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Auteurs: Authors:	Y. Hou, J. R. Liu, M. Buchanan, A. J. Spring Thorpe, P. J. Poole, H. C. Liu, Ke Wu, Sjoerd Roorda et X. P. Zhang
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Terahertz Generation Using Implanted InGaAs Photomixers and Multi-wavelength Quantum Dot Lasers

Y. Hou[1,2], J. R. Liu[1], M. Buchanan[1], A. J. Spring Thorpe[1], P. J. Poole[1], H. C. Liu[1,3,*], Ke Wu[4], Sjoerd Roorda[5], X. P. Zhang[6]

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Abstract: We report on a study of terahertz (THz) generation using implanted InGaAs photomixers and multi-wavelength quantum dot lasers. We carry out InGaAs materials growth, optical characterization, device design and fabrication, and photomixing experiments. This approach is capable of generating a comb of electromagnetic radiation from microwave to terahertz. For shortening photomixer carrier lifetime, we employ proton implantation into an epitaxial layer of lattice matched InGaAs grown on InP. Under a 1.55 μm multi-mode InGaAs/InGaAsP quantum dot laser excitation, a frequency comb with a constant frequency spacing of 50 GHz generated on the photomixer is measured, which corresponds to the beats of the laser longitudinal modes. The measurement is performed with a Fourier transform infrared spectrometer. This approach affords a convenient method to achieve a broadband multi-peak coherent THz source.

Keywords: Proton implanted InGaAs; Trahertz; Photomixer; Multi-wavelength quantum dot laser; Fourier transform infrared spectroscopy

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Introduction

Convenient sources of terahertz (THz) radiation, 100 GHz∼10 THz, fall between the capability of electronics and photonics. Many potential applications exist in this frequency region, for example in sensing, aerospace, medical and biological sciences, information and communication. A key advantage is its low energy, for example, the photon energy is only 4 meV at 1 THz, making it a safer alternative to X-ray in medical imaging. Many rotation and vibration modes of biological and chemical species are in the THz spectrum. Despite of many application prospects, due to the lack of convenient THz radiation sources, a wide spread application is yet to come.

There are mainly four approaches to generate THz radiation. One is the development of THz quantum cascade lasers [1,2], the other is to use femtosecond lasers [3], the third way is by nonlinear optics [4,5], and the fourth is heterodyne photomixing [6]. The quantum cascade laser approach is suited for the upper part of the THz spectrum, for example, greater than about

[1]Institute for Microstructural Sciences, National Research Council, Ottawa K1A 0R6, Canada
[2]Also with Department of Electrical Engineering, Concordia University, Canada
[3]Now with Key Laboratory of Artificial Structures and Quantum Control, Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China.
[4]Department of Electrical Engineering, Ecole Polytechnique, Montréal H3T 1J4, Canada
[5]Département de physique, Université de Montréal, Montréal H3C 3J7, Canada
[6]Department of Electrical Engineering, Concordia University, Montreal H3G 1M8, Canada
*Corresponding author. E-mail: h.c.liu@sjtu.edu.cn

2 THz. The femtosecond laser technique provides a broadband THz source, but needs a sophisticated laser and therefore tends to be expensive. The same is true for nonlinear optics. The heterodyne photomixing approach has attracted a lot of interests, and impressive advances have been made notably by Brown et al. [7] Such an approach has the potential of achieving convenient and low-cost THz sources based on semiconductor diode lasers and ultrafast photomixers, albeit more suited for the lower frequency region of about less than 2 THz. Substantial advances have been made based on low-temperature-grown GaAs materials and lasers at wavelengths less than about 0.9 μm, i.e., photon energy at about the GaAs band gap. But it was not convenient to apply it to telecommunication field with lasers working in the 1.3∼1.55 μm region.

In this research, we use proton implanted InGaAs THz photomixers and 1.55 μm multi-mode InGaAs/InGaAsP quantum dot (QD) lasers to achieve THz generation. With this method a broadband THz radiation comb with constant frequency spacing and high degree of coherence may be generated. This approach may result in convenient THz sources suitable for applications such as sensing and spectroscopy. Similar work using heavy ions was reported in Refs. [8,9].

Material and device

The InGaAs photomixing material was grown by MOCVD on an InP substrate. The layer structure consists of 0.1 μm InP buffer, 2.0 μm InGaAs, and 10 nm InP top capping layer. Ion implantation is expected to shorten the carrier lifetime. Different fluences of 1 MeV proton implantation are used from 3E10, 9E10, 3E11, 9E11, 3E12, 9E12, to 3E13 cm^{-2}.

To characterize the implanted materials photoluminescence (PL) spectroscopy is carried out. Figure 1 is a set of PL spectra taken on an un-implanted reference and implanted samples of various fluencies, all from the same wafer (M1094). With increasing implantation fluence, the PL intensity progressively decreases, implying an increase of non-radiative recombination rate and a decrease of the carrier lifetime. About a 1000-fold decrease is observed on the 3E12 cm^{-2} sample, expecting a decrease of the lifetime to the picosecond region. More heavily implanted samples (PL too weak to measure) are expected to have a lifetime much less than 1 ps, suitable for THz photomixing.

