Wireless audio and burst communication link with directly modulated THz photoconductive antenna

Tze-An Liu

Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, and Center for Measurement Standards, Industrial Technology Research Institute Hsinchu, Taiwan 300, R.O.C.

Gong-Ru Lin, Yung-Cheng Chang

Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 30010, R.O.C.

Ci-Ling Pan

Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 30010, R.O.C.
clpan@faculty.nctu.edu.tw

Abstract: We demonstrate transmission of audio and burst signals through a prototype THz analog communication link employing laser-gated low-temperature-grown GaAs dipole antenna as THz emitter and receiver. The transmission distance is about 100 cm. By using a direct voltage modulation format, we successfully demodulated a burst signal with a rising time of 41 μs. The corresponding modulating bandwidth achieved was 23 kHz in this first experiment. Noise analysis reveals a 10% power fluctuation in the received signal with on-off extinction ratio of greater than 1000. The transmission of a six-channel analog and burst audio signal with least distortion is also demonstrated. We further demonstrate the fidelity of the transmission of a melody through the THz link with and without any amplification.

OCIS codes: (320.7080) Ultrafast devices; (320.71600) Ultrafast Technology; (060.4510) Optical communications; (060.4080) Modulation; (260.3090) Infrared, far; THz communication

References and links

1. M. Z. Win and R. A. Scholtz, " Impulse Radio: How it works," IEEE Commun. Lett. **2**, 36-38 (1998).
2. S. Ramsey, E. Funk, and C. H. Lee, "A Wireless Photoconductive Receiver Using Impulse Modulation and Direct Sequence Code Division," in The Int. Topical Meeting on Microwave Photonics'99, Technical Digest, 265-268 (1999).
3. E. Mueller and A. J. DeMaria, "Broad bandwidth communication/data links using terahertz sources and Schottky diode modulators/detectors," Proc. SPIE, **5727**, 151-165 (2005).
4. R. Piesiewicz, J. Jemai, M. Koch and T. Kürner, "THz channel characterization for future wireless gigabit indoor communication systems," Proc. SPIE, **5727**, 166-176 (2005).
5. T. Kleine-Ostmann, K. Pierz, G. Hein, P. Dawson and M. Koch, "Audio signal transmission over THz communication channel using semiconductor modulator," Electron. Lett. **40**, 124-125 (2004).
6. M. Tani, S. Matsuura, K. Sakai, and S. Nakashima, "Emission characteristics of photoconductive antennas based on low-temperature-grown GaAs and semi-insulating GaAs," Appl. Opt. **36**, 7853-7859 (1997).
7. M. V. Exter and D. R. Grischkowsky, "Characterization of and Optoelectronic Terahertz Beam System," IEEE Trans. Microwave Theor. Tech. **38**, 1684-1691 (1990).
8. M. Tani, K. Sakai and H. Mimura, "Ultrafast Photoconductive Detectors Based on Semi-Insulating GaAs and InP," Jpn. J. Appl. Phys. **36**, L1175-L1178 (1997).
9. T. -A. Liu, M. Tani, M. Nakajima, M. Hangyo, K. Sakai, S. Nakashima and C. -L. Pan, "Ultrabroadband terahertz field detection by proton-bombarded InP photoconductive antennas," Opt. Express. **12**, 2954 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-13-2954.

#9157 - $15.00 USD Received 18 October 2005; revised 18 November 2005; accepted 25 November 2005

10. G. -R. Lin, Y. -C. Chang, T. -A. Liu, and C. -L. Pan, "Piezoelectric-Transducer-Based Optoelectronic Frequency Synchronizer for Control of Pulse Delay in a Femtosecond Passively Mode-Locked Ti:Sapphire Laser," Appl. Opt. **42**, 2843-2848 (2003).
11. R. A. Cheville, M. T. Reiten, R. McGowan and D. R. Grischkowsky in D. Mittleman, Ed., *Sensing with Terahertz Radiation* (Springer-Verlag, New York 2002), pp. 243

