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A Phase-Locked Terahertz Quantum Cascade Laser

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ABSTRACT

Progress in coherent receiver development at terahertz frequencies has been hindered by the lack of a suitable local oscillator source that can be qualified for space missions. Space systems now in development rely on harmonic multipliers of microwave sources. Multipliers have achieved usable performance up to 1.6 THz, and probably, with a lot of work can be extended to 2.0 THz, but above that hope dims. The science driving the development of THz spectral line receivers requires capability up to at least 4.75 THz (the neutral oxygen line). Ideally, the THz LO should be some type of tunable semiconductor laser that can be locked to a harmonic of a millimeter-wave source. In the early 1990's a new type of semiconductor laser was developed called the quantumcascade-laser. This device is unipolar in that only transitions of electrons between sublevels in the conduction band are needed to produce laser emission. Although the QCL was originally developed as an infrared laser operating well above the 8-9 THz reststrahl band of GaAs/GaAlAs, it was eventually realized that operation below the reststrahl band was also possible, but much more difficult. The first terahertz OCL was demonstrated two years ago at 4.4 THz, and now devices work as low as 2.1 THz, with even lower frequencies envisioned. State-of-the-art QCLs require only LN₂ cooling and a DC bias power as low as 2 W, and yet produce > 500 μ W of CW power from a chip no bigger than a transistor.

In order to demonstrate the potential of a QCL to serve as a THz local oscillator, we have phase-locked a QCL to a 3.1 THz methanol laser line. This particular QCL emits about 160 μ W at an operating temperature of 81 K. Spectra of the IF signal at the 3250.000 MHz offset frequency indicate a QCL linewidth of 350 kHz (FWHM) for this initial attempt. The lineshape is Lorentzian and has considerable fine structure, which suggests that bias current fluctuations are broadening a much narrower line. We expect to achieve a factor of 10 improvement to a 30 kHz linewidth (1 part in 10⁸ fractional bandwidth) after improved bias source and lock electronics are implemented.

Introduction

Compact THz sources are critically needed as local oscillators in space-qualified heterodyne receivers. LO applications require oscillators that are frequency programmable, have good amplitude stability and a linewidth consistent with observational objectives. For interstellar clouds, Doppler gradients can be a low as 0.1 km·s⁻¹, and so an LO fractional linewidth < 1 part in 10^7 is desirable. Phase noise should also be low so that LO noise is not detected in the IF band. Fixed-frequency gas lasers have the required frequency stability, but their relatively large size and required CO_2 pump source preclude their use in space applications, aside from one application in NASA's Microwave Limb Sounder instrument. Tunable millimeter wave sources also have good frequency stability and low phase noise under phase-locked conditions, and their harmonics are usable in the 1-2 THz band. Unfortunately the sub-microwatt power levels available from harmonic sources above 2 THz are not adequate for realistic LO applications. Even with HEB mixers, $> 5 \mu W$ of LO power (measured at the source) is needed to insure a low receiver noise and high dynamic range for the mixer. A recent invention, the terahertz quantum cascade laser (QCL), potentially solves the problem of a space-qualifiable THz LO. Recent 3 THz devices, no bigger than a transistor, need only LN_2 cooling and yet produce > 500 uW of CW power while dissipating 2-4 W with 10 V bias.

THz emission from a QCL was first demonstrated about 2 years ago, and already a large amount of progress has been made by several groups [1,2,3]. Although QCLs work best at higher THz frequencies (because the energy levels are more separated), they have been demonstrated in CW operation down to 2.1 THz so far [4]. QCLs are heterostructures made from materials of the III-V semiconductor group. A heterostructure is a multiple-quantum well (MQW) structure of alternating high and low gap materials. THz photons are emitted by these devices as electrons make transitions between sub-band states in the conduction band. A large number of repeating MQW subsections 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 any recombination (in contrast to conventional diode laser operation). Add optical feedback from facet reflectivity and you have a laser.

QCL Parameters

The QCL frequency is determined by the gain profile and the mode spacings of the basic FP cavity. The gain peaks at the design frequency determined by the quantum well structure and has an overall 3 dB bandwidth of \sim 1 THz. Within this bandwidth, the oscillating frequency is set by the FP longitudinal resonances. Higher order off axis modes may have sufficient gain to oscillate under some circumstances, but they can usually be suppressed by selecting the DC operating point. Frequency tuning is accomplished by changing the QCL channel temperature either via the cold plate temperature (slow tuning) or through the bias current (fast tuning). The emitted radiation is TM mode - the electric vector is parallel to the growth direction of the MQW stack,

which is nominally 10 μ m thick. These QCLs are edge emitters with typical facet dimensions of 10 μ m x 40 μ m. Because the material index is relatively high (n = 3.8), the emitting face has minimum dimensions of about $\lambda/2$, and optical coupling is not a serious problem.

Two distinguishing features of the MIT QCL lead to CW operation at higher temperatures and longer wavelengths. The first is that the lower laser level is depopulated by resonant optical phonon scattering, and the second is that mode confinement is achieved by a metal-semiconductor-metal waveguide. Figure 1 shows the power output and I/V curves for the device used here. This laser is 1.22 mm long, 40 μ m wide, and 10 μ m thick, and has 177 cascaded sections. This device was the first THz QCL to operate CW above the temperature of liquid nitrogen, and in fact oscillates CW at 3.1 THz up to 93 K [5]. The QCL was made at the MIT Research Laboratory of Electronics with MBE material grown at Sandia. We measured the THz polarization to be 88 ± 3 % parallel to the growth direction (as expected), and 12% cross polarized. (As a check we measured the polarization of the FIR gas laser used here with the same wire grid, and found it to be 98 ± 2% linearly polarized.)



