Photonic-Enabled Microwave and Terahertz Communication Systems

A. J. Seeds, M. J. Fice, F. Pozzi, L. Ponnampalam, C. C. Renaud, C. P. Liu, I. F. Lealman†, G. Maxwell†, D. Moodie†, M. J. Robertson†, D. C. Rogers†

Department of Electronic and Electrical Engineering, University College London, Torrington Place, London, WC1E 7JE, United Kingdom.
†CIP Technologies, Adastral Park, Martlesham Heath, Ipswich, Suffolk, IP5 3RE, United Kingdom.
Email: a.seeds@ee.ucl.ac.uk

Abstract: An optical heterodyne technique for generating millimetre-wave and THz carriers with high spectral purity and low phase noise is described, for application to Gb/s wireless communications systems. Progress on key integrated optical components is reported.

OCIS Codes: (040.5160) Photodetectors; (060.5625) Radio frequency photonics

1. Introduction

Microwave photonics research [1] has found applications in areas as diverse as electronic warfare and medical imaging, and the development of wireless-over-fibre systems for distribution of cellular radio and other wireless signals within large buildings and other areas where coverage from conventional hill-top sites is poor, has proved to be of considerable commercial importance, with sales of systems reaching some $250 m annually. Now, with wireless local area networks (LANs) ubiquitous and demand for higher wireless transmission rates using IEEE 802.16 and similar standards growing, new potential applications for photonics in wireless communications are emerging, to generate, modulate and detect signals at higher carrier frequencies (>60 GHz) that can support Gb/s data rates [2]. Extending this idea to terahertz frequencies may allow even higher rate, short-range wireless communications for applications such as fibre-break bridging, with the additional advantage of increased security due to the stronger atmospheric absorption at these frequencies. In this paper, we describe work towards developing key photonic components for generating millimetre wave and terahertz frequency signals and communication systems being built with them.

2. Millimetre-wave and THz generation

Generation of high spectral purity, low phase noise carriers at frequencies above 100 GHz is difficult by electronic techniques [3]. Photonic approaches based on optical heterodyning provide a means of overcoming some of these limitations. For low phase noise the two optical sources must be phase locked together, which can be achieved by locking each of the sources to a common reference. The overall scheme proposed is illustrated schematically in Fig. 1. An optical frequency comb generator (OFCG) produces multiple, phase-locked optical lines with well-defined frequency spacing, for use as the reference. Optical phase lock loops (OPLLs) are used to lock the optical sources to two lines in the OFCG spectrum, separated by the required millimetre-wave or terahertz frequency. The OPLL outputs are combined onto a high-speed photodetector, which could be integrated with a suitable antenna. Data modulation can be applied by modulating the output of one of the OPLLs, or the combined optical signal before it reaches the detector.

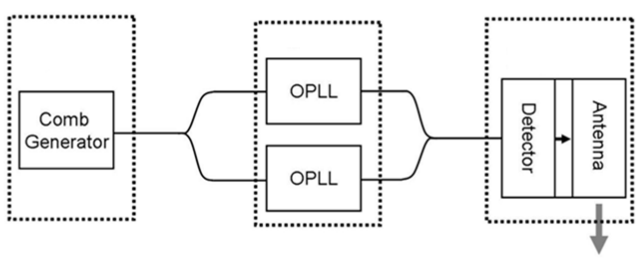


Fig. 1: Millimetre-wave or terahertz generator

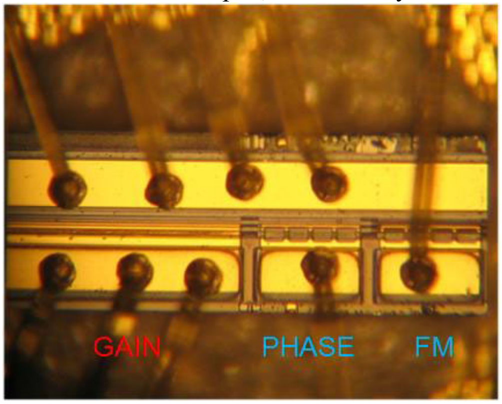
To overcome the complexity of this approach, a photonic integration strategy is being pursued, with the first step being to integrate separately each of the three elements of the millimetre-wave generator shown in boxes in Fig. 1.

3. Comb generator

One approach that has been investigated for use as a compact OFCG is a frequency modulated (FM) semiconductor laser [4]. Epitaxial growth of InGaAsP/InP material on a semi-insulating InP substrate was performed in a single

978-1-55752-865-0/09/$25.00 ©2009 IEEE

metallo-organic vapour phase epitaxy stage, with quantum well intermixing being used to selectively blue shift the band gap to create passive phase and frequency modulation sections. The laser fabrication was completed with a ridge waveguide structure and an oxide-bridged p-contact to enable modulation at high frequency. Fig. 2 shows a picture of the final device and a measured optical spectrum with lines spaced exactly by the 24.4 GHz modulation frequency. The potential comb spectrum width can be up to 2 THz (15 nm), although the output power is not uniform across the full span, due to Fabry-Perot cavity effects resulting from the etched isolation trenches.