1. Introduction

The demand for high-bit-rate, low-transmit-power, secured wireless communication capabilities continues unabated at the present time. Advanced microwave communication systems already operate near 60 GHz. The bandwidth requirements for such networks will likely exceed 300 GHz in the next decade. The fundamental limit on maximum bit rate is the time interval it takes to transmit one bit of signal or the duration of a chip pulse in wireless communication. The most economic use of time to transceive one chip bit of signal is by impulse radio [1]. RF impulses generated by pure electronic means usually lasting one nanosecond or longer. Using sub-picosecond optical-pulse-triggered photoconductive switch, one can easily generate and receive electrical pulses that last only a few picoseconds. These pulses have a central frequency of 200 GHz and nearly unity fractional bandwidth. The optical impulse radio scheme was first demonstrated by Lee *et al*. [2]. They used a mode-locked Ti: Sapphire laser as a laser source and combined impulse modulation with direct sequence code division to achieve high processing gain. Bit error rate (BER) of 10^{-5} could still be maintained at the chip rate of 85 KHz with signal-to-interference ratio of – 40 dB.

This idea can be extended to the THz regime, which offers prospect of even broader bandwidth. A single THz communication link will support broadband data transfer rates far beyond (> 20×) the limits of current microwave technology. Increased atmospheric absorption at THz frequencies, while unattractive in certain applications, should make possible secure ultra-high bandwidth THz communication systems. There are also advantages of highly directional and short distance bi-transportation with carrier bandwidth up to THz. To date, there are few studies of THz communication [3, 4], primarily due to a lack of suitable components, e.g., sources, modulators, detectors and quasi-optic components.

Recently, a prototype THz communication system using an external electro-optic modulator was demonstrated [5]. The reported transmission bandwidth was 6 kHz. In this paper, we first demonstrate a THz analog communication link employing low-temperature-grown GaAs dipole antenna as THz emitter and receiver. Detection bandwidth and transmitted signal of the link are analyzed. The transmission of a six-channel analog and burst audio signal with negligible distortion is also demonstrated. We further demonstrate the fidelity of the transmission of a melody through the THz link with and without any amplification.

2. Experimental methods

The THz communication link is based on encoding and decoding of audio signals carried on THz waves by laser-gated THz photoconductive antennas. A schematic diagram of the experimental setup is shown in Fig. 1. We employ a mode-locked Ti: sapphire laser with pulse width and repetition rate of 35 fs and 85 MHz, respectively. Emitter and receiver antenna were both dipole type photoconductive switches fabricated on low-temperature-grown GaAs (LT-GaAs) with carrier lifetime shorter than 2 ps [6]. The gap size and dipole length of the antenna were 5 μm and 30 μm, respectively. The average optical power for excitation and detection were both around 10 mW. The emitter antenna was biased using a sinusoidal signal from either a function generator (Agilent 33250A) or digital/analog output from the computer. Peak-to-peak voltages of the signals for the two cases were set at 10 V. The transmission distance between the modulated source and the receiving antenna was about 100

#9157 - $15.00 USD Received 18 October 2005; revised 18 November 2005; accepted 25 November 2005

cm. Photocurrent detected by the receiving antenna was amplified by a current preamplifier (with 3dB bandwidth of 2 MHz) and connected either to a lock-in amplifier for the transient waveform analysis, or a spectrum analyzer for modulation bandwidth analysis. An oscilloscope was also employed for measurement of the decoded signal waveform. The maximum signal was detected at the peak of the THz pulse. The peak-to-peak fluctuation of the integrated signal at the receiving antenna over 3 minutes was around 10 %. Signal to noise ratio of the detected THz waveform was around 1000 up to 1 THz. Signal to noise ratio (S/N) is defined as the peak value divided by the noise level of the THz amplitude spectrum. The THz radiation exhibited a 3dB bandwidth and center frequency of 0.4 THz and 0.3 THz, respectively.