For the device design, factors such as device area, number of interdigited electrodes, and spiral antenna geometry limit the frequency response. Simulations are carried out to ensure the device performance. In the following we concentrate on 36×36 μm^2 area devices with a simulated RC time of 0.62 ps. Figure 2 is a photograph of the completed device.

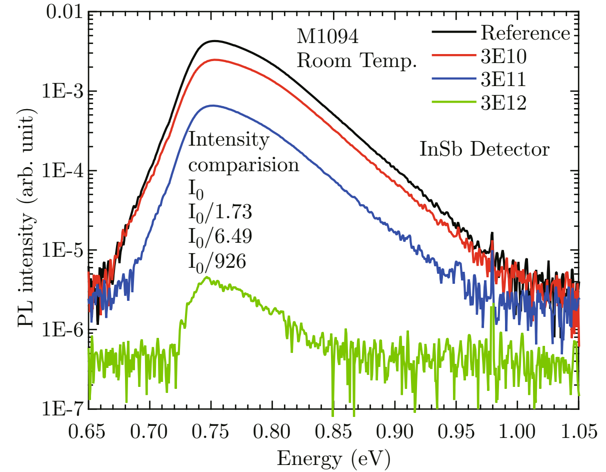

Fig. 1 PL spectra of implanted InGaAs materials together with a spectrum from an un-implanted reference sample.

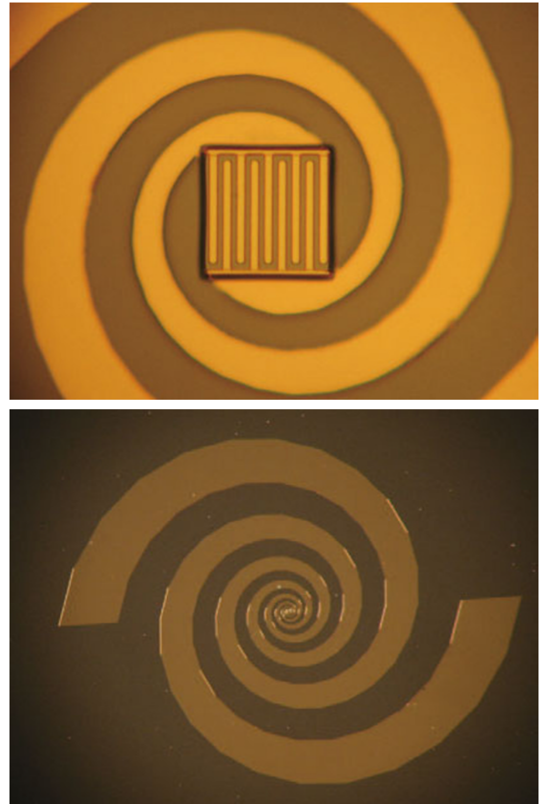

Fig. 2 Photographs of the device (36×36 μm^2) and interdigit (2 μm wide) details (above) and of the spiral antenna. The horizontal full picture dimensions are 150 μm and 7 mm for the above and below pictures, respectively.

Experimental and discussion

An optics based THz radiation measurement system was set up. Different from electronic instrument systems based on harmonic mixers, we used an FTIR (Fourier transform infrared) spectrometer. An electronic system would have limitations in reaching high

THz region due to the lack of harmonic mixers. Figure 3 is a schematic of the THz radiation detection system.

In this measurement system, the photomixer was illuminated by the laser beam, which was from the multi-mode QD InGaAs/InGaAsP laser at around 1.55 μm. An Er-doped amplifier was employed to increase the laser power. A 5 or 6 μm diameter conical lensed fiber was used to focus the laser power onto the photoconductive area. A 1.55 μm multi-mode QD laser spectrum taken on the FTIR is displayed in Fig. 4. From the laser spectrum, a constant frequency spacing between the modes which will create the different optical beats is seen. The minimum spacing is 50 GHz, which means in subsequent measurements the optical beats are at N times 50 GHz, N is a positive integer.

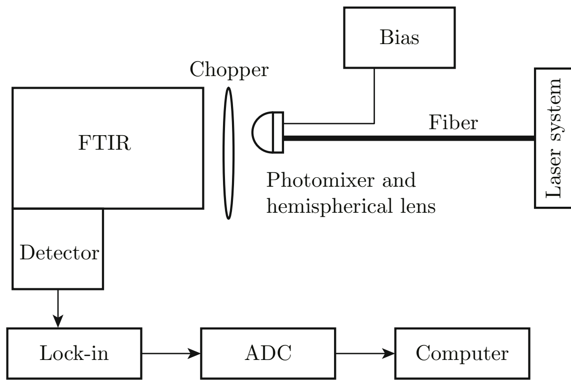

Fig. 3 Schematic of the THz radiation measurement system.

