Wireless communication demonstration at 4.1 THz using quantum cascade laser and quantum well photodetector

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A wireless terahertz (THz) analogue communication link using a quantum cascade laser (QCL) as the source and a quantum well photodetector as the receiver is demonstrated. The QCL operates in continuous-wave mode. By directly modulating the QCL emitting at 4.1 THz, analogue signals are transmitted over a distance of 2 m. The circuit-limited modulation bandwidth is about 580 kHz.

Introduction: There have been considerable advances in terahertz science and technology over the past two decades. Several types of wireless communication links have been demonstrated. These links, employing the terahertz (THz) time-domain [1], unitravelling carrier photodiode (UTC-PD) optoelectronics [2], monolithic microwave integrated circuits (MMICs) [3] and microwave multiplication [4] as the sources, mostly operate in the sub-THz region between 100–300 GHz.

In addition to those mentioned above, THz quantum cascade lasers (QCLs) as THz sources operating above 1 THz have attracted much interest in recent years. Since their invention in 2002, there have been considerable improvements in operation temperature, output power, threshold current density and the wavelength limit of THz QCLs. Now, the THz QCL has become one of the most promising THz radiation sources, which can be directly modulated up to very high frequencies of several tens of gigahertz [5], and can emit a high output power of more than 100 mW. To characterise the high modulation speed capability of THz QCLs, as well as to build a high speed THz communication link, a fast detector is necessary. One of the most promising detectors is the THz quantum well photodetector (QWP), which is the very far infrared region extension of quantum-well infrared photodetectors (QWIPs). As in the mid-infrared QWIPs, the intrinsic speed of these THz QWPs is also in the few picosecond range [6], indicating the potential for high speed operation.

Recently, a demonstration of an all-photonic THz communication link at 3.8 THz employing a QCL and a QWP was reported by Grant *et al.* [7], in which the QCL worked in pulsed mode. In this Letter, we report a wireless THz link using a QCL as the emitter and a QWP as the receiver. The QCL used in our work operates in continuous-wave (CW) mode, which is more appropriate for high frequency and advanced modulation schemes (e.g. quadrature phase shift keying). The transmission of a sinusoidal/sawtooth signal or audio signal through the link is demonstrated. The bandwidth of the link is also analysed.

Experiment: The QCL device, with size of 40μm × 1 mm, is based on a four-well resonant-phonon design and a double-metal waveguide. A detailed description of the optical and electrical properties of the laser is given in [8]. The QWP, based on a GaAs/AlGaAs material system, is grown by molecular beam epitaxy (MBE). Both devices work at cryogenic temperature. The QCL, operating at 10 K, is attached to a copper heatsink and mounted on the temperature-controlled cold finger of a closed-cycle helium cryostat. The QWP is cooled to 4 K by a continuous-flow liquid-helium cryostat.

As shown in Fig. 1, the QCL is driven by a home-made modulator, in which the input sinusoidal/sawtooth signal or audio signal is added to a DC current offset, and then amplified by a power amplifier (PA). The sinusoidal/sawtooth signal is provided by a function generator (Agilent 33250A), while the audio signal is from an MP3 player or a microphone. The modulator supplies a combined electrical signal with an 11.3 V DC offset and an ~0.6 V peak-to-peak AC component, raising the current above the 0.26 A threshold of the QCL. The combined signal directly drives the QCL, biasing it in the linear range of its light-current-voltage (*L-I-V*) curve, and causes an amplitude-modulated light output, with an average power of ~2 mW. The bias current is 0.313 A, and the amplitude of the modulation current is 0.04 A. The modulation depth is 75%. Using two off-axis parabolic mirrors of a 100 mm focal length, the emitted 4.1 THz radiation from the QCL is collected and guided along a 2 m optical path in room air, and focused onto the QWP. The 2 m range is limited by the length of the optical table where the emitter and receiver are fixed on. The maximum transmission distance is about tens of metres owing to the atmospheric absorption, which is about 1.5 dB/m at 4.1 THz, measured in the lab environment of 300 K and 47% relative humidity (RH). The signal from the QWP, which is photoconductive (PC), is amplified by a transimpedance amp, with a gain of 10^4 V/A and an upper cutoff frequency of about 6 MHz. This is followed by a highpass filter to eliminate the low frequency excess noise caused by the dark current and thermal drift, as well as a variable gain amplifier, before feeding the signals to an oscilloscope, or a loudspeaker.

