Widely tunable optoelectronic source of continuous-wave terahertz radiation

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A novel design of a waveguide-photodetector integrated with an antenna as a compact terahertz source is reported. Experimental measurements have demonstrated tunable emission over the range from 100 GHz to 1.1 THz.

Introduction: Optoelectronic components potentially offer a route to low-cost, compact sources of terahertz (THz) radiation since they can utilise semiconductor technology developed originally for optical fibre communication systems. Photomixing of the output from a pair of 1550 nm diode lasers in a conventional *pin* photodiode [1] or a photoconductor [2] has been used to demonstrate tunable sources of THz radiation up to 650 GHz and 2 THz, respectively. In this context, the uni-travelling carrier (UTC) photodiode has demonstrated a record 3 dB bandwidth of 310 GHz [3] and an output power of 10 dBm extracted at 110 GHz [4]. Recent publications have presented variations on the UTC structure by varying doping levels in order to optimise bandwidth and output saturation [5–7]. This Letter reports the use of such an alternative structure, termed the 'composite *pin*' (CPIN) photodiode [7], to generate THz radiation tunable over the range from 100 GHz to 1.1 THz.

Device description: Integrated antenna-waveguide-photodetectors were fabricated from wafers grown on a semi-insulating InP substrate using metal organic vapour phase epitaxy. The device comprised a simple rib-loaded passive optical waveguide which was used to evanescently couple light into a short detector section formed using an InGaAs absorber. The device was designed for operation where both holes and electrons contribute to photocurrent (CPIN operation [7]). A log-periodic antenna designed to cover the band 0.1 to 1 THz was formed on top of a 2 μm-thick dielectric layer on the 500 μm square InP substrate (Fig. 1) Completed devices were mounted within a package on a high resistivity silicon carrier wafer. THz emission passed through the substrate/carrier and a 3.5 mm-diameter Si lens to improve the THz collection efficiency.

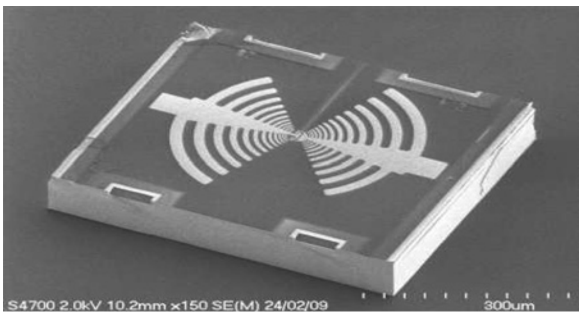

Fig. 1 *SEM of completed device*

Measurement setup: Polarisation controlled light from a DFB laser emitting at 1530 nm, and a tunable (1510–1590 nm) external cavity laser, were combined and, via an optical chopper and a high saturation power (+20 dBm) fibre amplifier, launched into the photomixer. The difference frequency was determined using an optical spectrum analyser, and THz output measured using a Golay cell.

Results: Fig. 2 shows the DC photocurrent and emitted THz signal at 300 GHz as functions of input optical power. The measurements are taken at room temperature without temperature control. The responsivity at low intensity is 0.2 A/W, and the series resistance is estimated to be below 10 Ω from *IV* measurements. The Figure shows excellent saturation behaviour, particularly at low reverse bias; even at zero bias the device performed well up to >40 mW input optical power (>10 mA photocurrent).

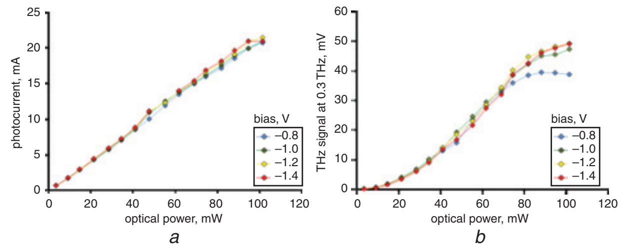

Fig. 2 *Photocurrent (mA) and THz response (mV Golay signal) against optical power measured at different reverse bias voltages (V)*

