Terahertz free space communications demonstration with quantum cascade laser and quantum well photodetector

P.D. Grant, S.R. Laframboise, R. Dudek, M. Graf, A. Bezinger and H.C. Liu

An all photonic terahertz communication link operating at 3.8 THz using a quantum cascade laser and quantum well photodetector has been demonstrated. The link consists of a quantum cascade laser transmitter and a quantum well photodetector receiver. The link was used to transmit audio through 2 m of room air. Carrier strength at the photodetector was 100 times greater than the noise level measured.

It is anticipated that many new applications of the terahertz (THz) spectrum are possible if simple compact sources and photodetectors were readily available. Many groups around the world are in the process of developing semiconductor sources and photodetectors for the THz spectrum [1–4]. In this Letter, we report on a demonstration of a free space link we have constructed to show the feasibility of laser generated free space communications at THz frequencies. We show that the basic characteristics needed for a simple telecommunications link can now be performed easily using a quantum cascade laser as a source and a quantum well photodetector as a receiver. A previous demonstration of a sub-THz analogue transmission system was reported by Jastrow *et al.* at 300 GHz using an electronic system [5]. The work we report here operates at 3.8 THz and is an all photonic design for THz generation, radiation, collimation and detection.

Fig. 1 is a schematic representation of the link. At the left a quantum cascade laser housed in a vacuum dewar provides 3.8 THz radiation which is collected and collimated by a parabolic mirror labelled M1. The laser transmitter was constructed from a multiple quantum well structure described earlier [6] with a 1 mm-long and 100 μm-wide surface plasmon waveguide formed on a semi-insulating GaAs substrate. A reflecting mirror was formed on the back facet by first coating the facet with an aluminium oxide insulator, to prevent short circuiting the electrodes, followed by evaporating a gold layer over the facet. The exit coupler of the laser is the cleaved surface. M1 is a 50 mm focal length off-axis parabolic reflector while M2 is 76 mm focal length. Both mirrors are 50 mm in diameter. The laser was mounted on an aluminium cold finger in a liquid nitrogen dewar with the laser facet approximately 2 mm from the low density polyethylene window. This permitted collecting a large fraction of the diverging beam with an off-axis parabolic mirror. A temperature sensor was mounted near the base of the QCL die and showed that the base temperature was maintained at 78 or 77 K for all of the work we report here.

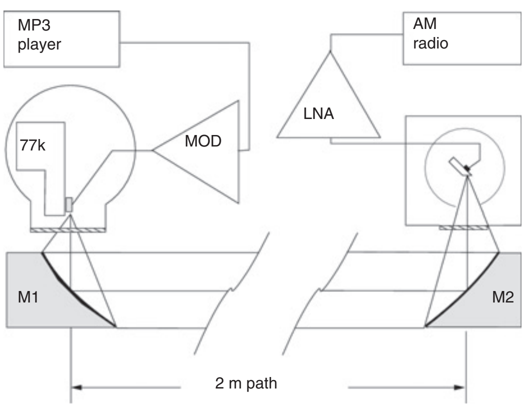

Fig. 1 *Schematic of link showing quantum cascade laser at left and quantum well photodetector on right*

The receiver is a large 1.5 × 1.5 mm mesa fabricated from a layer structure described earlier [7]. Terahertz radiation is coupled through the semi-insulating substrate to the mesa at a 45° angle as is done in quantum well infrared photodetectors (QWIP). The substrate is polished at a 45° angle to permit radiation entry to the device. The smallest dimension is the face of the facet which is 1 mm which is still 10 wavelengths, placing the design in the optical regime. The photodetector was mounted on a copper cold finger in a Janis continuous flow liquid helium cryostat with a 50 mm heat shield. The detector dark current increased with temperature and all demonstrations were performed at 12 K or less. The graph shown in Fig. 2 was measured with the detector temperature at 12 K.

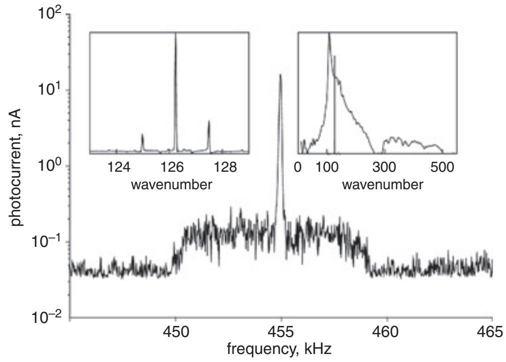

Fig. 2 *Spectrum of photocurrent measured after low-noise amplifier with insets showing laser spectrum at left and photodetector responsivity at right*

Photodetector spectrum measured at temperature of 12 K

Care was required to align the four optical components, the QCL, the QWIP and the two mirrors. The initial alignment was performed in air without the polyethylene windows. The photodetector was displaced by 2 mm using a translation stage and a visible laser beam was passed through the photodetector location to the two mirrors and then to the laser. Crude alignment was performed to ensure that the laser was near the focus of each mirror and that the visible light was arriving at the QCL facet. The optical coupling was quite sensitive to the position of the QCL which was rather small. Sometimes no coupling could be established after an optical component was moved and we used a piece of 50 mm diameter Plexiglass pipe 200 cm long as a light guide. The QCL could then be focused on the end of the light pipe which was only 10 cm away from the mirror. After a signal was established, the light guide could be removed and there was still sufficient signal to allow optimising alignment of the long path. The position of the larger QW detector was not as critical.

