TERAHERTZ PHOTONICS
Phase control of terahertz waves moves on chip

The phase of terahertz waves can now be precisely modulated electronically using a chip-based digitally coded phase shifter. The achievement is a step towards chip-scale integrated terahertz technology.

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Terahertz (THz) radiation, commonly referred to as T-waves, occupies a distinct niche in the electromagnetic spectrum between the microwave and infrared bands. With frequencies ranging from 0.1 to 10 THz, T-waves have long been of importance in radio astronomy and space science. However, advances in the development of detectors and, most importantly, sources of THz radiation have promoted wider interest in using T-waves in research laboratories and industry, for applications in spectroscopy, material characterisation, remote sensing and diagnostics, imaging and tomography [1]. In particular, T-waves hold great promise for the life sciences and medicine given that collective vibrations of many biologically important macromolecules occur at THz frequencies [2]. In addition, the THz frequency range is being considered for next-generation, short-range wireless systems which operate at high data rates and can be interfaced with optical fibre communication systems [3].

Nevertheless, progress in THz technology and its adoption has been hindered by the lack of efficient and compact components for dynamic control and modulation of T-waves, a functionality which still remains a key challenge [3]. The difficulty is largely because T-waves interact weakly with natural non-metallic materials except for, most notably, doped semiconductors and polar liquids (such as water), where they simply get absorbed.

One of the currently adopted, mainstream solutions is to enhance the interaction of T-waves with matter, in particular by exploiting electromagnetic resonances of artificially engineered materials, so-called metamaterials [4]. Such an approach has enabled the demonstration of active metamaterial-based components, such as switches and modulators, for T-waves propagating as collimated or focused beams in free space (see, for example, [5,6,7]). However, to date such designs cannot be readily scaled down to the size of integrated THz devices envisaged for chip-scale biomedical sensors and data processing systems in THz communications [3], not to mention the level of miniaturisation required for emerging THz electronics [8].

Now, reporting in *Nature Photonics*, Hongxin Zeng and colleagues have managed to devise and demonstrate experimentally one of the essential components of THz circuitry – a compact high-precision electronic phase shifter on a chip, which enables variable digitally-coded phase modulation of T-waves [9]. Among other notable features of the demonstrated phase coding chip is that it does not practically affect the amplitude of T-waves. Furthermore, it exhibits low transmission losses (unlike previous solutions exploiting resonant interaction).

The phase coding chip (see figure 1) is based on a conventional microstrip waveguide, one side of which is connected via microfabricated capacitors to a series of six identical short metal patches equally spaced along the waveguide. At a frequency of around 0.3 THz the resulting microstructures (known as stubs in microwave engineering) act as miniature electromagnetic resonators, each of which locally change the impedance of the waveguide and, hence, affect the propagation of the guided T-wave. They represent THz equivalent to the usual resonant LC circuits in electronics, which are not possible to implement at such high frequencies. Since the resonance of a stub results from the excitation of a standing wave, the spectral location of the resonance (and, hence, the magnitude of change it inflicts at a particular frequency) can be varied by changing the stub's effective electrical length. The authors accomplished this by making the microcapacitors in their stubs digitally switchable with control signals supplied individually via the respective stubs. As a result, they were able to blue-shift the resonance of any given stub by an impressive 20%.

The key to achieving such a large spectral shift is the integration of an AlGaN/GaN heterojunction into the structure of the microcapacitors (across their gaps). An AlGaN/GaN heterojunction is known to spontaneously generate a 2D electron gas (2DEG), a single layer of densely packed electrons trapped at the interface between the two materials [10]. The electrons in the 2DEG are free to move along the interface effectively forming a conducting sheet, which almost completely bridges the gap in the fabricated microcapacitors extending from one plate towards another (see inset to figure 1). By applying a bias voltage across the gap it is possible to retract the 2DEG further away from one of the plates and, consequently, reduce the capacitance of the structure. The authors found that the capacitance decreased more than 10-fold upon switching the bias voltage from 0 V (state '1') to 7 V (state '0').

To avoid changes in the amplitude of the guided T-wave, which would accompany changes in its phase for an electronically controlled stub on resonance, Hongxin Zeng and colleagues elected to operate their chip in an off-resonance state, in the frequency range 0.26 – 0.27 THz. Such a trick allowed them to maintain the overall transmission of the chip at a relatively high constant level (−6 to −8 dB, depending on the frequency) with the fluctuations limited to just 0.5 dB. While the phase shift attainable in this frequency range by switching any single stub is naturally smaller than at resonance (below 10 degrees), it accumulates as the guided wave propagates from one stub to another and can become as high as 55 degrees. Importantly, the phase shifts imposed by the stubs individually do not simply add up due to interactions among the latter, which makes many (otherwise equivalent) switching combinations unique. For example, feeding the chip with the codes 100001, 010010 and 001100 will produce different phase shifts. To lift the degeneracy completely Hongxin Zeng and colleagues used yet another trick – the ground electrode for control signals was introduced as an additional, 'passive' stub, which they placed on the other side of the microstrip, closer to its end (see figure 1). The resulting structural imbalance of the microstrip ensures that all control stubs, even when switched separately, have a unique effect on the guided T-wave – that is the codes 100000, 010000, 001000, 000100, 000010, 000001 will programme different phase shifts. In fact, all the codes featuring the same number of '1' states now correspond to different outputs.

