The Quantum Cascade Laser as a Terahertz Local Oscillator

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Abstract **– A quantum-cascade-laser is being developed as a local oscillator for a THz spectral line receiver.**

I. Introduction

The goal of this project is to develop an all-solid state terahertz receiver for spectroscopy of the upper atmosphere. The instrument illustrated in Fig. 1 uses heterodyne techniques to achieve a spectral resolution exceeding 1 part in a million in the frequency band between 2-3 THz. The mixer is a GaAs Schottky diode, and the local oscillator (LO) is a laser. Heretofore receivers of this type required a large optically pumped FIR gas laser for the LO. However, recent breakthroughs in semiconductor device technology now make a solid state alternative possible. In particular, devices called quantum cascade lasers (QCLs) appear to satisfy the basic requirements for a THz LO. Our focus for the first year of the project is to improve QCL device performance so that one can be used in a practical receiver.

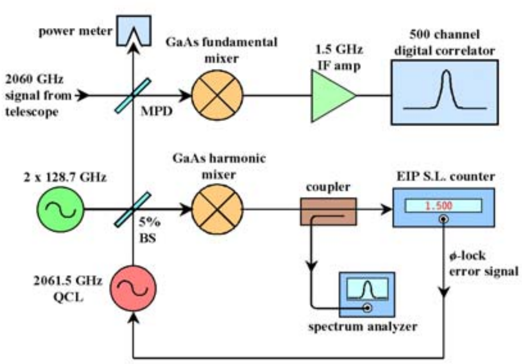

Fig.1 – Layout of the all-solid-state THz heterodyne receiver

II. Quantum-cascade-lasers

Quantum-cascade-lasers (QCLs) are heterostructures made (in this case) from materials in the III-V semiconductor group (e.g., GaAs/GaAlAs). An unbiased heterostructure, as shown in Fig. 2, is a planar multiple quantum well (MQW) deposition of alternating high and low bandgap materials. When an appropriate DC bias is applied, QCLs emit photons as electrons make transitions between sub-band states in the conduction band. In Fig. 3, the emission occurs when electrons make downward transitions between states 5 and 4. The electrons are introduced into state 5 by a leading quantum well called the “injector”. They are depopulated from state 4 in our type of laser by a resonant phonon process that relies on a lattice mode of GaAs. A large number of repeating MQW sections are cascaded during MBE layer deposition to enhance the gain path. A single electron traveling through this composite structure under DC bias emits hundreds of identical THz photons without recombination (in contrast to a single photon per recombination in a bipolar diode laser). The emission frequency is a function of energy level differences, which can be controlled by appropriate choice of the GaAs well thicknesses. With the addition of optical feedback from the cleaved ends of the MQW gain region, the device acts as a laser. TM selection rules for these type II superlattices dictate that the emission emanates from the edge

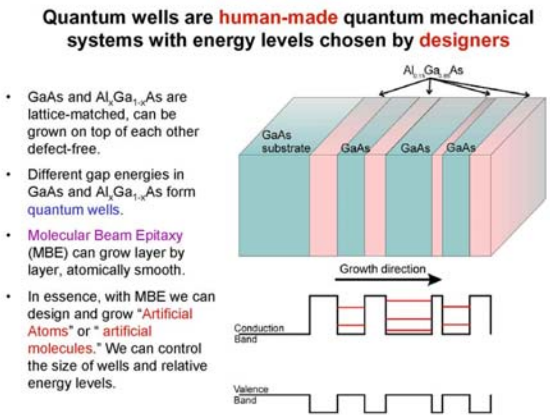

Fig. 2 – Multiple-quantum-well deposition

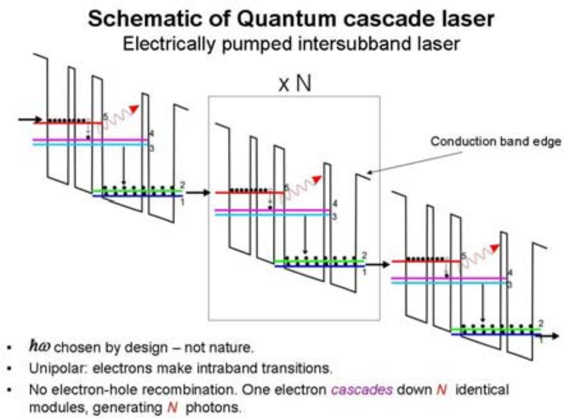

Fig. 3 – QCL Energy Level Diagram

facets of the device (*i.e.*, perpendicular to the MBE growth direction) with a polarization parallel to the growth direction. To control the THz emission, QCLs are fabricated as long waveguides, with lengths around 1 mm and transverse dimensions typically 10 x 40 microns.

For our receiver application we need to achieve simultaneously > 1 mW of single mode laser power, a linewidth and frequency uncertainty <200 KHz, and an operating temperature > 90 K. So far THz QCLs have produced output powers exceeding 10 mW, linewidths less than 100 kHz, and CW operating temperatures above 100 K, although the specifications have not yet been achieved simultaneously.

