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THz Integrated Circuits

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***Abstract*—We will review our latest efforts at making THz integrated circuits, focusing mostly on integration of a Schottky diode into the core of a quantum cascade laser to create a heterodyne receiver. We will show its capability to detect external radiation and its ability to explore the behavior of the QCL itself.**

I. Introduction

Since their first demonstration in 2001, much of the work on THz QCLs has focussed on improving the performance of the QCLs [1]. More recently people have begun to take advantage of the microphotonic nature of the QCL's to integrate QCLs with other on-chip active devices to enhance the functionality of the QCLs such as adding a modulator [2] or ultrafast switch for pulse amplification [3]. For the past couple years we have pursued two thrusts to allow integration of QCLs with other active devices. The first involved integrating THz QCLs with on-chip lithographically defined rectangular waveguides which allows controlled movement of the QCL output around on the chip [4], [5]. This opens the possibly of coupling THz QCL output to other devices on the same chip or to antennas to couple the radiation into free space. The second technology involves monolithically integrating a Schottky diode into the core of the THz QCL to make a simple THz integrated circuit - a THz heterodyne receiver on a chip [6].

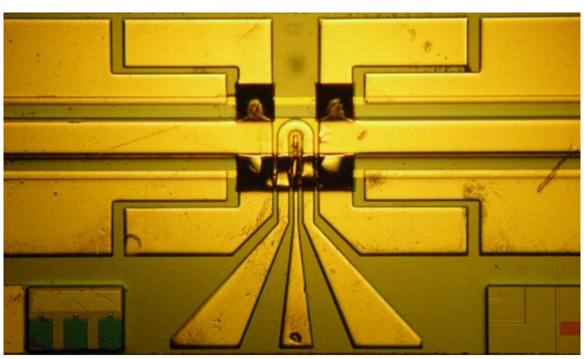

Fig. 1. Picture of an integrated receiver consisting of a Schottky diode embedded in the core of a THz QCL. The size of the image is 3mm x 1.5 mm.

II. THz monolithic receiver

A top view image of an integrated heterodyne receiver is shown in Fig. 1. The horizontal bar near going from the left of the image to the right is the THz quantum cascade laser that performs the function of local oscillator. The active region of the QCL is based on bound-to-continuum design [7] and uses a semi-insulating surface plasmon waveguide [8]. A Schottky diode is created in a small hole in the metal contact on top of the laser consisting of a Ti metal contact to the doped laser contact layer. The 1 micron diameter diode (too small to be seen in the picture) sits in the middle of the inverted U-shape on top of the laser stripe. A coplanar waveguide (the three metal traces coming in from the bottom) carry signal from the diode off the chip. Due to the nature of the surface plasmon waveguide, the internal laser field is strong at the semiconductor/ metal interface and couples well to the diode at this interface. Placing the diode in the core of the laser eliminates both the need to emit light from the laser and the optics normally used to collect and refocus the light into a separate heterodyne mixer. The monolithic integration results in a much more compact system compared to discrete component systems and takes advatage of semiconductor fabrication techniques to achieve straightforward and precise alignment of the devices.

III. Results

The device shown in Fig. 1 performs all the basic receiver functions performed by discrete component THz photonic systems (e.g., transmission of a coherent carrier, heterodyne reception of an external signal, frequency and phase locking and tuning). In addition, the integrated device can be used to explore the behavior of the QCL, such as measuring with high precision the Fabry-Perot mode spacing or the laser frequency dependence on current and temperature, exploring the laser sensitivity to feedback, chaos, or injection locking to a strong external THz source.

