Optoelectronic detection of millimetre-wave signals with travelling-wave uni-travelling carrier photodiodes

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Abstract: Optically pumped mixing in travelling-wave uni-travelling carrier photodiodes is proposed as a novel technique for detecting millimetre-wave signals. An experimental demonstration was performed at a frequency of 100 GHz. From DC measurements, an increase in the responsivity was found at high levels of optical power. The mixing mechanism is attributed to the variation of the responsivity with the applied reverse bias and the optical input power. The maximum intermediate frequency power was found to be –35 dBm for a 4 dBm radio frequency power, while an average conversion loss of 40 dB was achieved. A wide dynamic range of more than 42 dB was measured, limited by the maximum available millimetre-wave power.

OCIS codes: (250.0250) Optoelectronics; (040.0040) Detectors; (040.5160) Photodetectors; (040.2840) Heterodyne.

References and links

1. P. H. Siegel, "Terahertz Technology," IEEE Trans. Microw. Theory Tech. **50**(3), 910–928 (2002).
2. M. Tonouchi, "Cutting edge terahertz technology," Nat. Photonics **1**(2), 97–105 (2007).
3. N. Karpowicz, H. Zhong, J. Xu, K.-I. Lin, J.-S. Hwang, and X.-C. Zhang, "Comparison between pulsed terahertz time-domain imaging and continuous wave terahertz imaging," Semicond. Sci. Technol. **20**(7), S293–S299 (2005).
4. H.-W. Hübers, "Terahertz Heterodyne Receivers," IEEE J. Sel. Top. Quantum Electron. **14**(2), 378–391 (2008).
5. S. Verghese, E. K. Duerr, K. A. McIntosh, S. M. Duffy, S. D. Calawa, C.-Y. E. Tong, R. Kimberk, and R. Blundell, "A photomixer local oscillator for a 630-GHz heterodyne receiver," IEEE Microw. Guided Wave Lett. **9**(6), 245–247 (1999).
6. I. Cámara Mayorga, P. M. Pradas, M. Mikulics, A. Schmitz, P. van der Wal, C. Kasemann, R. Güsten, K. Jacobs, M. Marso, H. Lüth, and P. Kordoš, "Terahertz photonic mixers as local oscillators for hot electron bolometer and superconductor-insulator-superconductor astronomical receivers," J. Appl. Phys. **100**(4), 043116 (2006).
7. S. Kohjiro, K. Kikuchi, M. Maezawa, T. Furuta, A. Wakatsuki, H. Ito, N. Shimizu, T. Nagatsuma, and Y. Kado, "A 0.2–0.5 THz single-band heterodyne receiver based on a photonic local oscillator and a superconductor-insulator-superconductor mixer," Appl. Phys. Lett. **93**(9), 093508 (2008).
8. M. C. Wanke, E. W. Young, C. D. Nordquist, M. J. Cich, A. D. Grine, C. T. Fuller, J. L. Reno, and M. Lee, "Monolithically integrated solid-state terahertz transceivers," Nat. Photonics **4**(8), 565–569 (2010).
9. M. Tsuchiya, and T. Hoshida, "Nonlinear Photodetection Scheme and Its System Applications to Fiber-Optic Millimeter-Wave Wireless Down-Links," IEEE Trans. Microw. Theory Tech. **47**(7), 1342–1350 (1999).
10. J.-W. Shi, Y.-S. Wu, and Y.-S. Lin, "Near-Ballistic Uni-Traveling-Carrier Photodiode- Based V-Band Optoelectronic Mixers with Internal up-Conversion-Gain, Wide Modulation Bandwidth, and Very High Operation Current Performance," IEEE Photon. Technol. Lett. **20**(11), 939–941 (2008).
11. H. Pan, Z. Li, and J. C. Campbell, "High-Power High-Responsivity Modified Uni-Traveling-Carrier Photodiode Used as V-Band Optoelectronic mixer," J. Lightwave Technol. **28**(8), 1184–1189 (2010).
12. E. Rouvalis, C. C. Renaud, D. G. Moodie, M. J. Robertson, and A. J. Seeds, "Traveling-wave Uni-Traveling Carrier photodiodes for continuous wave THz generation," Opt. Express **18**(11), 11105–11110 (2010).
13. C. C. Renaud, M. Robertson, D. Rogers, R. Firth, P. J. Cannard, R. Moore, and A. J. Seeds, "A high responsivity, broadband waveguide uni-traveling carrier photodiode," Proc. SPIE **6194**, 61940C, 61940C-8 (2006).
14. N. J. Gomes, and A. J. Seeds, "Novel optically pumped electronic mixer using a Mott diode structure," Electron. Lett. **23**(20), 1084–1085 (1987).
15. S. Verghese, K. A. McIntosh, S. Calawa, W. F. Dinatale, E. K. Duerr, and K. A. Molvar, "Generation and detection of coherent terahertz waves using two photomixers," Appl. Phys. Lett. **73**(26), 3824–3826 (1998).