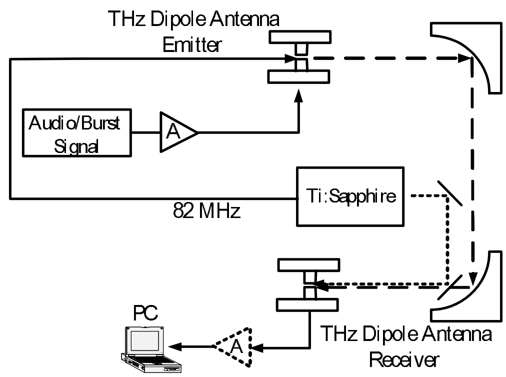


Fig. 1. Schematic diagram for experimental demonstration of the THz communication link: Ti: Sapphire: mode-locked Ti: Sapphire laser; A: amplifier; PC: personal computer

3. Results and discussions

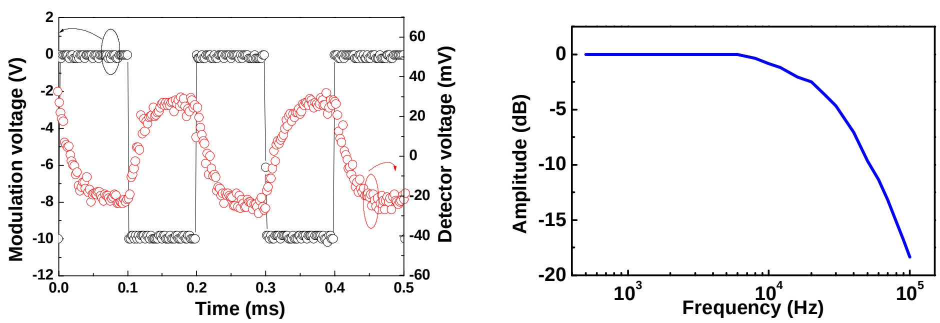


Fig. 2. (a) Time traces of the input modulation voltage and corresponding decoded signal. (b) Frequency response of the THz transmission channel.

We checked the bandwidth of the communication link in the time domain by modulating the emitter antenna with a rectangular voltage alternating between 0 and –10 V. Figure 2(a) shows the time traces of the input modulation voltage and corresponding decoded signal. The 90% rise time to the maximum level of the decoded signal was ~41 µs. To measure the frequency response of the communication link, we replaced the input square wave signal by a sinusoidal signal, which oscillated between 0 and 10V and its frequency was swept from 100 Hz to 0.1 MHz. The decoded signal was normalized to its highest level of –39 dBm and shown in Fig. 2(b). The 3dB bandwidth of the prototype THz communication link is thus about 20 kHz. From the rise time of the decoded signal (see Fig. 2(a)), we can also determine the system cutoff frequency, ~23 KHz. This is in good agreement with the frequency domain measurement and about four times higher than that reported in the previous work [5]. Our photoconductive dipole antennas are not designed for high frequency modulation. The finite modulation bandwidth of the THz link is primarily limited by the RC time constant of the emitter and receiver. The capacitance of the antenna is ~ 0.86 pF as determined from the capacitance to voltage (CV) measurement. The resistance of the antenna is measured to be ~ 0.5 MΩ under Ti:sapphire laser illumination, corresponding to a calculated RC time constant of about 0.43 μs. The RC-limited cut-off frequency is thus around 370 kHz. Un-illuminated, the resistance of antenna is up to 250 MΩ, leading to a calculated RC time constant of 215 μs and a cut-off frequency of 0.74 kHz. Resistivity of the antenna is significantly changed by optically excited carrier density and varies with time between values for dark and optical illuminated cases. We thus expect the RC-limited modulation bandwidth to fall between 0.74 and 370 kHz. Experimental results are qualitatively in agreement with this picture.