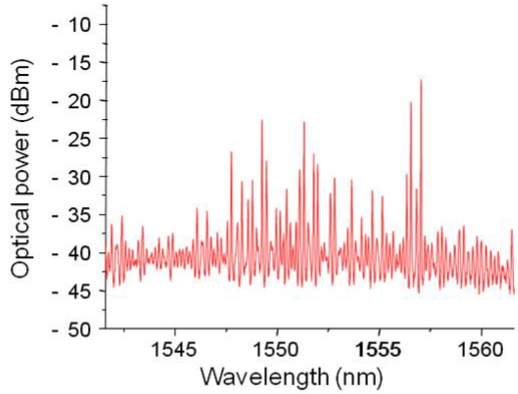


Fig. 2: Micrograph of the FM laser OFCG (left) and measured spectrum (right)

4. Optical phase lock loop

OPLLs are used to phase lock slave lasers to selected lines in the OFCG spectrum. The phase error between the comb line and the locked source depends on the sum of their linewidths and the loop bandwidth of the OPLL. The loop bandwidth is limited by the loop feedback delay, which for lasers with summed linewidths of 2 MHz must be less than 1 ns for locking with acceptably low phase error variance (<0.03 rad^2) [5]. Using discrete optical components, it is very difficult for the optical section of the loop to meet this requirement. However, by integrating the optical components the delay for the optical section can be reduced to a fraction of a nanosecond. Design of the electronic feedback loop to achieve a low overall loop delay is challenging, but values of <1 ns appear to be feasible. We are investigating optical integration by both an hybrid approach and a monolithic process. Fig. 3 shows a mask design for a monolithic device incorporating a single input (for connection to the OFCG), a Y-branch splitter, two tunable DBR lasers, further splitters / combiners, photodiodes to interface to the electrical circuit, and a single output for the heterodyne signal. The total length of the photonic integrated circuit is 4.1 mm.

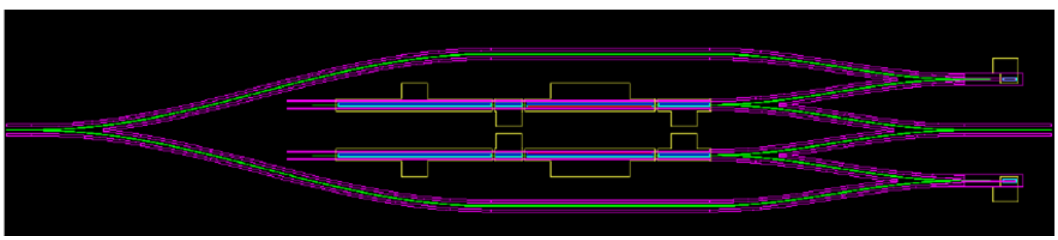


Fig. 3: Mask layout for monolithically integrated dual OPLL photonic integrated circuit.

5. Millimetre-wave and THz emitters

To generate the millimetre-wave or terahertz signal itself, the optical heterodyne signal must be detected using a very high bandwidth photodiode. We are investigating a development of the uni-travelling carrier (UTC) photodetector [6] using travelling wave techniques [7]. The UTC structure gives high electron drift velocity and reduces the carrier space-charge effect, giving higher saturation powers. An early device showing a parasitic capacitance of around 25 fF gave a capacitance-limited -3 dB bandwidth of 127 GHz with a 50 Ω load. When integrated with a resonant antenna operating at 457 GHz, the emitted power was measured as 148 µW at 457 GHz and 24 µW at the harmonic frequency of 914 GHz [8].

6. Coherent detection

Techniques generally used for THz detection and power measurement, for instance Golay cells, do not have a fast enough response for high-speed data demodulation. In addition, amplifiers do not exist that operate in the higher frequency bands that we are investigating. It is therefore of considerable interest to consider coherent detection, which can offer higher sensitivity, while also down-converting the data signal to an intermediate frequency (IF) in the microwave bands where amplification and other processing can be carried out more easily. The key elements are a local oscillator (LO), which could be generated by the same optical heterodyne technique used for generation of the data carrier, and a suitable mixer. We are investigating the use of UTC photodiodes as optoelectronic mixers, where the received data-modulated signal is applied to the electrical terminals of the UTC and an optical heterodyne LO is applied to the optical input of the UTC (Fig. 4). Non-linear mixing between the signal and the LO beat frequency produces an IF electrical output carrying the data.

