Terahertz free space communication based on acoustic optical modulation and heterodyne detection

Y. Ma, S.C. Saha, A.L. Bernassau and D.R.S. Cumming

A terahertz free space communication system based on acoustic optical modulation and heterodyne detection is demonstrated. A high resistivity silicon acoustic optical modulator was used to modulate a continuous terahertz wave at 2.52 THz. A pyroelectric detector was used to detect the modulated terahertz signal via heterodyne detection mode. A modulation frequency of 937 kHz and sampling rate of 1 kbit/s was achieved.

Introduction: In the last twenty years, research in terahertz technologies (0.1–10 THz) has grown significantly owing to its promising applications such as nondestructive imaging, spectroscopy and wireless communication. Although terahertz imaging and spectroscopy have been intensively investigated, only a few studies have been reported regarding terahertz wireless communications. This is due to the technical barriers that have to be overcome for developing suitable sources, modulators and receivers. Yet the advantages of terahertz communication over conventional microwave wireless are obvious [1]. Terahertz systems have the potential to provide a much broader bandwidth, more directional transmission (useful to reduce the size of the antenna) and more secure information communication due to the short transmission distance.

Considerable work has been carried out into components and systems for terahertz communications [2–7]. One of the key components is the modulator. Liu *et al.* and Möller *et al.* have demonstrated direct modulation of terahertz sources by applying a modulation signal onto the photoconductive antennas in a terahertz time domain spectroscopy system [2, 3]. A modulation rate of 1 Mbit/s and bandwidth of 23 kHz was achieved. External modulation based on semiconductor devices with a quantum-well structure has also been demonstrated [4, 5]. However, the operating temperature must be extremely low, which is not suitable for practical applications. For room-temperature operation, Kleine-Ostmann reported a terahertz semiconductor modulator with a modulation frequency of 23 kHz and demonstrated audio transmission based on this modulator in THz TDS [6]. Chen *et al.* reported a terahertz modulator based on all electrically driven active metamaterial. A modulation frequency up to 2 MHz was achieved [7].

In this Letter, we demonstrate a potential signal communication system at room temperature using an acoustic optical modulator (AOM) and a pyroelectric heterodyne detector. The AOM provides a simple method for modulation over a broadband frequency range. In an AOM, a travelling acoustic wave at frequency ω_A causes the incident terahertz wave at frequency of ω_T to diffract, as shown in Fig. 1*a*. The diffracted beam is frequency modulated by the acoustic wave at ω_A. The diffracted beam together with the undiffracted beam are focused onto the pyroelectric detector that works in a heterodyne mode. Pyroelectric detectors have broad detection bandwidth at room temperature, from visible to terahertz frequencies. In addition, they are capable of responding to modulation frequencies of the order of several tens of megahertz. When the pyroelectric detector works in heterodyne mode, the detector output will contain a signal component with frequency ω_A that is proportional to $\sqrt{P(\omega_T)P(\omega_T - \omega_A)}$ [8], where $P(\omega_T - \omega_A)$ and $P(\omega_T)$ are the power of the modulated beam and the unmodulated beam, respectively. Consequently, the noise is reduced by needing only a narrowband filter for the broadband signal. The signal-to-noise ratio is therefore significantly improved using the heterodyne detection technique. A noise equivalent power of 10^{-13} W/Hz can be achieved using the pyroelectric detector working in heterodyne mode [9]

Experimental setup: Fig. 1*b* shows a picture of the mounted AOM. A high resistivity silicon crystal with dimensions of 3 × 3 × 3 cm was used for the AOM material since it has good transmission and acoustic optical properties in the terahertz frequency range. A PZT 8 transducer with dimensions of 3 × 3 cm was attached to the side of the silicon crystal. The resonant frequency of the transducer was 937 kHz. A backing layer was used to minimise the acoustic reflection at the interface surfaces of the transducer as well as the silicon crystal. Fig. 2 shows the experimental setup of the communication system. Continuous terahertz radiation at 2.52 THz with power of 150 mW was generated via a CO_2 pumped methanol vapour laser. The terahertz beam was transmitted through the AOM. RF pulses of 150 W peak power at 937 kHz were applied to the transducer via a signal generator and a power amplifier. An electrical impedance matching circuit was used to adapt the transducer impedance to the 50 Ω impedance of the power amplifier. The transmitted beams after the AOM, including both modulated and unmodulated waves, were collected and focused onto the pyroelectric detector by a 90° off axis parabolic mirror. The output signal of the detector was acquired by a lock-in amplifier at the reference frequency of 937 kHz. A digital oscilloscope was used to display the signal of the lock-in amplifier. Electrical pulses synchronised with the RF pulses were to trigger the oscilloscope. The time constant of the lock-in amplifier was set to be 100 μs in order to resolve the signal pulse with 2 ms pulse width on the oscilloscope.