Although QCLs have been available at near infrared wavelengths for more than 10 years, the first THz QCL (at 4.4 THz) was only produced 2 years ago. Because it becomes more difficult to produce a population inversion as the energy levels are brought closer together (by increasing the layer thicknesses), it is more difficult to produce a 2 THz QCL than a 3 THz one. Currently the lowest frequency CW QCL operates at 1.9 THz up to T=95 K [1].

The laser oscillates close to the 2.06 THz line of atomic oxygen, but requires cooling to T<40 K to achieve the desired 1 mW output. The bias power requirement is also large at >5 W, and so more work is needed here. Other QCLs have frequencies close to important water lines at 2.8 THz. QCL local oscillators will soon be practical for small satellite missions. Already a QCL from MIT has been used as a LO for a superconducting NbN mixer at T=4 K. Only 4 μW of LO power was required for that experiment, but similar QCLs produce enough LO power to drive cooled GaAs Schottky mixers at 2.8 THz. Harmonic multiplier systems, which are commonly used with cryogenic SIS and HEB mixers, do not produce enough power at 3 THz to drive a Schottky. In fact, the best anyone has done with a THz multiplier is only 0.5 μW at 1.9 THz. QCLs should be the only viable tunable LO technology for space missions above 2.0 THz. Here we exclude the special FIR laser LO developed for the 2.5 THz receiver of the MLS instrument on AURA because of its size (21 kg and 22.5 liters), power consumption (120 W), and lack of tunability.

Last year MIT produced a 2.757 THz QCL, which is near a strong water line of atmospheric interest. Fig. 4 illustrates the laser's performance. At optimum bias, this prototype dissipates 1 W DC to achieve 1 mW of CW LO power at T=10 K. A number of design enhancements have subsequently been identified that should help us achieve a 2 mW output for T>60 K in a year or two. For example, better bonding techniques have increased the output to 2.5 mW at T=10 K and 1 mW at T=80 K for a 3 THz device [2].

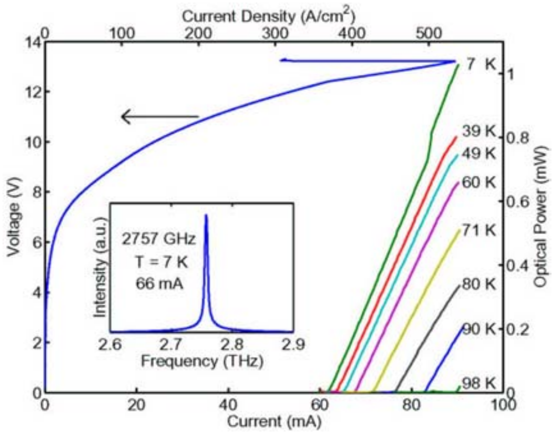

Fig. 4 - (a) Right Side: QCL emission in CW mode versus current characteristics at various temperatures. (b) Inset: CW spectrum taken using Nicolet 850 Fourier transform spectrometer and a deuterated triglycine sulfate (DTGS) detector at 0.125 cm^{-1} resolution. (c) Left side: I/V curve for QCL showing the onset of negative differential resistance above 13.2 V at T=7K.

A. Laser Mixing Experiments

At U. Colorado we have showed that a 3 THz QCL can be readily offset-locked to a FIR laser signal [3]. Fig. 5 illustrates the hardware, and Fig. 6 shows the difference frequency signal between a FIR laser and a QCL, which is offset-locked by 48 GHz. The 48 GHz IF signal is down-converted to 1.2 GHz for spectral analysis. From the plot we see that QCL linewidths are 65 kHz and 141 kHz at the – 3 dB and – 10 dB levels, respectively. The QCL linewidth under locked conditions is a factor of 10 narrower than

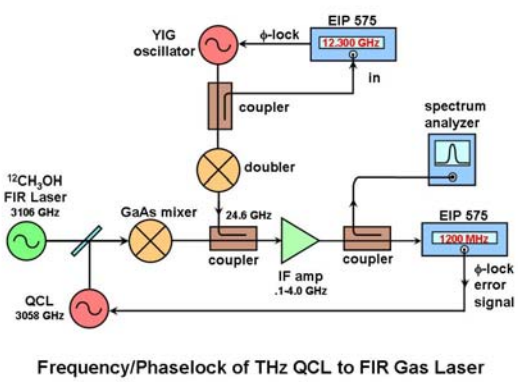

Fig. 5 –Diagram of QCL Frequency Lock Circuit

that required for the proposed THz receiver. The QCL frequency can be fine-tuned by adjusting its temperature and bias current. For this particular QCL, temperature tuning yields –205 MHz/K, and bias tuning is -45 MHz/mA. As part of the project, we intend to phase-lock the QCL to a harmonic of a synthesized microwave source. This will allow the QCL frequency to be set by computer control. We have no doubt that QCLs will be the LO of choice for frequencies > 2 THz and perhaps even lower after cooling requirements have been met.