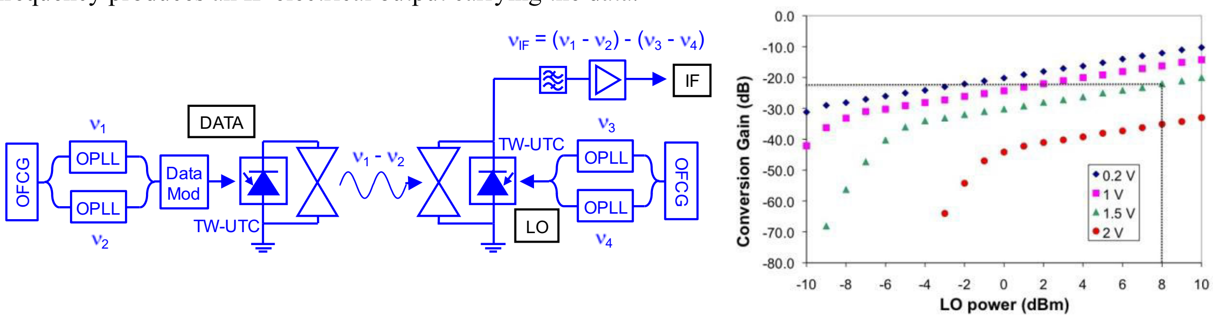


Fig. 4: THz data transmission scheme with coherent detection (left) and measured conversion gain for down-conversion from 10 GHz to 40 MHz (right) using UTC as an optoelectronic mixer

A proof of concept demonstration of optoelectronic mixing was made with the UTC detector, using a signal frequency of 10 GHz and an IF of 40 MHz (Fig. 4). Conversion loss decreased as the magnitude of the reverse bias applied to the UTC was reduced towards zero, as the device non-linearity is increased. However, the UTC frequency response becomes worse as the reverse bias is decreased. For a reverse bias of 1.5 V, the conversion loss was measured to be 22 dB for a detected optical local oscillator power of 8 dBm. These results encourage us to believe that such devices are a potential option for coherent detection of millimetre-wave or terahertz signals.

7. Conclusions

A scheme for generating millimetre-wave and terahertz carriers by an optical heterodyne technique has been described. High spectral purity and low phase noise are obtained by phase locking the optical sources used for the heterodyning to a common optical comb reference using optical phase lock loops (OPLLs). The optical heterodyne signal is converted to millimetre-wave or terahertz frequencies using a high-speed photodiode which is integrated with an antenna. By modulating the optical heterodyne signal, this scheme could form a transmitter for short-range Gb/s wireless communication links. Progress on key components has been presented, including a frequency modulated laser optical frequency comb generator, monolithically integrated OPLLs, and uni-travelling carrier (UTC) photodiodes. Using the scheme, emitted powers of 148 µW at 457 GHz and 24 µW at 914 GHz have been obtained from a resonant antenna integrated with a UTC. Preliminary results on using the UTC detector as an optoelectronic mixer for coherent detection and down-conversion are reported for operation at 10 GHz. Future work will investigate extending this to millimetre and THz frequencies.

8. Acknowledgements

This work is supported by the European Union under the Integrated project IPHOBAC; by the UK Engineering and Physical Science Research Council under projects PORTRAIT and PHITSIN; and by the European Office of Aerospace Research & Development.

9. References

[1] A. J. Seeds and K. J. Williams, "Microwave photonics," JLT **24**, 4628-4641 (2006).
[2] T. Nagutsuma, "Radio spectral evolution with photonics," IEEE MWP2008, Gold Coast, Sept. 30-Oct. 3 2008, PLE1 pp. 1-4 (2008).
[3] J. E. Carroll, *Hot electron microwave generators*, (Arnold, London, 1970), pp. 166-173.
[4] C. C. Renaud, *et al.*, "A monolithic MQW InP–InGaAsP-based optical comb generator," IEEE JQE **43**, 998-1005 (2007).
[5] R. T. Ramos and A. J. Seeds, "Fast heterodyne optical phase-lock loop using double quantum well laser diodes," EL **26**, 389–91 (1990).
[6] H. Ito, *et al.*, "High-speed and high-output InP-InGaAs unitraveling-carrier photodiodes," IEEE JSTQE **10**, 709-727 (2004).
[7] K. S. Giboney, J. W. Rodwell and J. E. Bowers, "Traveling-wave photodetector theory," IEEE TMTT **45**, 1310-1319 (1997).
[8] C. C. Renaud, *et al.*, "A high responsivity, broadband waveguide uni-travelling carrier photodiode," Proceedings of SPIE Photonics Europe, (2006), pp. 61940C-1-61940C-8.