According to M. V. Exter *et al.* [7], the quantum noise and thermal radiation noise of photoconductive THz detectors are not significant, while Johnson noise (thermal noise due to photoexcited carriers) and laser shot noise are dominant. Johnson noise in the signal current is due to the photoexcited carriers, which is proportional to the inverse of the square root of the resistance, or the square root of the laser power [8]. Previously, we have shown that THz photoconductive detectors fabricated on LT-GaAs exhibited the lowest noise among similar devices [9].

In Fig. 3, we have plotted the time traces of (a) the square-wave modulation waveform biasing the transmitting antenna, (b) received digital signal from the Lock-in amplifier and (c) detector noise in the absence of THz transmission. The extinction ratio between on and off state of 1000 has been demonstrated. The modulation depth is nearly 100%.

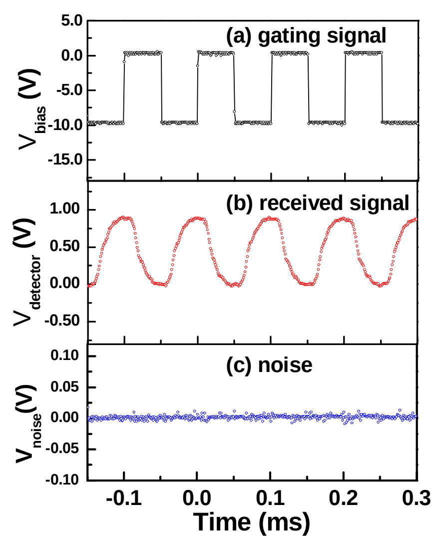
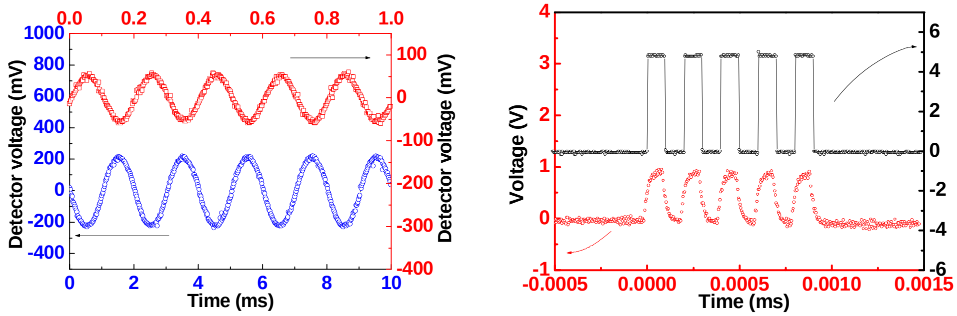


Fig. 3. Time traces of (a) the square-wave modulation waveform, (b) received digital signal and (c) detector noise in the absence of THz transmission

We also transmitted two audio signals of different frequencies and a burst-coded signal over the THz communication link. Figure 4(a) shows time traces of decoded audio signals at 513 Hz and 5130 Hz, respectively. Although the signal amplitude drops at the higher of the two frequencies, it did not exhibit significant distortion. The direct modulation bandwidth of the proposed transmitter is thus one-order of magnitude better than that obtained using

#9157 - $15.00 USD Received 18 October 2005; revised 18 November 2005; accepted 25 November 2005

