Audio signal transmission over THz communication channel using semiconductor modulator

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The first demonstration has been made of the transmission of an audio signal via a THz communication channel using a recently developed room temperature semiconductor THz modulator which is based on the depletion of a two-dimensional electron gas. A standard THz time-domain spectroscopy setup is modified to transmit signals up to 25 kHz over a 75 MHz train of broadband THz pulses.

Introduction: The increased demand of bandwidth for fast data transmission applications requires the extension of communication systems to higher frequencies. One can expect that wireless short-range communication networks will soon push towards the THz frequency range. It is likely that systems that operate at several 100 GHz will be developed in a few years' time. Since THz radiation is strongly absorbed by the atmosphere, working distances may be short and individual THz picocells may cover only single rooms or at the most one building [1]. In any case, THz communication systems will require the development of devices such as emitters and detectors as well as modulators and frequency filters [2].

A first approach for the direct modulation of THz radiation was demonstrated by Libon *et al.* [3] using an optically controlled mixed type-I/type-II GaAs/AlAs multiple quantum well structure. Alternatively Kersting *et al.* [4] developed an electrically driven modulator consisting of five identical parabolic quantum wells (PQWs) with equally spaced electron subbands. An applied electrical field was used to control the electron occupation of the PQWs and thus the THz absorption of the device. However, a distinct disadvantage of both these schemes is that they only operated at low temperature ($T \leq 80$ K).

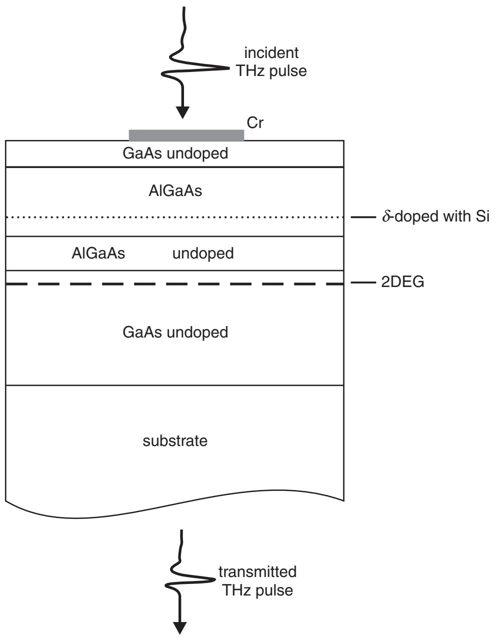

Fig. 1 *Schematic diagram of 2DEG modulator device structure*

Recently we proposed a new modulator structure based on the well-established technology for producing high electron mobility transistors (HEMTs), in which a two-dimensional electron gas (2DEG) is confined at a $GaAs/Al_xGa_{1-x}As$ heterointerface [5]. The electron density of the 2DEG can be controlled by the application of an external gate voltage. Simple Drude model calculations indicate that the depletion of such an electron gas should provide sufficient depth of modulation for transmitted THz radiation [5]. A schematic diagram of the HEMT-like device that we have used is shown in Fig. 1. The 2DEG is confined at the interface between an undoped GaAs buffer layer and an undoped $Al_{0.3}Ga_{0.7}As$ spacer layer. A 10^{12} cm^{-2} silicon doped monolayer grown on top of the spacer provides the electrons for the 2DEG. Van-der-Pauw measurements at room temperature and zero gate voltage yield a free carrier concentration of 9.7×10^{11} cm^{-2} and a mobility of 7200 cm^2/(Vs). Using THz time-domain spectroscopy [6] we measured a modulation depth of 3% for a negative gate voltage of −10 V at room temperature.

Setup: We placed our modulator at the intermediate focus of a standard THz time-domain spectroscopy setup [6] as shown in Fig. 2. Pulsed THz radiation is generated in a photoconductive GaAs antenna excited by 20 fs pulses from a Ti:sapphire laser with a repetition rate of 75 MHz. The THz pulses with frequencies between 100 GHz and 3 THz were collimated and focused with off-axis parabolic mirrors and finally directed onto a silicon-on-sapphire (SOS) antenna. For signal transmission the detector delay line was moved to the maximum of the THz pulse where also the modulation signal was at a maximum. A transimpedance *I–V* amplifier with a gain of 10^8 V/A and an upper cutoff frequency of 7 kHz was used to amplify the detector signal. The transmission channel with a length of 48 cm is located between the 2DEG modulator and the SOS detector antenna.

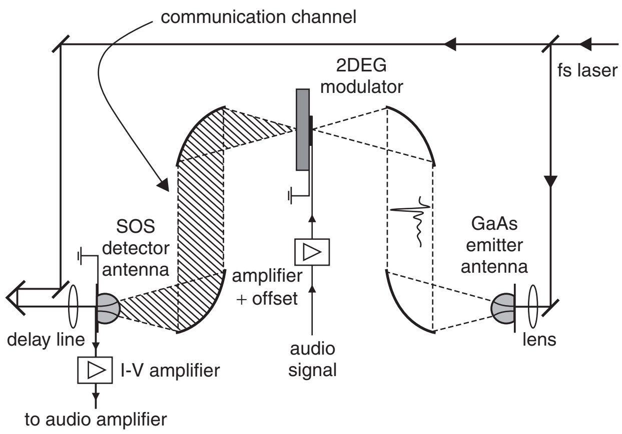

Fig. 2 *Modified THz time-domain spectroscopy setup*

THz beam is modulated at its intermediate focus, 48 cm-long transmission channel is highlighted