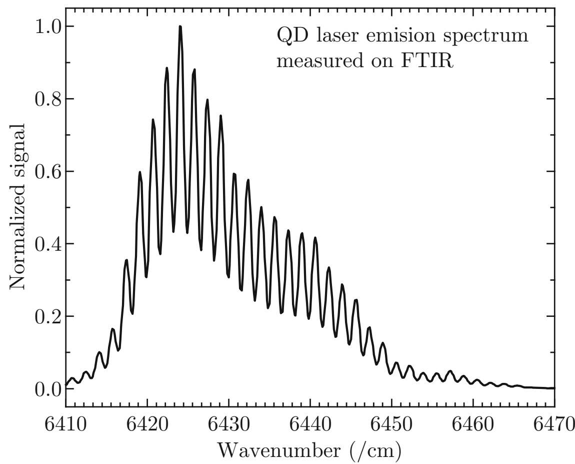

Fig. 4 Spectrum of the multi-mode QD InGaAs/InGaAsP laser taken with an FTIR.

The packaged photomixer is fixed to a stand which is about 1inch away from the FTIR input-port window. The DC biased device is excited by the 1.55 μm laser beam from the lensed fiber. To couple out the THz emission more efficiently, a 3 mm diameter high resistivity hyperhemispherical silicon lens is affixed to the backside of the photomixer substrate. The laser output power from the Er-doped amplifier is in the range of 30∼50 mW. When the multi-mode QD laser output total power is 35 mW, the highest single mode output power is about 8 mW. A black polyethylene film is placed after the photomixer to block the laser from reaching the FTIR detector which is a liquid He cooled Si bolometer. The signal is sent to a lock-in amplifier and then to the FTIR analog to digital converter.

Photomixers with different proton implantation fluences are measured. Figure 5 is an FTIR spectrum of a photomixer with a proton fluence of 9E12 cm^{-2} (Device A). From this spectrum, three peaks with wavenumber values of 1.66, 3.38, 5.32 cm^{-1} are observed. Given the FTIR resolution, this spectrum shows generated radiation at 50, 100, and 150 GHz from the photomixer. The spectrum also shows that the signal intensity decreases with increasing frequency, an effect of the phtomixer frequency roll-off. The spectrum from another photomixer (Device B) with a higher fluence (3E13) and the same device area is shown in Fig. 6. Though a calibrated power measurement was not done, in relative

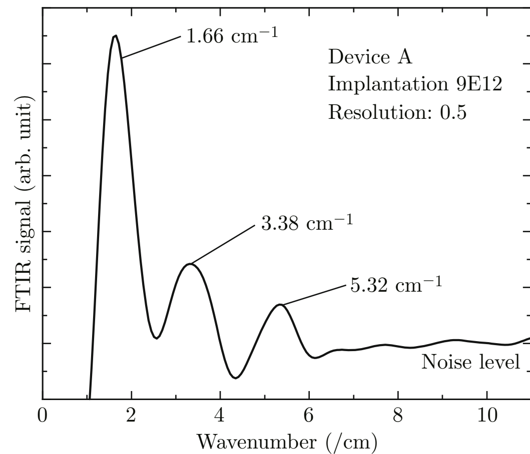

Fig. 5 FTIR spectrum of Device A.

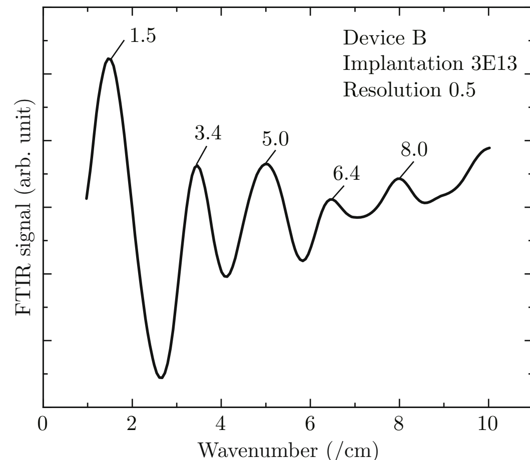

Fig. 6 FTIR spectrum of Device B.

terms, signal in Fig. 6 is weaker than that in 5, likely due to a lowering of the responsivity on increasing the

fluence. In the FTIR spectrum of Fig. 6, five peaks at 1.5, 3.4, 5.0, 6.4, and 8.0 cm^{-1} are observed, corresponding to 50, 100, 150, 200, and 250 GHz, respectively. Comparing Figs. 5 and 6, the higher implanted device shows a higher frequency capability, and one could therefore conclude that the carrier lifetime is the limiting factor.

Conclusion

We have investigated the approach of using ion-implanted InGaAs photomixer and muti-wavelength QD laser to generate a frequency comb covering from microwave to THz frequencies. The InGaAs materials system is technologically advanced due to its relevance in the telecom applications, and the QD laser works in the telecom wavelength region of 1.55 μm. For the experimental testing, we used a FTIR spectrometer suitable for measurements extending in the high THz region. With this approach a broadband THz frequency comb may be generated, which would be useful for various applications such spectroscopy and sensing.

Acknowledgments

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