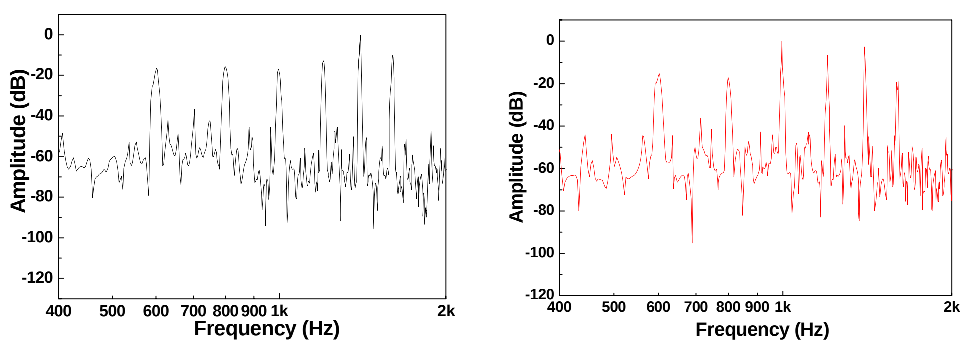
external modulation [5]. The transmission of digital signal through the THz link was demonstrated by encoding the THz beam with a 5 kbit/s burst signal modulating the emitting photoconductive antenna. The encoded and decoded burst signals are shown in the upper and lower part of Figs. 4(b) respectively.



(a) (b)

Fig. 4. Time traces of (a) decoded audio signals at 5130 Hz (upper trace) and 513 Hz (lower trace) and (b) encoded (upper trace) and decoded 5 kbit/sec burst signal transmitted over the THz communication link.

In another experiment, a six-channel voice signal from the analog output of computer was first amplified by a low-power (average power ~ 2 W) computer speaker and used to bias the emitter antenna with peak-to-peak voltage of around 5 V. Figure 5 shows the (a) encoded and (b) decoded signals in the frequency domain. The audio signal can thus be reproduced with a quality comparable to that transmitted through commercial cellular phone networks with similar frequency spectral response.



(a) (b)

Fig. 5. Spectra of (a) encoded and (b) decoded six-channel voice signals transmitted over the THz communication link.

We further demonstrate the fidelity of the transmission of a melody through the THz link. The music score is the School Song of National Chiao Tung University. The system is the same as that for one and six channel transmission experiments discussed above. The signal amplitudes were controlled to be lower than 8 volts. Figure 6(a) displays the whole time sequence (left hand side) and a sample spectrum (right hand side) of a portion of the encoded music score from computer speaker. Figures 6(b), (c) and (d) are the corresponding decoded audio signals from the receiving photoconductive antenna only, with current preamplifier set at a gain of 5×10^6 V/nA and 2×10^7 V/nA, respectively. A portion of the encoded and decoded music scores (from 17 to 31 seconds of the whole time sequence) for Figs. 6(a), (b), (c) and (d) can be played by downloading the corresponding multimedia files of the same name. In each of these files, the visual display shows spectra for the musical score in log (upper part of the video display of the multimedia file) and linear scales (lower part of the video display of the multimedia file) of frequency axis. Note that the fidelity of the transmitted music is already high for the system without the amplifier.

