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High-accuracy heterodyne detection of THz radiation exploiting telecommunication technologies

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Abstract: We report the first open-loop heterodyne technique using standard telecom optical fiber components for spectral characterization of THz semiconductor lasers. This allows the measurement of continuous modal tuning with sub-GHz accuracy and 20dB dynamic range.

OCIS codes: (060.2840) Heterodyne; (140.5965) Semiconductor lasers, quantum cascade

1. Introduction

The poor free space transmission of THz Quantum Cascade Laser (QCL) emission can be overcome through up-conversion to near infrared (NIR) frequencies by exploiting the nonlinearity of the laser cavity itself. This allows THz signals to propagate down an optical fiber (so called THz-over-Fiber) [1] and opens up the possibility of using advanced optical fiber technology to control and measure THz emission. In this paper we show how we can use an open-loop heterodyne technique [2], based on standard telecom optical fiber and radio-frequency (RF) components to characterize spectral emission from conventional Fabry Perot (FP) QCLs. We can detect the QCL linewidth, frequency and current tuning with sub-GHz resolution and 20dB dynamic range in this un-optimized setup, comparable with measurements obtained by direct heterodyning at THz frequencies [3]. The measured heterodyne linewidth is significantly broadened from the intrinsic QCL linewidth due to both the free running operation of the NIR lasers and rise time effects inherent to pulsed operation of the QCL. We use this heterodyne technique to measure current tuning of the THz QCL, which can be compared with that measured by a Fourier transform infrared (FTIR) spectrometer. This technique could be extended to produce an all fiber phase lock loop for a THz QCL, allowing the realization of high speed coherent communication via a THz laser.

2. Device Fabrication, Characterization and Methods

Terahertz QCLs based upon semi-insulating surface plasmon waveguides were fabricated from a GaAs/Al_{0.15}Ga_{0.85}As wafer, using a bound to continuum active region with integrated NIR guide layer [1] and operated in pulsed mode (10kHz, 20% duty cycle) at 10K. THz laser emission was measured directly using a Bruker Vertex 80 FTIR with 2.1GHz of frequency resolution. The scheme used for up-conversion THz to NIR frequencies and subsequent down-conversion to an RF beat note is illustrated in Figure 1a. First, NIR light generated by a tuneable 1.3μm external cavity laser was injected into the QCL waveguide via butt coupling single mode optical fiber to a QCL facet. The subsequent intracavity up-conversion of THz light to a telecoms side mode via nonlinear mixing with NIR light has been discussed in ref [1]. In brief the large $\chi^{(2)}$ nonlinear coefficient of the GaAs active region results in strong interaction between injected NIR light and generated THz light. Secondly, the anomalous dispersion of the Reststrahlen band in GaAs results in the phase matching between the NIR and THz waves (so called polaritonic phase matching). This means that NIR and THz light interact and mix efficiently inside the QCL cavity, producing NIR \pm THz side modes. The main NIR mode and generated THz side modes were collected from the other facet of the QCL using a second butt coupled single mode fiber, and measured using both a fast photodiode (Thorlabs DET08CFC/M) and an optical spectrum analyzer (Yokogawa AQ6370Z). A sample optical spectra is shown in figure 1b, showing both the NIR carrier and a THz side mode. In order to generate the heterodyne signal, light from a second 1.3μm external cavity laser was coupled into the optical fiber after the QCL (see figure 1b). The heterodyne signal was amplified by a 20MHz-3GHz low noise amplifier (Minicircuits ZX60-3018G-S+), and then could be detected by an electrical spectrum analyzer (Keysight HSA N9344C).

3. Results and Conclusions

An example heterodyne RF spectrum is shown in figure 1(c). The frequency of this signal reflects the difference between the second NIR laser and the up-converted THz signal. The RF signal linewidth is a combination of the intrinsic linewidth and frequency jitter from each of the three lasers. For example, the 200MHz heterodyne linewidth

of the two free running NIR lasers contributes significantly to the measured linewidth, but results are still consistent with those measured directly in the THz [3]. We can use this characterization method to study the current driven continuous tuning properties of THz QCLs. Current tuning of THz QCLs is crucially important for producing tuneable sources of THz light, and although often attributed to Joule heating of the active region, the negligible temperature tuning of THz QCLs suggests that an alternative mechanism must be in play [4]. It has been suggested that in THz QCLs current tuning may be attributed to mode pulling from the effective gain shape [4], and using this accurate heterodyne method we can study this phenomena with sub-GHz frequency accuracy. In figure 1(d) we show current tuning as measured by the FTIR, where low resolution limits the capabilities of our characterization, and in figure 1e we show the equivalent tuning as measured by heterodyne detection. The range of current tuning for both methods are comparable (2GHz measured by FTIR, 2.148GHz measured by heterodyne detection), and follow the current driven movement of the gain peak in this active region design. The accuracy of this technique could be significantly improved by frequency locking the two NIR lasers to a stable reference.