The main goal of our QCL development work will be to raise the operating temperature of the 2 THz laser from 20 to 60 K, while maintaining a minimum output power of 1 mW. A second goal will be to raise the laser output power to >2 mW without increasing the DC power dissipation beyond 1 W. To do this we must improve the

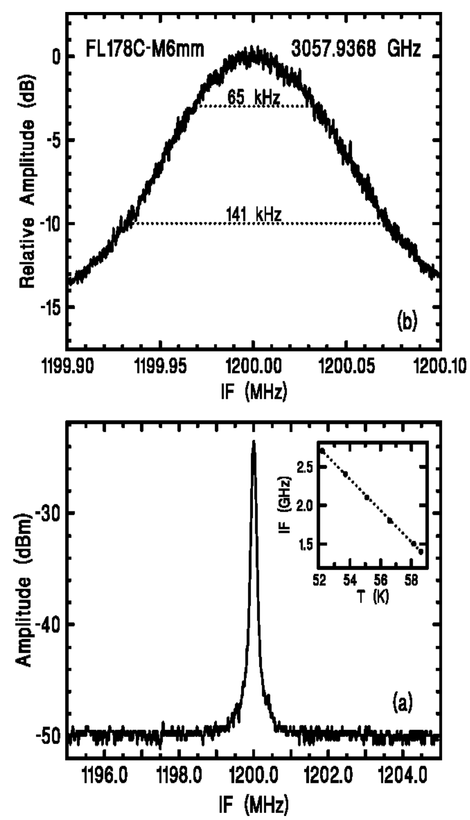

Fig. 6 -- High resolution spectrum of a 3.058 THz QCL offset-locked to a FIR laser line. Panel (a) shows the IF signal at 1.2 GHz. The inset of panel (a) shows the temperature tunability in un-locked conditions. Panel (b) shows a magnified view at line center under locked conditions.

laser efficiency. To first order, the output power of a QCL is proportional to the volume of the gain region. Another group has achieved a CW output power of 12 mW at 2.3 THz from a different type of QCL with 11 times the volume of the devices we use. This laser was cooled to 10 K and dissipated 12 W of DC bias. Even larger devices achieved up to 50 mW when similarly cooled. Although these are impressive power outputs, the operating conditions cannot be easily met in a spacecraft instrument. We intend to improve output powers by using more sophisticated coupling techniques so that we can use small lasers with small DC bias requirements and higher temperature operation.

B. Absolute Frequency Control

Fig. 1 also shows a phase-lock circuit that uses a GaAs Schottky diode as a harmonic mixer. Here the QCL locks onto the 8th harmonic of a frequency-doubled 128.75 GHz Gunn oscillator, which itself is phase-locked to a microwave frequency standard. With the QCL locked to the microwave source, and the latter locked to a GPS-stabilized 10 MHz-crystal oscillator, the long term frequency accuracy of the spectrometer in the lab is 1 part in 10^{11} and the short-term value is 1 part in 10^9, equivalent to 30 cm/s uncertainty on the absolute Doppler velocity. This spectral purity more than meets our 0.2 MHz requirement.

Out first attempt at THz harmonic mixing is shown in Figs. 7 and 8. Initially we are using a FIR gas laser as the THz source, because is has a very narrow linewidth (< 10 kHz), and so the mixing process reveals the broader phase noise of the frequency-multiplied microwave source, as shown in Fig. 8. Here we are mixing a 1962.7 GHz laser signal with the 12th harmonic of a phase-locked 130.9 GHz Gunn oscillator. The weaker signal spikes in Fig. 8 are beats between high-order gas laser modes and the microwave harmonic. The broad triangular pedestal is the multiplied phase noise of the microwave source.

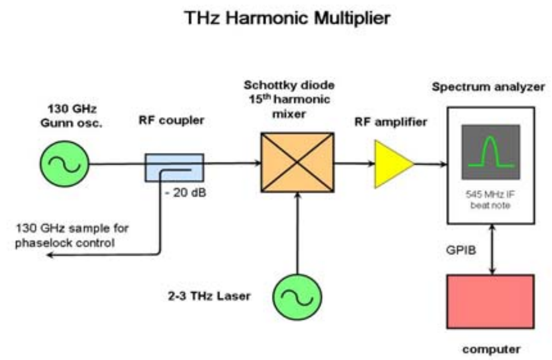

Fig. 7 – Generating a beat signal between a THz laser line and a harmonic of a microwave source.

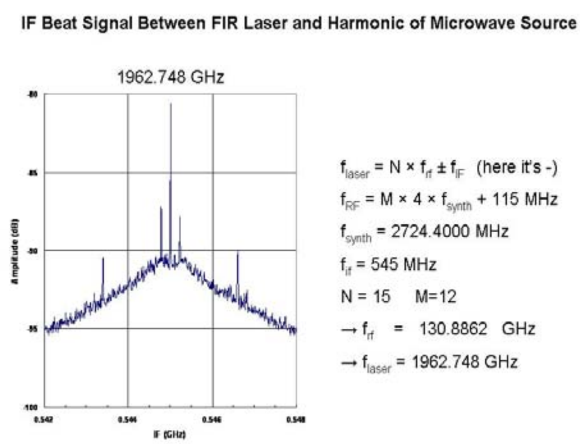

Fig. 8 -- Laser mixing with a microwave harmonic

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III. References

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