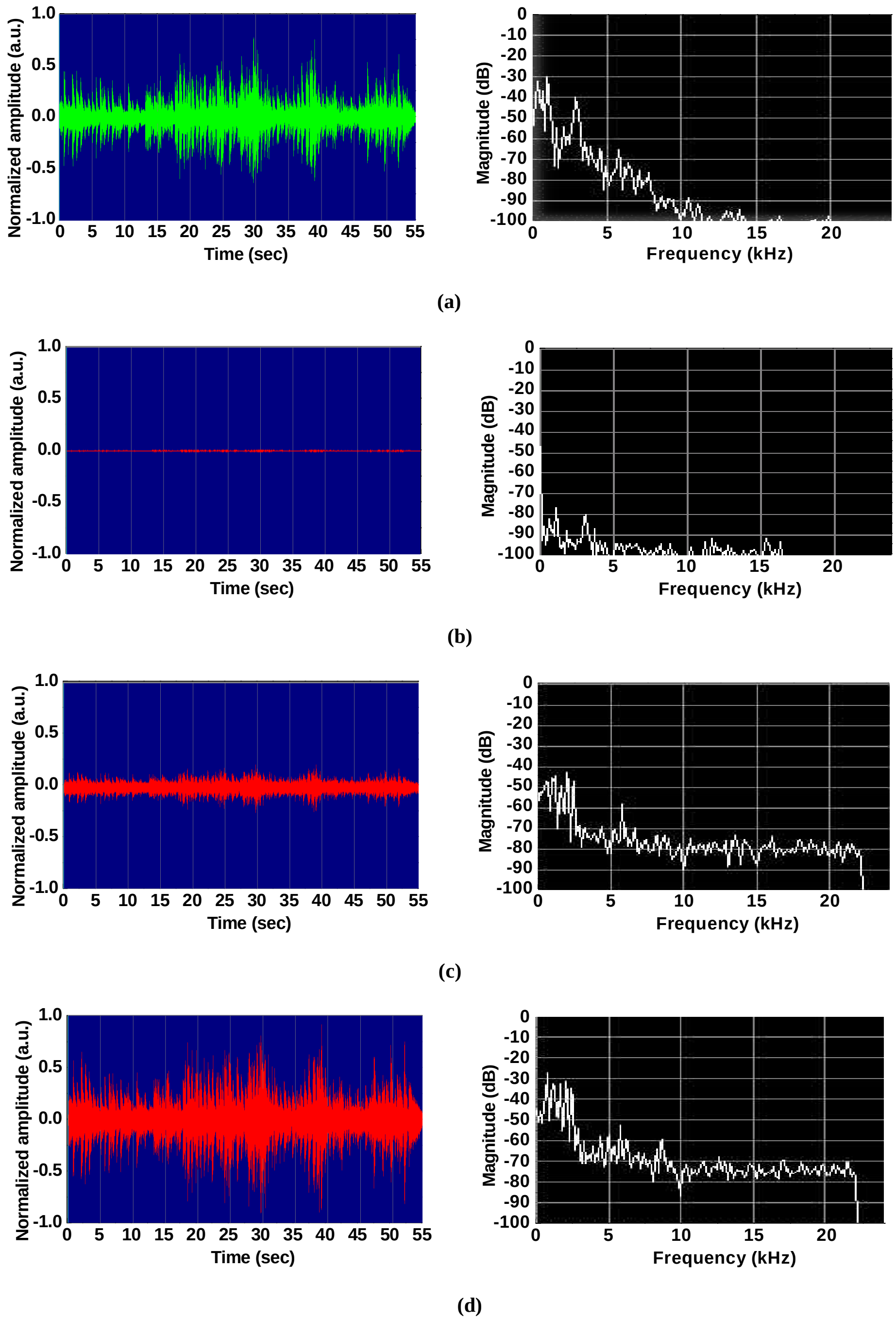
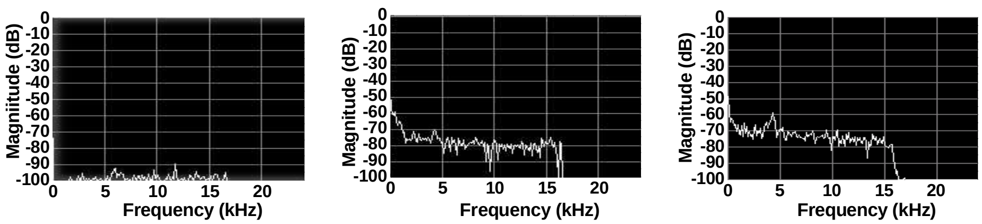


Fig. 6. (a) The whole time sequence (left hand side) and a sample spectrum (right hand side) of a portion of the encoded music score from computer speaker; (b), (c) and (d) are the corresponding decoded audio signals from the receiving PC antenna only (b), with current preamplifier set at a gain of 5×10^6 V/nA (c) and 2×10^7 V/nA (d), respectively.