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16. B. Sartorius, M. Schlak, D. Stanze, H. Roehle, H. Künzel, D. Schmidt, H.-G. Bach, R. Kunkel, and M. Schell, "Continuous wave terahertz systems exploiting 1.5 µm telecom technologies," Opt. Express **17**(17), 15001–15007 (2009).
17. T. Nagatsuma, A. Kaino, S. Hisatake, K. Ajito, H.-J. Song, A. Wakatsuki, Y. Muramoto, N. Kukutsu, and Y. Kado, "Continuous-wave Terahertz Spectroscopy System Based on Photodiodes," PIERS Online **6**(4), 390–394 (2010).
18. C. C. Renaud, L. Ponnampalam, F. Pozzi, E. Rouvalis, D. Moodie, M. Robertson, and A. J. Seeds, "Photonically Enabled Communication Systems Beyond 1000 GHz," *International Topical Meeting on Microwave Photonics 2008 (MWP 2008)*, (Gold Coast, Australia), pp. 55–58.

1. Introduction

Frequencies located in the Terahertz (THz) band of the electromagnetic spectrum have been used extensively for material and spectroscopic studies [1]. Most existing THz spectroscopic systems are based on time domain techniques where signals are detected by utilising either electro-optic or photoconductive effects [2]. Frequency domain techniques are expected to dominate future applications since they can offer portable, low-cost systems with superior resolution and a high scanning speed [3]. Several types of devices have been used for heterodyne detection of THz signals [4] such as Schottky diode mixers, Superconductor-Insulator-Superconductor (SIS) mixers and Hot Electron Bolometer (HEB) mixers. So far, at THz frequencies photomixers have been used to generate the Local Oscillator (LO) for pumping HEB or SIS mixers [5-7]. This approach is particularly attractive for radio-astronomy receivers or other applications where the LO has to be controlled remotely. However, room temperature operation remains elusive for these mixers. For applications where high level of integration is desirable [8] photomixers can offer an alternative to other THz sources since they have an extremely wide frequency range of operation. Optoelectronic Mixing (OEM) in photodiodes has been proposed for photonic distribution of the LO signal in Radio-over-Fibre links [9]. Uni-Travelling Carrier Photodiodes (UTC-PDs) have successfully demonstrated low up-conversion loss when used with a microwave LO [10], [11].

In this paper we investigate the capability of the Travelling-Wave Uni-Travelling Carrier Photodiode (TW-UTC-PD), originally studied in [12], [13] for efficient photonic THz generation, for down-conversion of THz signals with an optically supplied LO signal– an Optically Pumped Mixer (OPM) [14]. Previously demonstrated coherent detection schemes were either based on photoconductive techniques [15], [16] or on homodyne detection [17]. Both functions of generating the LO and mixing are implemented in a standalone, room-temperature, InP-based device. A first set of OPM experiments was performed at a frequency of 100 GHz and the results of the different experiments are presented in this paper. The purpose of this work was to investigate the effect of the variation of different parameters on the performance of the mixer. For this set of experiments the LO is photonically generated and the incoming signal to be down-converted is in the millimetre-wave range. By definition, in a mixer the power of the Radio Frequency (RF) signal is substantially lower than the LO power. However, for the measurements that will follow this is not always the case. One of the most important parameters of an OPM is the Conversion Loss (CL). In this paper the CL will be defined as the ratio $CL = P_{IF}/P_{RF}$ where P_{IF} is the calibrated power of the Intermediate Frequency (IF) signal and P_{RF} the calibrated power of the RF signal. All the experiments were performed at an LO frequency, f_{LO}, of 100 GHz. The mixing mechanism can be explained by the introduction of the differential conductance G_D in the I-V characteristic of the device that is a function of the applied reverse bias and the optical power. At large reverse bias and low optical powers G_D takes small values. However, we found that when the optical power is increased G_D is considerable even for high levels of reverse bias (>2.5 V) voltage where the device frequency response is optimum. It was experimentally verified that the lowest CL was obtained for the highest photocurrent at the maximum reverse bias of 4 V. This is of high importance for the development of a broadband THz photomixing receiver since the frequency response of the photogenerated LO will be optimum. Finally, a very wide dynamic range of 42 dB was measured limited by the available THz power.