A custom-made electronic pulse generator was fabricated to provide low duty cycle pulses of amplitude V_H. The maximum V_H required was 17 V at a current of 2.6 A for a peak power of 43 W. The pulse width above threshold was approximately 8 ns. Pulse repetition frequency was 455 kHz. Total power injected was calculated from the recorded voltage waveform and integrated to give an average power of 0.16 W or a peak-to-average ratio of 268 to 1. The generator contained power amplifiers which forced V_H to follow the modulation voltage which we wanted to transmit, typically a sine wave at 500 Hz or music. The optimum conditions for V_H and modulation amplitude (V_M) were found by transmitting a 455 kHz carrier modulated by a 500 Hz sine wave while measuring the second harmonic at 1 kHz. Clipping by modulating below threshold or above saturation rapidly increased the second-harmonic content of the detected signal. It was found that the best V_M was about 1 V peak-to-peak with V_H of 15 V.

Numerical calculation of the Fourier transform of the expected photocurrent indicated that there should be a DC term, a modulation term and a large number of replications of the pulse repetition frequency. Each replication would have a carrier plus modulation side-bands. The DC term is proportional to the average laser power and for the low duty cycle pulses which we are using, the carrier amplitudes are equal to each other and to the DC term. This is a central point in the demonstration. Even though the laser was pulsed, the Fourier transform of the photocurrent contains useful continuous-wave (CW) components with amplitude equal to the average photocurrent. Further, the modulation side-bands contain the Fourier transform of the time variations of V_M.

Experimentally, the 500 Hz basic modulation term could be easily detected using a bolometer and lock-in amplifier. The 455 kHz pulse repetition frequency was also easily detected using the QWIP and could be observed on a spectrum analyser as a typical amplitude modulated waveform. Fig. 2 shows a typical non-modulated spectrum measured at the pulse repetition frequency after the transimpedance amplifier. The left inset in Fig. 2 is an expanded spectrum of the laser measured using an Fourier transform infrared (FTIR) spectrometer.

Both were measured while the QCL was being pulsed at 455 kHz with no modulation. While none of the modulation can be resolved using the FTIR, the central emission line width is at the FTIR resolution of 0.04 wavenumbers or 1.2 GHz. The right inset shows the QW photodetector spectral responsivity overlaid with the 126 wavenumber laser spectrum at the left. The RMS photocurrent at the 455 kHz is two orders of magnitude greater than the noise level. The noise level from 450 to 460 kHz originates in the custom-made laser driver electronics and is not a fundamental limitation of the devices. Finally, the signal could be coupled to the antenna input of an AM radio (Sony ICF 2010) and music recovered.

The low-noise amplifier (LNA) has a transimpedance amplifier, a filter and a buffer amplifier as well as the photodetector bias circuit. The capacitance of the cable from the cold section to room temperature was measured as 160 pF plus the large QW photodetector capacitance of 88 pF caused instability in high-speed amplifiers which we initially tried to use. A general purpose operational amplifier with a 12 MHz gain bandwidth product could be made stable in a 1 kΩ transimpedance configuration. This was followed by a 455 kHz centre frequency, 10 kHz bandwidth filter and a line driver amplifier to provide an effective transimpedance of 10 kΩ. Detector bias was introduced at the input of the transimpedance amplifier. Typically, our measurements were performed with -20 mV of bias and 2 μA of total photodetector current. DC photocurrent was always less than 0.1 μA, the resolution of the meter which was used for monitoring bias current. Using the QW detector responsivity measured in [7] of 1A/W and the property of the Fourier transform of a narrow pulse that the low harmonics have the same amplitude as the average, the average optical power can be determined. The recovered 455 kHz carrier current was 18 nA RMS from which we calculate the average optical power to be $1.414 \times 18 = 25$ nW.

While there are many atmospheric absorption bands known in the THz frequency region, we observed very little impairment of our link owing to atmospheric absorption. The centre frequency of the laser was 3787 GHz as determined by FTIR measurement of the emission. Empirically we measured the air in our laboratory in Ottawa, Canada, and observed that this frequency is at the upper edge of an essentially transparent region of the electromagnetic spectrum that extends from 3700 to 3789 GHz This band is 89 GHz wide and is only one of many which we observe to be essentially transparent in room air. We point out that while there are many absorption bands owing to water vapour, as much as one half of the spectrum space we observe is transparent or low absorption. We used a 50 mm diameter Plexiglass pipe as a gas cell and compared transmission through room air with transmission through dry nitrogen and found no difference. The only strong absorber that we observed was liquid water.

Conclusions: This work demonstrates several achievements in fabrication of THz quantum well devices: 1. a single chip GaAs/AlGaAs QCL can generate and radiate useful THz power; 2. the QCL operated at 78K; 3. 10 kHz bandwidth CW functions were demonstrated without incurring the much greater power dissipation CW would require; 4. ‘all optical’ devices function well at THz frequencies.

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P.D. Grant, S.R. Laframboise, R. Dudek, M. Graf, A. Bezinger and H.C. Liu (*National Research Council of Canada, Institute for Microstructural Sciences, 1200 Montreal Road, Ottawa K1A 0R6, Canada*)

E-mail: peter.grant@nrc.ca

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