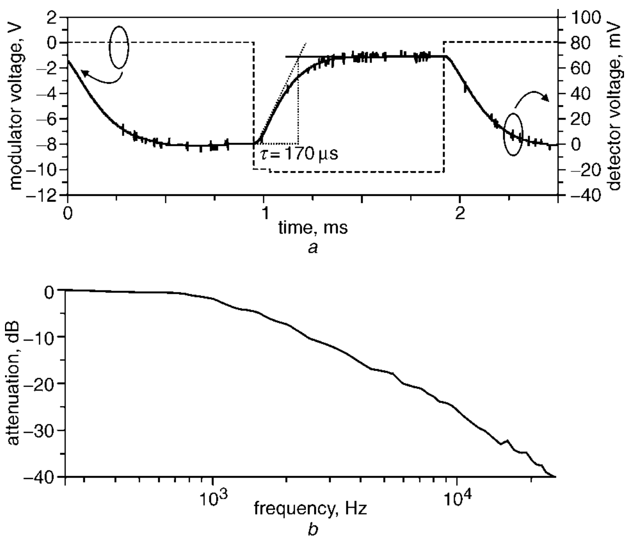

Fig. 3 *Measurement of channel bandwidth*

a Time traces of rectangular voltage applied to modulator and corresponding detector signal
b Transmission channel attenuation measured with spectrum analyser

Results and discussion: To measure the transmission channel bandwidth we applied a rectangular voltage alternating between 0 and −10 V to the modulator gate. Fig. 3*a* shows the time traces of the gate voltage and corresponding detector signal. From the rise time of the detector signal we determined a system cutoff frequency of $f_c \simeq 6$ kHz. This is consistent with a cutoff frequency of $\simeq$10 kHz estimated from the RC time constant of the modulator and the 7 kHz cutoff frequency of the *I–V* amplifier. To measure the actual frequency response of the

channel we swept the frequency from 250 Hz to 25 kHz of a sinusoidal gate voltage which oscillated between 0 and −10 V and measured the detector signal level with a spectrum analyser. Fig. 3*b* shows attenuation against frequency, which indicates a somewhat lower cutoff frequency than that estimated above. The precise nature of the discrepancy is not clear yet and will be investigated in the future.

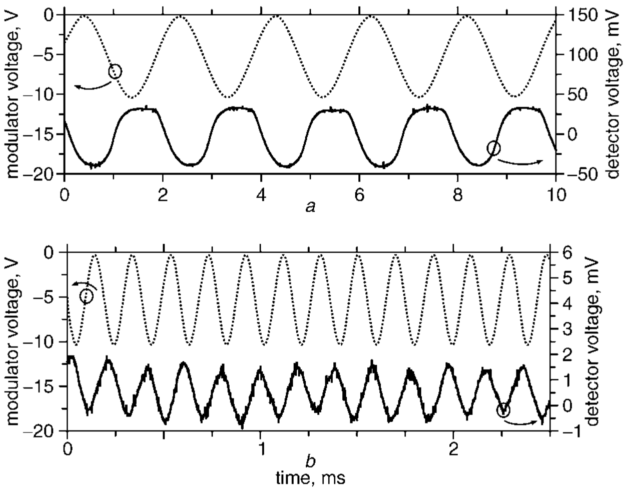

Fig. 4 *Time traces of different signals transmitted over communication channel*

a Sine wave at 513 Hz *b* Sine wave at 5130 Hz

We also transmitted different audio signals over the THz communication channel. Fig. 4 shows time traces of the gate and detector signal at 513 and 5130 Hz, respectively. Clearly, the signal amplitude drops for higher frequencies. The distortion of the detector signal (obvious for 513 Hz) is attributed to the nonlinear dependence of the modulation signal on the gate voltage (not shown). However, we were able to transmit music over the THz communication channel after amplifying a standard baseband signal from a CD player by a factor of 100 and adding a negative voltage offset. When played back via a loudspeaker the transmitted music was reproduced with a quality similar to that produced in a telephone.

Conclusion: To the best of our knowledge we have demonstrated the first audio signal transmission at carrier frequencies above several 100 GHz using the new developed 2DEG THz modulators which operate at room temperature. Instead of a continuous carrier wave we used THz pulses that were amplitude modulated to a depth of 3% with a baseband signal. By reducing the diameter of the modulator gate we are confident of being able to increase the cutoff frequency up to a few MHz. Then the transmission of amplitude or frequency modulated signals instead of baseband signals should be possible.

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References

1 Mann, C.M.: 'Towards terahertz communications systems' *in* Miles *et al.* (Eds.): 'Terahertz sources and systems' (Kluwer, 2001), pp. 261–267

2 Bowen, J.W.: 'Towards terahertz communications—systems requirements' *in* Miles *et al.* (Eds.): 'Terahertz sources and systems' (Kluwer, 2001), pp. 269–283

3 Libon, I.H., Baumgärtner, S., Hempel, M., Hecker, N.E., Feldmann, J., Koch, M., and Dawson, P.: 'An optically controllable terahertz filter', *Appl. Phys. Lett.*, 2000, **76**, (20), pp. 2821–2823

4 Kersting, R., Strasser, G., and Unterrainer, K.: 'Terahertz phase modulator', *Electron. Lett.*, 2000, **36**, (13), pp. 1156–1158

5 Kleine-Ostmann, T., Koch, M., and Dawson, P.: 'Modulation of THz radiation by semiconductor nanostructures', *Microw. Opt. Technol. Lett.*, 2002, **35**, (5), pp. 343–345

6 Grischkowsky, D., *et al.*: 'Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors', *J. Opt. Soc. Am. B*, 1990, **7**, (10), pp. 2006–2015