In conclusion we have developed and demonstrated the first open-loop heterodyne technique based on conventional fiber optic components for the detection of THz radiation. This can be used to study the properties of THz QCLs with high frequency resolution, and could be extended to allow coherent control and phase locking of the QCL source. This work was supported by EPSRC NOWNANO funding. The authors would like to thank Prof. A. Seeds (UCL) for useful discussions and Dr. D. Heard (Yenista Optics) for loan of a 1.3μm laser.

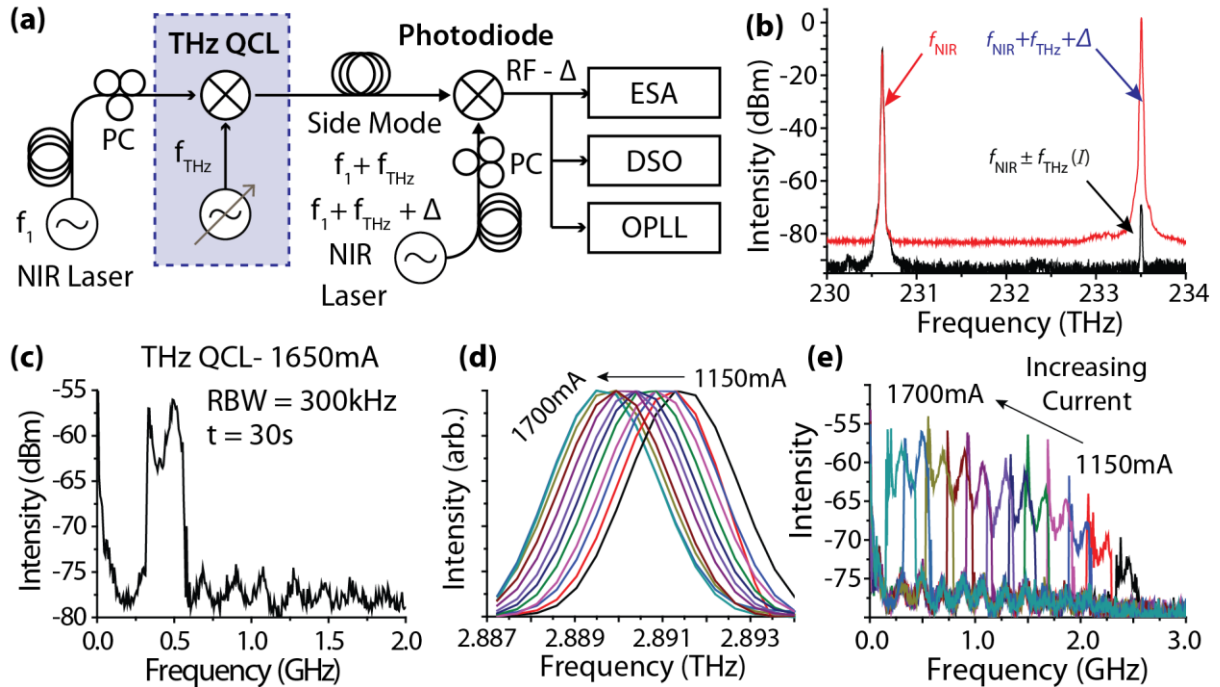


Figure 1. (a) A schematic of our heterodyne detection scheme for THz emission, (ESA – electrical spectrum analyser, DSO – digital sampling oscilloscope, OPLL – optical phase lock loop). (b) Optical spectra showing the primary NIR carrier, generated THz side mode (black) and NIR laser generating the heterodyne beat (red). (c) shows a sample heterodyne beat signal, where oscillations arise from the RF components in our detection circuit (d)&(e) shows current tuning in of the THz emission via both FTIR and heterodyne measurement techniques, illustrating the improvement in accuracy for the second.

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