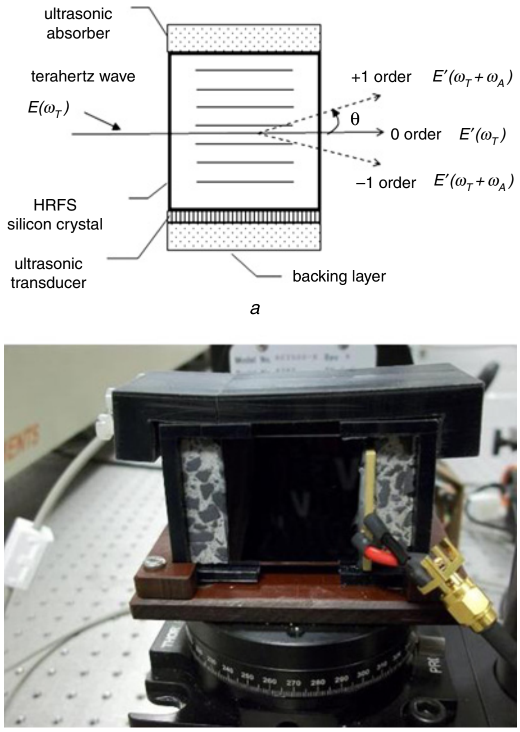

Fig. 1 *Sketch and photograph of terahertz acoustic optical modulator (THz-AOM)*

a Sketch
b Photograph

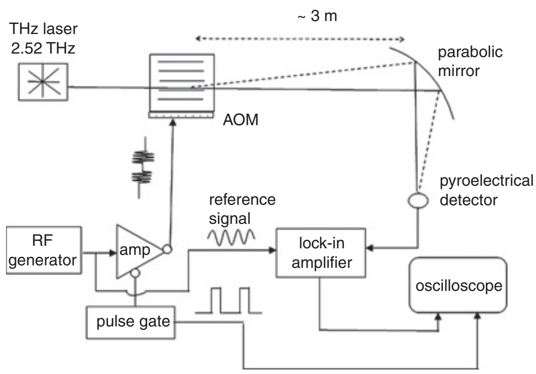

Fig. 2 *Experimental setup for terahertz signal transmission using acoustic modulator and pyroelectric heterodyne detector*

Experiment results: The inset of Fig. 3 shows the displayed signal of the oscilloscope. The received signal (solid line) with pulse width of 2 ms is synchronised with the modulating pulse (dash line). The signal amplitude (voltage peak to peak) linearly increases with the amplitude of the modulating signal, as shown in Fig. 3. The signal reaches saturation when the power of the modulating signal increases above 10 mW due to the saturation of the power amplifier. To evaluate the communication system, ASCII coding was applied to the modulating pulses in order to send text information via the communication system, as shown in

Fig. 4. A Labview program was used to code the modulating pulses into the AOM and decode the received signal pulses from the detector. A signal-to-noise ratio of 40 was measured. A sampling rate of 1 Kbit was achieved when modulating pulses with a pulse width of 1 ms were applied. The sampling rate was limited by the time constant of the lock-in amplifier. The sampling rate could be improved by using a low-noise preamplifier before the lock-in amplifier. Increasing the modulating frequency would also contribute to a higher sampling rate. A Schottky mixer could be used to replace pyroelectric heterodyne detectors which would provide a higher signal-to-noise ratio.