Received 18 October 2005; revised 18 November 2005; accepted 25 November 2005

Surprisingly, the signal quality for the case of detector only is still acceptable. The sound for amplified signal is, of course higher than that without amplification. The high frequency noise of the former, however, is also higher because of the amplifier. It cannot reveal high frequency components of the sound well, as opposed to the case of detector only. That is, the fidelity of sound for detector only is better than that using the amplifier. This suggests that the transmission of video signal should be feasible merely by improving the electronic interface.



(a) **(b)** **(c)**

Fig. 7. Noise spectra s detected by the receiving THz PC antenna only (a), with current preamplifier set at a gain of 5×10^6 V/nA (b) and 2×10^7 V/nA (c), respectively.

In the absence of the transmitted signal, the noise spectra as detected by the receiving THz photoconductive antenna only, with current preamplifier set at a gain of 5×10^6 V/nA and 2×10^7 V/nA are shown in Fig. 7(a), (b), and (c) respectively. The noise levels of the above cases are –100 dB, –80 dB and –70 dB with reference to the maximum input of the sound card, in that order. It also proves that the amplifier introduce noise with gain.

The signal transmission-receiver system presented in this paper use optical triggers separated from the pump laser. We have previously demonstrated a method for controlling the pulse positioning or timing of a femtosecond Ti:sapphire laser using a Piezoelectric-Transducer-Based Optoelectronic phase lock loop [10]. This technique could potentially be used to lock the repetition rates of Ti:sapphire pump and gating lasers at the transmitting and receiving stations to a remotely distributed clock signal, using for example the Global Positioning System (GPS). Our prototype THz communication link is thus not practical for broadcast type wireless communications in which the signal is detected at an arbitrary position without any physical connection or trigger. The niche application for the THz communication link is most likely secure communication for short-distance, point-to-point, and demanding high information data rate (multi-Mb/s to Gb/s).

The effective range for free-space transmission of THz signals is also a concern. There are many water vapor absorption lines in the far infrared. Further, there is a general rise in absorption from sub-THz to ~ 1 THz [11]. As a result, the absorption coefficient of water vapor at 1 THz, which does not correspond to a transition, is higher than that at certain sub-THz water absorption lines. Average attenuation over a range of frequencies is more relevant for our optically-gated THz link. Following Cheville *et al.* [11], we estimated that the average absorption coefficient is around 10 km^{-1} for the frequency band of 0.1~0.5 THz Assuming a humidity of around 50% and neglecting other propagating losses such as diffraction and particle scattering, the maximum transmission distance for typical optically excited THz pulse is thus over 300 m.

4. Conclusions

In conclusion, we demonstrate transmission of audio and burst signals through a prototype THz analog communication link employing laser-gated low-temperature-grown GaAs dipole antenna as THz emitter and receiver. The THz radiation exhibits a 3dB bandwidth and center frequency of 0.4 THz and 0.3 THz, respectively. By using a direct voltage modulation

#9157 - $15.00 USD Received 18 October 2005; revised 18 November 2005; accepted 25 November 2005

format, we observed a clearly demodulated burst signal with a rising time of 41 μs. The highest audio modulating bandwidth achieved was 23 kHz in this first experiment. Noise analysis reveals a 10% power fluctuation in the received signal with on-off extinction ratio of greater than 1000. The beaming of a six-channel analog and burst audio signal with negligible distortion is also demonstrated. The transmission distance was about 100 cm in the laboratory environment. Assuming a humidity of around 50% and neglecting other propagating losses such as diffraction and particle scattering, we estimated the maximum transmission distance to be over 300 m. We further demonstrate the fidelity of the transmission of a melody through the THz link with and without any amplification. The transmission of video signal should be feasible by improving the electronic interface.

Acknowledgments

The authors acknowledge the support from the Pursuit of Academic Excellence Program of the Ministry of Education and National Science Council of the Republic of China under various grants. We also acknowledge valuable suggestions and comments by Prof. Chi H. Lee, University of Maryland.