



Microelectronics and Microsystems Photonics

Terahertz devices

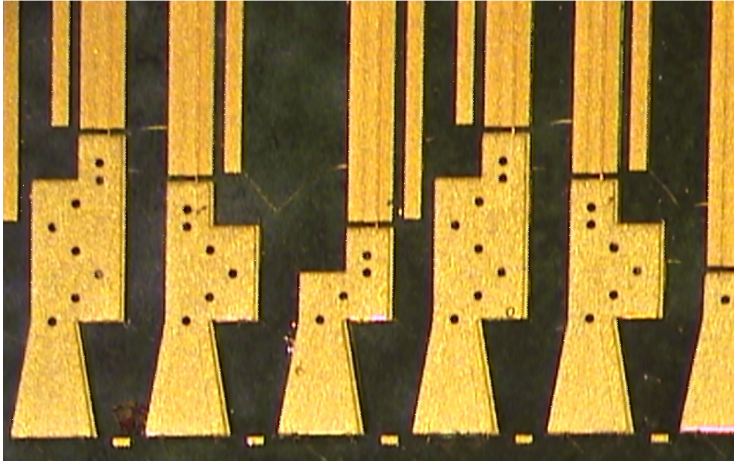


Figure 1: Collection of completed rectangular waveguides integrated with THz QCLs on a single chip. The lasers (the straight wider lines extending off the top), penetrate a little distance into the hollow waveguides (at the bottom).

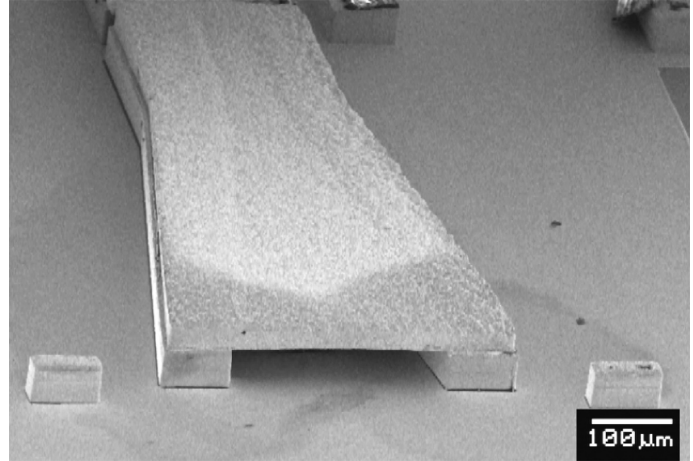


Figure 2: Close-up, scanning electron microscopy image of a terahertz (THz), rectangular, metal-waveguide horn antenna formed over a THz semiconductor laser mounted to the chip. The flare of the horn improves the spatial pattern of the emitted THz radiation.

From vacuum tubes to solid state

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The range of frequencies around 1 terahertz (THz = 10^{12} cycles per second) is like the neglected middle child in the electromagnetic spectrum. Both microwave (below roughly 0.1 THz) and infrared (above roughly 20 THz) are used widely, thanks to a high performance, mass-produced semiconductor technology base. Caught in between, THz radiation lacks the microelectronic foundation of its spectral siblings and still relies to a great extent on large-scale tube-based components analogous to using vacuum tubes for radios. Nonetheless, there has been broad interest in exploiting the THz spectrum. Laboratories worldwide have carried out proof-of-principle demonstrations showing how THz is far more effective than microwave or infrared in very rapid and highly precise hazardous chemical sensing and identification, concealed threat detection and imaging, noninvasive medical and biological diagnostics, and secure high-speed telecommunications. To get such THz applications out of the laboratory and into widespread use will require bringing THz into the solid-state era.