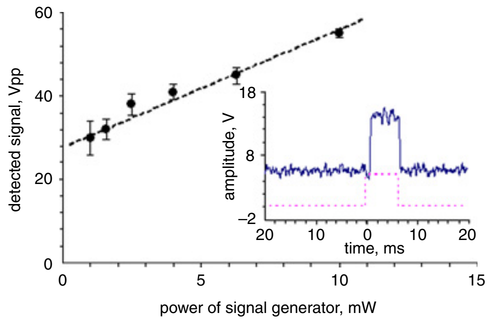

Fig. 3 *Modulation power dependence of detected signal*
Inset: Detected heterodyne signal at frequency of 937 kHz when modulating signal is 2 ms pulse with carrier frequency of 937 kHz

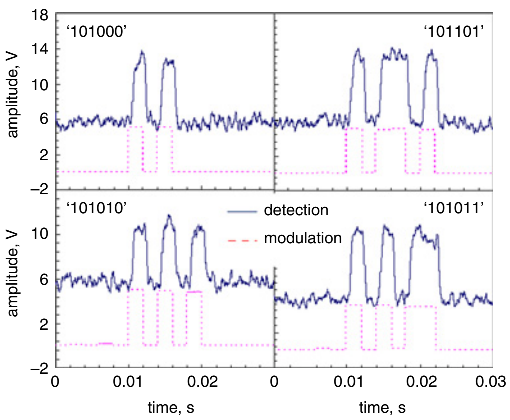

Fig. 4 *Experimental results of terahertz digital signal transmission of ASCII code using modulation pulse train*

Conclusion: We have demonstrated signal transmission at a carrier frequency of 2.52 THz using a high resistivity silicon AOM and pyroelectric detector working in a heterodyne mode. A modulation frequency of 937 kHz and a sampling rate of 1 kbit/s were achieved.

28 May 2011
doi: 10.1049/el.2011.1637
One or more of the Figures in this Letter are available in colour online.

Y. Ma, S.C. Saha, A.L. Bernassau and D.R.S. Cumming (*School of Engineering, University of Glasgow, Rankine Building, Oakfield Avenue, Glasgow G12 8LT, United Kingdom*)

E-mail: David.Cumming.2@glasgow.ac.uk

References

1 Federici, J., and Moeller, L.: 'Review of terahertz and subterahertz wireless communications', *J. Appl. Phys.*, 2010, **107**, p. 111101
2 Liu, T.-A., Lin, G.-R., Chang, Y.-C., and Pan, C.-L.: 'Wireless audio and burst communication link with directly modulated THz photoconductive antenna', *Opt. Express*, 2005, **13**, pp. 10416–10423
3 Möller, L., Federici, J., Sinyukov, A., Xie, C., Lim, H.C., and Giles, R.C.: 'Data encoding on terahertz signals for communication and sensing', *Opt. Lett.*, 2008, **33**, pp. 393–395
4 Libon, I.H., Baumgärtner, S., Hempel, M., Hecker, N.E., Feldmann, J., Koch, M., and Dawson, P.: 'An optically controllable terahertz filter', *Appl. Phys. Lett.*, 2000, **76**, (20), pp. 2821–2823
5 Kleine-Ostmann, T., Koch, M., and Dawson, P.: 'Modulation of THz radiation by semiconductor nanostructures', *Microw. Opt. Technol. Lett.*, 2002, **35**, (5), pp. 343–345
6 Kleine-Ostmann, T., Pierz, K., Hein, G., Dawson, P., and Koch, M.: 'Audio signal transmission over THz communication channel using semiconductor modulator', *Electron. Lett.*, 2004, **40**, pp. 124–126
7 Chen, H.-T., Padilla, W.J., Zide, J.M.O., Gossard, A.C., Taylor, A.J., and Averitt, R.D.: 'Active terahertz metamaterial devices', *Nature*, 2006, **444**, p. 597
8 Gebbie, H.A., Stone, N.W.B., Putley, E.H., and Shaw, N.: 'Heterodyne detection of sub-millimetre radiation', *Nature*, 1967, **214**, pp. 165–166
9 El-Hadj Tidjania, M., Belland, P., and Verona, D.: 'Comparison of a pyroelectric detector with a tungsten-carbon point-contact diode. Application to the measurement of temporal coherence of an HCN laser', *Infrared Phys.*, 1979, **19**, pp. 677–681