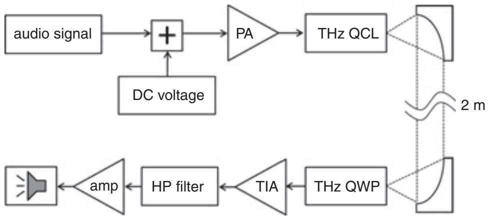

Fig. 1 *Scheme of THz transmission setup*

Results and discussion: A 500 kHz sinusoidal signal was transmitted through the link. The time traces of the modulation signal and demodulated signal are shown in Fig. 2*a*. The received signal shows a delay of about 800 ns, which is caused by the circuit and the response time of the devices. A slight nonlinear distortion could be found, which we attribute to the nonlinear dependence of the THz QCL output power on the modulation voltage, the light current of the THz QWP on the receiving light power, and the distortion of the circuit. For further measurement, we replaced the input sinusoidal signal by a 100 kHz sawtooth signal, which results in more harmonics. The resulting time traces are shown in Fig. 2*b* and spectra in Fig. 2*c*. For the received signal, besides the distortion caused by the nonlinearity of the system, we observe that in the frequency domain the signal-to-noise ratio is greater than 30 dB at 100 kHz, greater than 20 dB at 300 kHz and it meteorites quickly as the frequency increases. This is because the signal drops, limited by the bandwidth; while the noise level is nearly the same, attributed to the receiving circuit.

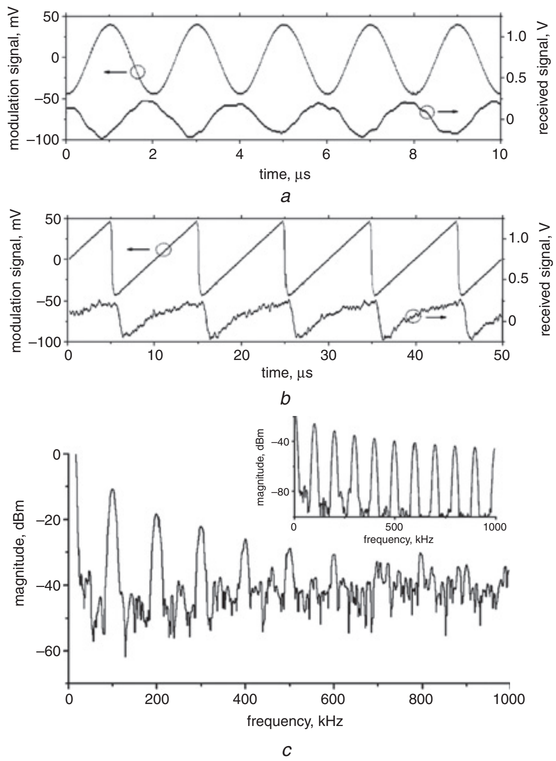

Fig. 2 *Time traces of (Fig. 2a) 500 kHz sinusoidal and (Fig. 2b) 100 kHz sawtooth input modulation voltage and received signal; (Fig. 2c) spectra of received signal (lower trace in Fig. 2b)*

Inset: Spectra of sawtooth modulation signal (upper trace in Fig. 2*b*)

We then used a network analyser (Agilent 4395A) to measure the actual frequency response of the transmission channel. The analyser

supplies a sweeping signal from 100 Hz to 1.5 MHz, which is transmitted through the link. We then measured the detector signal. The transmission characteristics trace shows that the 3 dB bandwidth is about 580 kHz. This bandwidth represents a measurement of the overall transmission characteristics of the communication link, including the laser, the detector, and the circuit in the modulator and receiver. It is mostly restricted by the power amplifier we used in the modulator. Although the potential large bandwidth of the THz QCL and THz QWP was not realised in this link, it should be mentioned that neither the packaging nor the processing of the devices were optimised for high frequency operation.

Lastly, we transmitted an audio signal through the link, and got the oscilloscope traces of the modulator signal and the received signal, illustrated in Fig. 3. The music we reproduced via a loudspeaker in the receiving side was of a quality very similar to that produced in an MP3 player in the emitting side.

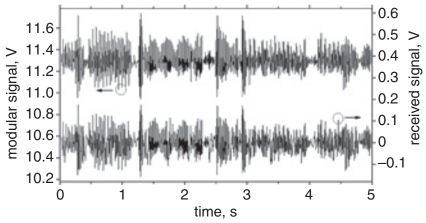

Fig. 3 *Time traces of audio signals transmitted over the link*

Upper trace: modulator signal; lower trace: received signal

Conclusion: We present a THz analogue communication link over a distance of 2 m, which employs a QCL as the source and a QWP as the receiver. The QCL operates in CW mode. Using a directly voltage modulation scheme, we transmitted sinusoidal/sawtooth/audio signals through the link. The modulating bandwidth is about 580 kHz. Both the THz QCL and the QWP have a theoretical modulation bandwidth in the tens of gigahertz region. In our particular case, the modulation bandwidth is limited by the electric circuit.

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