a potential to demonstrate the UTC-PD in a transceiver configuration that could be fully-integrated within a chip similar to the one presented in [16].

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