The approach works well enabling the authors to digitally control the phase of T-waves and shift it in small constant increments of 2 – 5 degrees (depending on the operation frequency) with an average error of just 0.36 degree. Given very short switching time of 100 fs estimated for the 2DEG-based microcapacitors, the modulation rate of the phase coding chip might be as high as 3 Gbps, as a recent study suggests [11]. This high speed, combined with the small footprint of the chip (active area is 2.3×0.3 mm^2) and its 'digital readiness' render the demonstrated phase shifter particularly attractive as an active component of future integrated THz systems.

Its practical use, however, may still be delayed by a few remaining issues. In particular, the operation of the phase shifter is inherently narrowband, as it relies (although not directly) on a resonance and, hence, both the smallest and total attainable phase shifts depend on the working frequency. Transmission losses of the chip are predicted to increase proportionally with the number of active stubs, which limits the scalability of the proposed phase modulation scheme and, in fact, renders the currently demonstrated maximal phase shifts of 30 – 55 deg as the likely optimal output. Finally, at present the on-chip active phase control has been demonstrated for the low-frequency edge of the THz band and it remains to be seen whether the same operation principle can be implemented for T-waves oscillating at frequencies of 1 THz and beyond.

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Competing Interests
The author declares no competing interests

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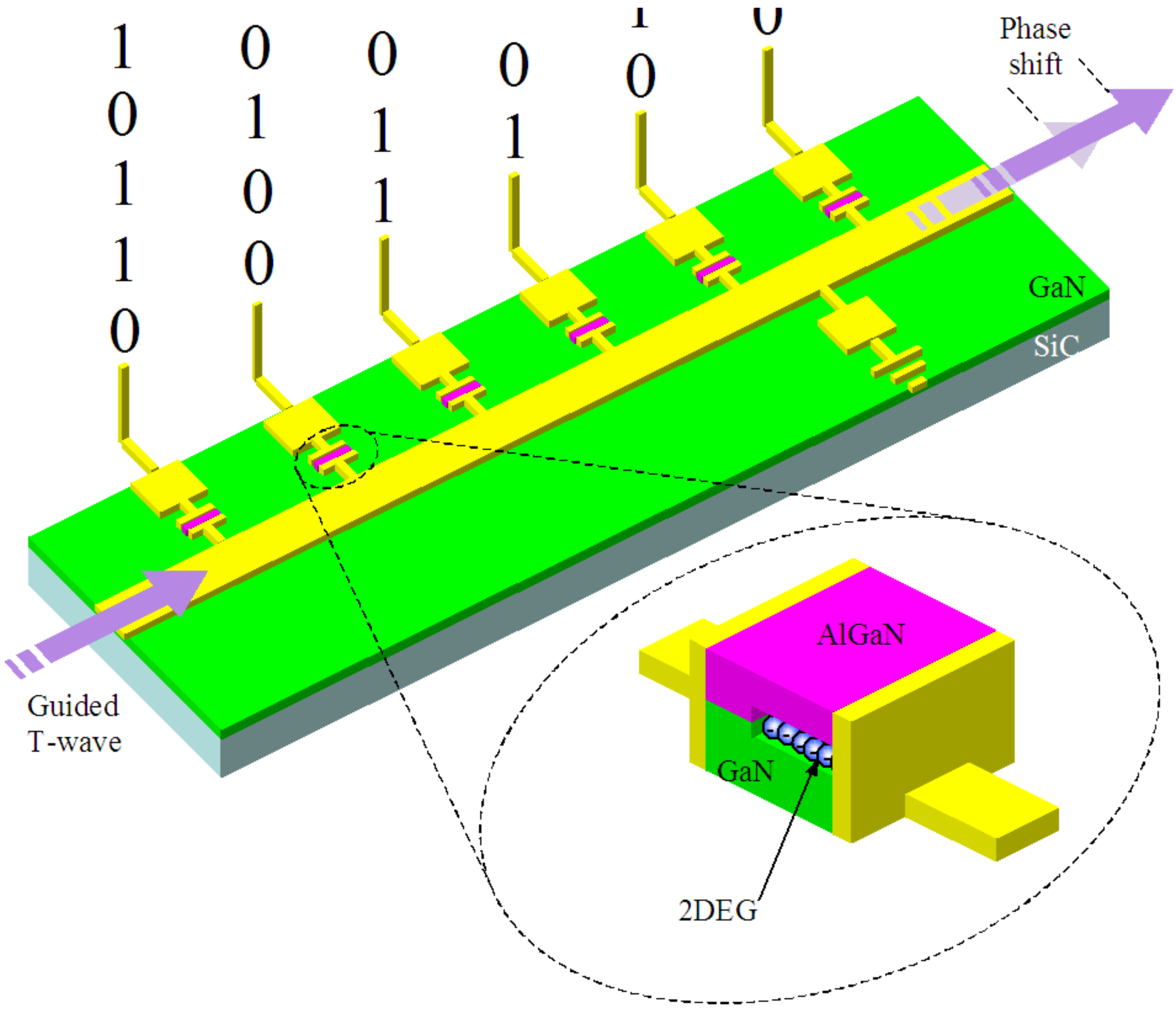

Figure 1. Schematic of the THz phase shifting chip and how it imparts digitally coded phase modulation to a T-wave, which is propagating along the central waveguide. The phase shift is introduced via the stubs that run along the upper side of the waveguide and act as tiny THz resonators controlled by micro-capacitors featuring a 2D electron gas.