a Photocurrent against optical power
b THz response against optical power

Fig. 3 shows the measured THz emission against frequency. Given a measured device capacitance of 30 fF and a nominal antenna impedance of around 75 Ω (based on simulation results) we calculate a −3 dB bandwidth of <100 GHz. Based on the modelling in [7] we anticipate this to be well below the intrinsic bandwidth of the devices which is expected to be in the range 250–350 GHz. Thus, overall, we expect a THz response which is capacitance limited, rolling off at 6 dB/octave above ∼100 GHz, and would further anticipate a faster rate response roll off above the intrinsic device bandwidth in the range ∼300 GHz. From the frequency response in Fig. 3 it is clear the device does indeed exhibit a response which falls above 100 GHz (which is the lower limit of the antenna). However, a comparatively slow rate of roll off, between f^{-2} and f^{-3} is maintained out to 1.1 THz. This contrasts with previously reported work [1–3] where the response has typically fallen off as f^{-3} to f^{-4}. The detailed response which shows a number of 'resonance'-like features corresponds in part to the characteristics of the antenna. We conclude that the intrinsic design features of this integrated device has resulted in a useful improvement in performance, providing a source of CW THz power over a full decade of frequency response, 100 GHz–1.1 THz. The measurement is ultimately limited by noise but with improved device heatsinking and temperature control we anticipate further enhancements in performance.

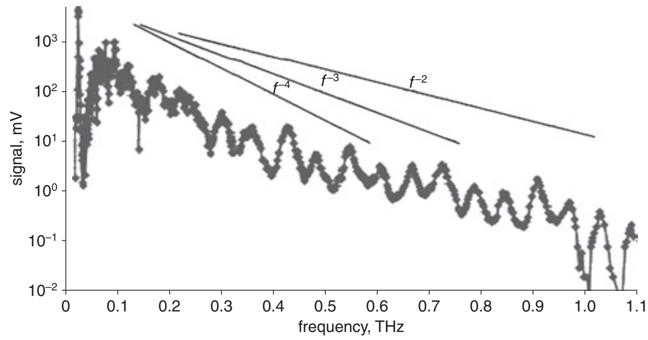

Fig. 3 *THz emission measured using Golay cell against beat frequency at 18 dBm optical input power*

Conclusion: A novel design of a high-speed waveguide photodiode has been used in a photomixer for generation of tunable THz radiation over the range from 0.1 to 1.1 THz. Combining this device with tunable diode lasers operating close to 1550 nm offers a potentially low-cost, compact source of THz radiation.

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References

1 Huggard, P.G., Ellison, B.N., Shen, P., Gomes, N.J., Davies, P.A., Shillue, W., Vaccari, A., and Payne, J.M.: 'Generation of millimetre and sub-millimetre waves by photomixing in 1.55 μm wavelength photodiode', *Electron. Lett.*, 2002, **38**, (7), pp. 327–328

2 Mangeney, J., Merigault, A., Zerounian, N., Crozat, P., Blary, K., and Lampin, J. F.: 'Continuous wave terahertz generation up to 2 THz by photomixing on ion-irradiated $In_{0.53}Ga_{0.47}As$ at 1.55 μm wavelengths', *Appl. Phys. Lett.*, 2007, **91**, (24), p. 241102

3 Ito, H., Kodama, S., Muramoto, Y., Furuta, T., Nagasuma, T., and Ishibashi, T.: 'High-speed and high-output InP-InGaAs unitraveling-carrier photodiodes', *IEEE J. Sel. Top. Quantum Electron.*, 2004, **10**, (4), pp. 709–727

4 Renaud, C.C., Moodie, D., Robertson, M.J., and Seeds, A.J.: 'High output power at 110 GHz with a waveguide uni-travelling carrier photodiode'. IEEE Lasers and Electro-Optics Society (LEOS) Annual Meeting, Lake Buena Vista, Florida, 2007, pp. 782–783

5 Yoder, P.D., and Flynn, E.J.: 'Quasi-unipolar InGaAs/InP photodetection for enhanced optical saturation power and maximal bandwidth', *Appl. Phys. Lett.*, 2007, **91**, (6), p. 062114

6 Klamkin, J., Chang, Y.-C., Ramaswamy, A., Johansson, L.A., Bowers, J.E., DenBaars, S.P., and Coldren, L.A.: 'Output saturation and linearity of waveguide unitraveling-carrier photodiodes', *IEEE J. Quantum Electron.*, 2008, **44**, (4), pp. 354–359

7 Dyson, A., Henning, I.D., and Adams, M.J.: 'Comparison of type I and type II heterojunction unitraveling-carrier photodiodes for terahertz generation', *IEEE J. Sel. Top. Quantum Electron.*, 2008, **14**, (2), pp. 277–283