Fig. 2 demonstrates that the diode is coupled to the internal laser field. The top panel of the figure shows the output power of the laser as a function of the laser current. For this laser the threshold current is near 420 mA. At a bias of 0.6 V, the diode draws around 0.75 μA of current. This current is fairly constant until the laser reaches threshold. As can be see in the lower panel of the figure, the current increases as the laser output power increases with a maximum percentage change of around 4% for this device. Below threshold there is a little change in the diode current as the laser current changes. Part of this change is probably do to the fact that the ground of the laser and the ground of the diode are shorted together on top of the laser allowing the laser driver and diode driver circuits to affect each other. The output power of the laser is fairly linear above threshold, but the diode response is sub-linear especially above about 460 mA which is where the laser transitions from single mopde behavior to multi-mode behavior. It is possible that the different modes have different coupling strengths to the diode because of thier different spatial profile inside the laser waveguide.

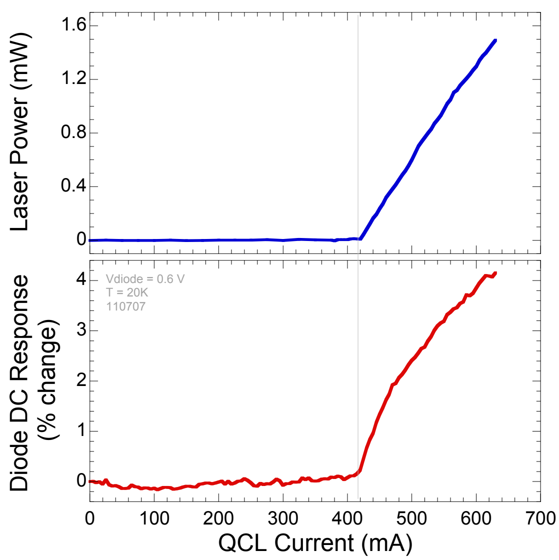

Fig. 2. Laser output power (top) and percent change in the diode current (bottom) at a fixed diode bias of 0.6V as a function of the laser current demonstrating that the diode is coupled to the internal laser field and produces a rectified response. The heat sink temperature was held at 20 K.

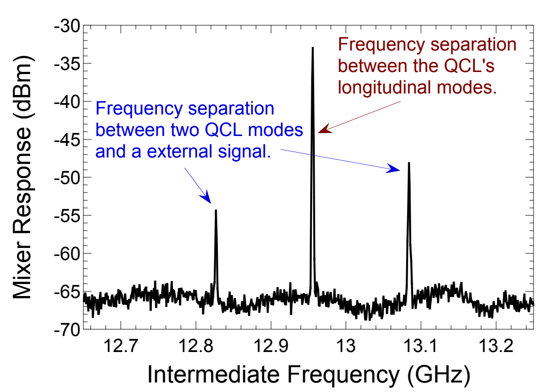

Fig. 3. Frequency response of the integrated diode on a Fabry-Perot THz QCL showing the difference frequency between the longitudinal modes of the QCL (12.7 GHz) and the difference frequencies of an externally applied signal mixing with two different modes of the QCL.

Fig. 3 show the basic response of the diode receiver when a molecular gas laser illuminates one facet of the QCL. The central peak is the response due to the diode mixing the multiple internal Fabry-Perot modes of the QCL. The frequency corresponds to the difference frequency separating the QCL modes. The left and right peaks are the result of mixing of the molecular gas laser line with two different QCL modes. For this example the molecular gas laser light was not coupled to the diode via an antenna as is normally done with Schottky diode receivers. Instead the molecular gas laser was focussed on one QCL facet and part of the incident radiation couples into and propagates through the QCL waveguide to the diode. Since the incident signal propagates through the active region of the QCL it should also be amplified by the gain media as it propagates, although we have not explored this yet.

The results shown here demonstrate that the QCL power is coupled to diode mixer and can act both as a direct detector or as a heterodyne reciever. Ideally a local oscillator would generate only one well known frequency rather than the comb of different laser frequencies our QCL currently generates. This will be corrected in the future by utilizing a distributed feedback grating on the laser, but for the moment we are using the integrated device to explore the behavior of free running QCLs and use an external laser source as the frequency reference when needed.

Acknowledgment

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