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2. Experimental arrangement

For a given device, CL is a function of several parameters such as the frequency of the LO, f_{LO}, the DC photocurrent, I_{ph}, the applied reverse bias, V_b, the input optical power, P_{opt}, the DC responsivity of the device, R, the power of the RF signal, P_{RF}, the IF, f_{IF}, and many other parameters. To simplify the process, several of the above parameters were kept constant. The full experimental arrangement for this series of measurements can be seen in Fig. 1:

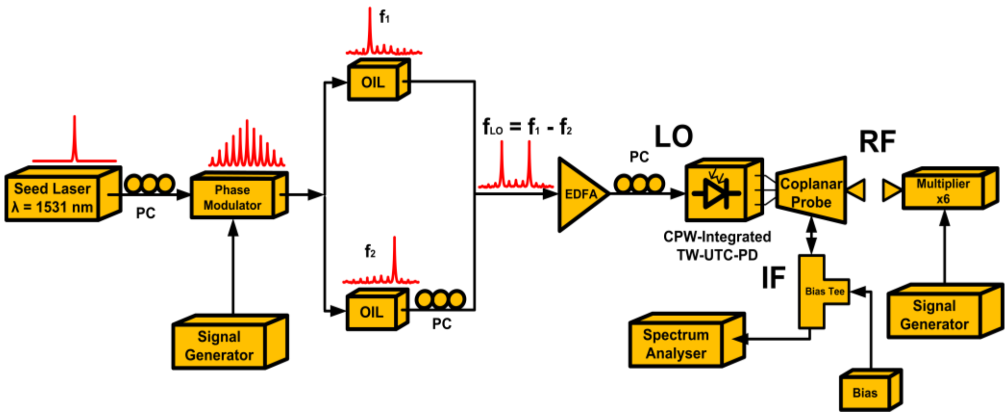

Fig. 1. Experimental Arrangement used for Optoelectronic Mixing experiments at 100 GHz.

An optical LO was generated by Optically Injection Locking (OIL) two widely tuneable slave lasers to a comb generated by a phase modulator. The Seed Laser wavelength was at 1531 nm and the phase modulator was driven with a 20 GHz signal. This allowed for the two slave lasers to be locked at a spacing of 100 GHz. A W-Band (75-110 GHz) × 6 frequency multiplier was used as the RF source, pumped by a signal generator. The experiments were performed on a Coplanar Waveguide (CPW)-integrated device with the same epitaxial structure as the type 1 devices in [12] and an active area of 4 × 25 μm^2. A W-Band coplanar probe was used to feed the RF signal into the device and to extract the IF. The RF signal from the multiplier was fed into the photodiode through a free space path employing two 20 dBi gain W-Band horn antennas. The IF signal was extracted from the DC port of the internal bias-tee of the probe. A second external bias-tee was used to split the DC bias from the IF signal and the IF signal level was measured with a spectrum analyser. It was found from the experiment that the RF and the IF signals experience some losses. Some essential calibrations were performed before as part of the measurement procedure. Since the output power of the multiplier is a function of the input power, the output power was measured with a power meter and a spectrum analyser that employed a down-converting mixer. It was experimentally verified that the output power P_{RF} increases with $(P_{RF}^{in})^6$ for input power levels up to −4 dBm, with $(P_{RF}^{in})^4$ from −4 dBm to −1 dBm and shows saturating behaviour above −1 dBm. The total loss for the RF signal was found to be 2.7 dB for frequencies around 100 GHz and depended mostly on the insertion loss of the equipment used. Another set of calibrations was performed for the IF signal. As previously mentioned, the IF signal was extracted from the DC port of the built-in bias-tee of the W-Band probe, thus the IF signal is measured after passing through a low pass (probe) and a high pass (bias-tee) filter. The IF bandwidth, measured by sweeping the RF frequency, was found to be 60 kHz, centred on 50 kHz. This was confirmed by measuring the response of the IF path when a swept-frequency amplitude modulated optical signal was input to the photodiode. A minimum total loss of 5 dB was obtained at 50 kHz, and hence this frequency was used as the IF for all measurements. The results presented in this paper are calibrated to the measured insertion loss for both the IF and the RF signals. The narrow IF bandwidth is determined by the combination of the high- and low-pass frequency responses of the two bias tees in the IF path. By improving the method of extracting the IF from the photodiode, an IF bandwidth of several GHz should be achievable.