Figure 1 – Output Power and I/V Curve of 3.1 THz QCL labeled FL177C-M5

Optical Coupling

The 10 μ m × 40 μ m end faces of the QCL are uncoated. The reflections from the facets are governed by the impedance discontinuity between the QCL waveguide and free space. A 2-dimensional EM simulation shows that the reflection is greater than 80%, which is much larger than the 34% expected from simple Fresnel reflection. The front, back, and sides of the QCL are defined by a mesa structure. The top and bottom planes are defined by copper metallizations that provide waveguide confinement. Emission from one output face is coupled through a hemispherical silicon lens (4 mm diam. - transmission 60%) in near contact. The diverging beam proceeds through a crystal quartz window on the dewar (transmission 65%), and is refocused by a 90-degree off-axis ellipsoidal mirror. Fig. 2 shows a simplified schematic of the experimental hardware. The beam propagates in air for 1.25 m and is reflected from a wire grid polarizer used as a variable beam-combiner. A signal from an optically-pumped FIR gas laser passes through the same beam-combiner. A second off-axis ellipsoid focuses the combined QCL and FIR laser signals onto a room-temperature GaAs Schottky-diode-mixer (UVa type 1T15) in a corner reflector mixer mount [6].



Figure 2

Only 40% the laser signal is transmitted over this open-air path because of absorption by atmospheric water vapor. Fig. 3 shows 1-m path transmissions calculated from the HITRAN data base. The maximum QCL power measured in the focal plane of the mixer was about 25 μ W (\pm 30 %). This power and the measured absorptions imply that the QCL power at the output face was about 160 μ W (\pm 30 %), which is comparable to that expected for the operating temperature of 81 K used in this experiment (see Fig. 1). The FIR laser runs on the 3105.9368 GHz line of methanol. IF signals over a bandwidth of 15th International Symposium on Space Terahertz Technology

0.1-4.0 GHz are amplified by 65 dB and directed to a source locking counter (EIP Model 575). A -13 dB directional coupler diverts part of the IF signal to the spectrum analyzer. The phase-lock output signal from the counter is added as an error voltage to the negative sense lead of the QCL bias supply (HP 6632B). For protection purposes, the error voltage is limited to 1 volt by a resistive divider network. This divider also effectively cuts the overall laser oscillator gain down to 270 MHz/volt, which is within the operating range of the source locking counter.



Atmospheric Transmission 1-m path





Figure 4

Figure 3

Mixing Results

A plot of the beat note frequency as a function of OCL bias voltage is given in Fig. 4. The open-loop tuning sensitivity is about -2.7 GHz/V. With a differential resistance of 13 ohm at the operating tuning sensitivity point. the equivalently -35 MHz/mA. Examples of OCL spectra under offset-locked conditions are provided in Figure 5(a-d). The lock-offset frequency is arbitrarily set to 3250.000 MHz, and the QCL runs in the upper sideband at 3109.1868 GHz. The circuit locked on first try and remained locked for 1 hour, after which the test was intentionally terminated. During lock, the DC component of the error voltage at the QCL bias terminal gradually increased by +20 mV. This bias change corrects for thermal effects that otherwise would have produced a total drift of 54 MHz.

The QCL linewidth when locked is about 350 kHz (FWHM). This is similar to the unlocked linewidth, which is to be expected since the loop bandwidth of 10 kHz is insufficient to correct the obviously wider sidebands. The overall Lorentzian lineshape is but has considerable fine structure. which suggests that current fluctuations are broadening an intrinsically narrower line. The "noise" apparent in the linearscale plots of Fig. 5(a-c) is all due to laser fluctuations. Given the -2.7 GHz/V tuning sensitivity of the OCL, and the specified 1.5 mV ppk AC noise of the power supply, we would roughly expect bias noise to broaden the line by 4 MHz. The source of the sideband peaks at multiples of 700 kHz is under investigation but probably is due to the power supply. Future experiments will



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use a low noise constant current source (perhaps a battery) and increase the loop bandwidth to at least 10 MHz. Although line widths of 0.4-4 MHz are tolerable for astronomical spectroscopy at 3.1 THz, we must be certain that phase noise is low within the expected IF band (*e.g.*, 4-8 GHz away from the LO).

Conclusions

The deleterious effects of temperature drift and optical feedback can be corrected by phase-locking the QCL frequency to an external reference. A phase-locked QCL can be stable in both frequency and amplitude. Although both the laser power and frequency are functions of bias current, we can use the low-frequency component of the phase-error signal to control the block temperature (and thereby the laser frequency) such that the bias current remains constant long term. In this experiment we used a FIR laser as the reference (the FIR laser linewidth is <10 kHz). Next we will try locking to a high harmonic of a 120 GHz source. At that point the QCL frequency can be set by computer control, as astronomers expect (and demand). Further refinements on loop electronics and bias noise control should lead to linewidths of 30 kHz at 3 THz, or 1 part in 10^8 .

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