Sandia researchers recently took a major step along an innovative route towards a THz microelectronic technology base. The Sandia team, working under a Grand Challenge project, demonstrated the first successful integration of a THz quantum cascade laser (QCL) with a micro-machined gold rectangular waveguide, all on a semiconductor chip (Fig. 1). QCLs have been researched and developed extensively at Sandia and are the only solid-state source capable of producing more than a few milliwatts of coherent average power between 1 to 5 THz. Unfortunately, QCLs generate highly divergent and non-uniform radiation beam patterns into free space that curtail their usefulness in practical applications. The solution pioneered by Sandia forces a QCL to radiate into a three-dimensional waveguide structure (Fig. 2) in such a way that the THz electromagnetic field is guided and shaped by the waveguide boundaries in a simple and predictable manner that can ultimately be manipulated by standard waveguide design techniques.

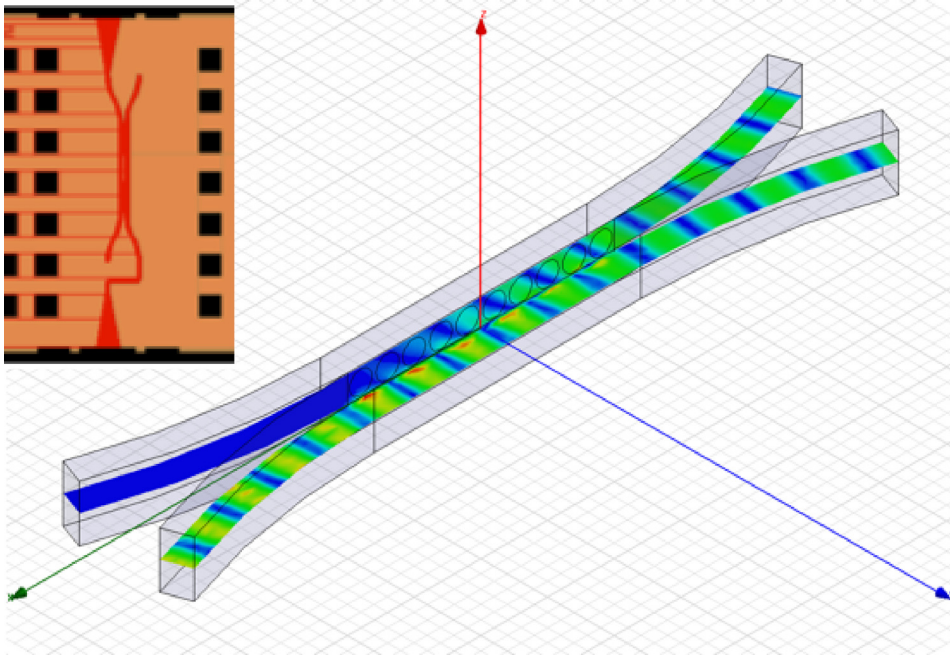


Figure 3: (Left) THz rectangular waveguide coupler device. (Right) Results of electromagnetic modeling of the device performance.

The integration of QCLs and waveguides on a chip posed significant technical challenges stemming from the small cross-sectional dimensions of the QCLs and the waveguides (typically tens of microns thick by ~ 100 microns wide), the requirement for the strict alignment of a QCL and its waveguide, and a QCL's need for roughly 1 Amp of bias current while being electrically isolated from the gold waveguide walls. Waveguides for THz are usually made by high precision traditional metal machining tools, but the Sandia team recognized that this conventional approach was unsuitable to the integration task and also wanted to make the entire process compatible with semiconductor fabrication methods scalable to mass production. The Sandia strategy was to start with a working QCL device, design a proper waveguide for the QCL using electromagnetic simulation software, and then apply sophisticated semiconductor micromachining methods to build the designed waveguide structure around the QCL.

Sandia's demonstration of a QCL-integrated waveguide clears the way to making THz radiation from QCLs much more widely practical. In the waveguide, the THz electromagnetic field propagation characteristics can be engineered using known waveguide techniques such as couplers (Fig. 3), twists, bends, splitters, and horn antennas. A rectangular waveguide is also the preferred way for mating THz components into larger scale circuits and systems. Ultimately, the Sandia team aims to further integrate a THz detector device with the QCL/waveguide structure and create a compact, microelectronic THz transceiver, which will finally put the THz spectrum on a technological par with microwave electronics and infrared photonics.