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3. Results and discussion

Some initial measurements were taken to ensure the quality of beat signal generated with OIL. The resulting signal that corresponded to the LO was found to be stable enough to perform mixing measurements with a variation of ± 1 dB. From this set of measurements, it was found that the drop in the response of the photodiode relative to low frequencies at 100 GHz was 8 dB, while a 3-dB bandwidth of 63 GHz was measured with the same optical heterodyne system. These values were confirmed with measurements taken with a power meter. The lower 3-dB bandwidth resulted from the larger active area (4 × 25 μm^2) of the device compared to those reported in [12]. The first set of measurements involved the static I-V characteristics of the device. The DC photocurrent was measured at a wavelength of 1531 nm, the central wavelength used for these measurements. The I-V curves for various levels of input optical power are plotted in Fig. 2:

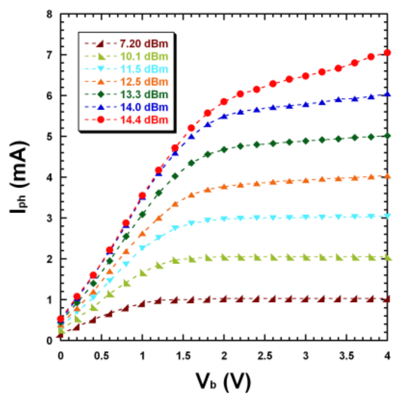

Fig. 2. DC Photocurrent versus reverse bias for various levels of optical input power.

The device showed an increasingly nonlinear response for high optical power. In general, this behaviour is more common in small area photodiodes. It can be seen that at low levels of photocurrent, the photocurrent remains constant with increasing applied reverse bias. However, at higher photocurrents, a slope in the I-V curve can be seen even at high levels of reverse bias. This is a desirable effect since the high LO power that is generated at high levels of bias is correlated with a weaker but still important nonlinearity in the static I-V curve. The next step was to confirm these effects with OEM experiments. The calibrated IF power measured with a spectrum analyser is shown in Fig. 3:

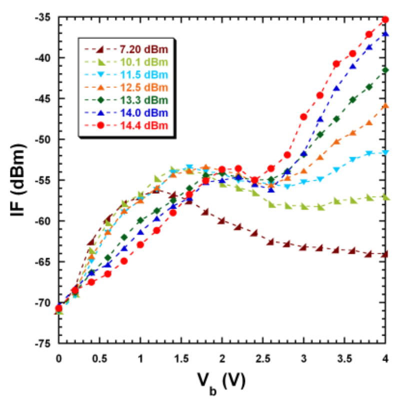

Fig. 3. Calibrated IF power versus applied bias for different levels of optical input power. The incoming calibrated RF power was kept constant at approximately 4 dBm and the IF was 50 kHz for all measurements.

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For low optical input powers, the IF power shows a maximum at a relatively low bias (typically about 1-1.5 V reverse bias) and then drops smoothly for higher levels of bias. As the photocurrent increases, this point is shifted to a higher reverse bias but a second overall maximum is obtained at the maximum applied reverse bias of 4 V. At a maximum photocurrent of 7 mA and a bias of 4 V, the highest IF power is obtained, that is −35 dBm. The mixing effects can be explained by incorporating the change of G_D for a certain level of bias that is a figure of merit of the associated nonlinearity. The generated photocurrent without the presence of the RF signal consists of DC and AC components. At a low bias G_D takes large values but the AC photocurrent is very small. When the bias is increased, the LO generated power increases substantially and a difference of about 25 dB is measured on a 50 Ω load when the reverse bias voltage changes from 1.5 V to 4 V. At the point where the maximum IF power was detected the device shows a considerable value of G_D together with a high AC photocurrent. The modulation of the bias voltage by the LO signal in turn modulates the total photocurrent. The result of this modulation on the photocurrent is believed to be the main mixing mechanism.

The noise performance of the optoelectronic mixer was also assessed. At an I_{ph} of 7 mA and a V_b of 4 V, the IF noise floor was found to be −104.1 dBm/Hz. This value was determined by the measured noise floor calibrated to the non-ideal response of the input filter and the logarithmic gain shape of the input amplifier of the spectrum analyser. This noise floor was found to be associated with the ASE noise from the EDFA that was used to amplify the LO signal and is not down-converted from the millimetre-wave regime. By removing the incoming RF signal from the input port of the mixer, the IF noise floor was not altered indicating that the IF noise floor was caused by the photonic LO.

From the mixer definition, the LO power is typically orders of magnitude higher than the RF power. In the next set of measurements the optical power was kept constant at 14 dBm resulting in a peak photocurrent of about 6 mA at 4 V. The LO power was measured on a 50 Ω load for these levels of optical power and applied bias and was found to be about −9 dBm. The IF power versus the applied reverse bias for three different levels of input RF power was obtained. The RF power levels were selected to be comparable to the LO power (−9 dBm) and ± 10 dB (1 and −19 dBm respectively). The experimental results are illustrated in Fig. 4:

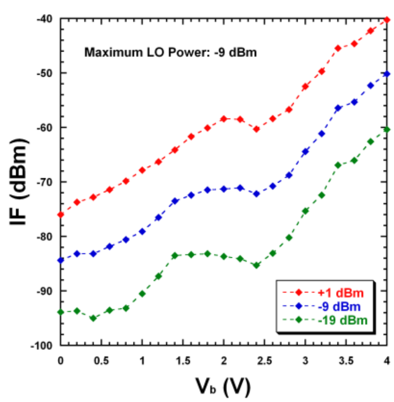

Fig. 4. Calibrated IF power versus applied bias for different levels of optical input power. The incoming calibrated RF power was 1 dBm (red), −9 dBm (blue) and −19 dBm (green).

The mixing performance showed a very weak dependence on the incoming RF power indicating that the modulation of the static I-V is the most important source of mixing. For the next set of measurements, the LO was kept constant. The reverse bias was at 4 V and the optical power at 14.4 dBm where the LO power was about −8 dBm. The RF power was swept over a very wide range of powers. The results are plotted in Fig. 5:

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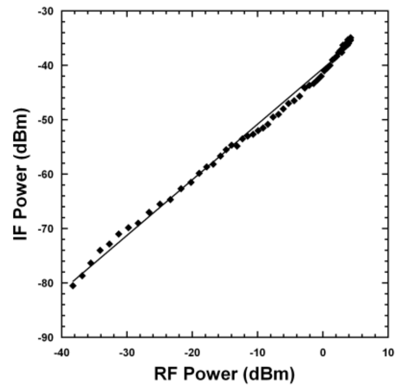

Fig. 5. IF Power versus RF power for a certain LO value (solid line: linear fit) at a reverse bias voltage of 4 V.

Figure 5 shows a linear dependence of the IF with respect to the input RF power. The maximum deviation from the linear fit is of the order of 1 dB that is within the error of the spectrum analyser. The fluctuations might also arise from fibre misalignment during the measurement. By calculating the CL from the previous plot, the expected values range from 42 to 39 dB. One of the most important parameters in the mixing performance is the voltage swing that the LO signal is causing to the reverse bias of the device. In principle, a mixer has to be operated at the small signal limit, meaning that the voltage swing from the RF signal is much smaller than the voltage corresponding to the LO. This result is in good agreement with the proposed mixing mechanism since the RF signal is considered to be a small signal compared to the high applied reverse bias of 4 V despite the significantly smaller LO power measured on a 50 Ω load. Therefore the quasi-linear approximation is valid and an IF that has a linear relation with the RF is obtained.

4. Conclusion

Optoelectronic mixing at an LO frequency of 100 GHz was demonstrated and an optimum average Conversion Loss of about 40 dB was achieved. A substantial dependence on the response of the generated IF as a function of the applied reverse bias was obtained for different levels of the optical input power. A linear response of the mixer was measured for input RF powers from −38 dBm to 4 dBm. The lower power level that can be detected is limited by the conversion loss and the IF that was used in this experiment. Experiments using devices with a larger 3dB bandwidth, such as those with a bandwidth of 110 GHz demonstrated in [13], are expected to achieve a significantly lower conversion loss. Our previous results at a frequency of 10 GHz showed an optimum conversion loss at an applied reverse bias of 0.2 V [18]. However, the results presented in this paper show great promise for the use of the TW-UTC-PD as a THz detector since the lowest conversion loss is obtained for an applied reverse bias where the frequency response of the device is optimum. In addition, the study of the device performance at higher frequencies together with a design suitable for extracting an IF in the GHz range is expected to allow for good performance of the detector at frequencies between 300 GHz and 1.5 THz. The use of the TW-UTC-PD both as a THz emitter and an optoelectronic THz detector is expected to deliver a room-temperature, continuous wave spectroscopic system based entirely on the established InP technology originally developed for optical communications.

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