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Terahertz Time Domain Spectroscopy, T-Ray Imaging and Wireless Data Transfer Technologies

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Abstract

This study reviewed terahertz technologies of time domain spectroscopy, T-ray imaging, and high rate wireless data transfer. The main topics of the terahertz research area were investigation of materials and package modules for terahertz wave generation and detection, and setup of the terahertz system for time domain spectroscopy(TDS), T-ray imaging and sub-THz wireless communication. In addition to Poly-GaAs film as a photoconductive switching antenna material, a table-top scale for the THz-TDS/imaging system and terahertz continuous wave(CW) generation systems for sub-THz data transfer and narrow band T-ray imaging were designed. Dielectric properties of ferroelectric BSTO($Ba_xSr_{1-x}TiO_3$) films and chalcogenide glass systems were characterized with the THz-TDS system at the THz frequency range. Package modules for terahertz wave transmitter/receiver(Tx/Rx) photoconductive antenna were developed.

Key words : T-ray Imaging, Terahertz Wave, Time Domain Spectroscopy, Femtosecond Laser, CW THz Wireless Communication.

Ⅰ. Introduction

The frequency range of the terahertz wave is from 0.1 to 10 THz and lies between radio waves and photonic waves in the electromagnetic spectrum. The wave length range is one of the shortest among radio waves and one of the longest among light waves. Because of the lack of proper sources and detectors for the terahertz wave, there has been a gap in terahertz technology so far. However, recent developments in optics and electronics have contributed to terahertz technologies and are promising tools for science and engineering in a variety of applications in fields such as biomedical, security, defense, and energy[1]~[3]. The Terahertz wave has the properties of both radio and light waves, which enables images and spectroscopy for non-metallic and non-polar materials. Terahertz time domain spectroscopy(THz-TDS) and T-ray(terahertz-ray) pulse/continuous wave image technologies are the most widely investigated application areas. Wireless data transfer using 100 GHz to several THz as a carrier frequency indicates a future 100 Gbps level data communication system[4].

We review here the research and development trend of terahertz technologies in the fields of T-ray imaging, time domain spectroscopy, and wireless data transfer systems. The terahertz technologies were divided into two groups of terahertz pulse wave sensing and continuous wave sensing. In the terahertz pulse sensing group, we introduced a basic laboratory scale, the THz-TDS system, using low temperature(LT) GaAs based photoconductive switching antennas and a movable table-top scale, the terahertz pulse imager(THz-TDS/TPI) system. By using the THz-TDS system, we have investigated photoconductive antenna materials for terahertz wave generation/detection, and optical and dielectric properties of ferroelectric films on oxide substrates, and also developed package modules for terahertz Tx/Rx photoconductive antenna devices with a high resistivity silicon hyper- hemispheric lens. In the sub-THz CW group, a 120 GHz CW generation system for short distance wireless data transfer with a data rate of 10～100 Gbps was developed with a double side band suppressed carrier(DSB- SC) and photo mixing with a uni-travelling carrier photodiode (UTC-PD). In addition, a terahertz CW imaging system using two DFB-LDs(distributed feedback-laser diode) and a LT GaAs photomixer was developed.

Ⅱ. Terahertz Pulse Wave Sensing Systems

2-1 THz-TDS System

A THz-TDS laboratory scale system was constructed. It consisted of a Ti: sapphire femtosecond laser, an optical delay line, an optical chopper, photoconductive switching terahertz transmitter/receiver antenna devices made by LT grown poly-GaAs films on semi-insulating(SI)

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GaAs substrates, a set of off-axis parabolic mirrors for collimating and focusing the terahertz beam, and a lock-in amplifier. A mode-locked Ti: sapphire femtosecond laser(Coherent, Micra 10) emitted ultra-short pulses of 17 fs duration, center wavelength 795 nm, and spectral width 62 nm(full width at half maximum). The average power of the incident laser to the transmitter and receiver were 40 and 20 mW, respectively. Bias voltage of 15~21 V was applied to the transmitter. Fig. 1 shows the ETRI THz-TDS system(top-left), the femtosecond laser set(top-right), and the configuration diagram of the system(bottom). The system is contained in a dry station to avoid the absorption of the terahertz signal by water vapor in the air. Relative humidity in the dry station should be maintained to be lower than 4 % with nitrogen gas purge during the measurement. Using the THz-TDS system, we investigated the optical and dielectric properties of ferroelectric BSTO films on oxide substrates and chalcogenide glass(Ge-As-Ga-Se) systems[5],[6]. For bio-medical applications, the difference of refractive indices between human lung cancer cells and normal tissues was measured, revealing that lung cancer cells can be distinguished from normal tissues by using THz-TDS and T-ray imaging methods(Fig. 2).

We made a table-top THz-TDS system as shown in Fig. 3(left). The dimension of the system was 70×85×30cm^3, and it contained a 100 fs fiber laser(Menlo Sys.)

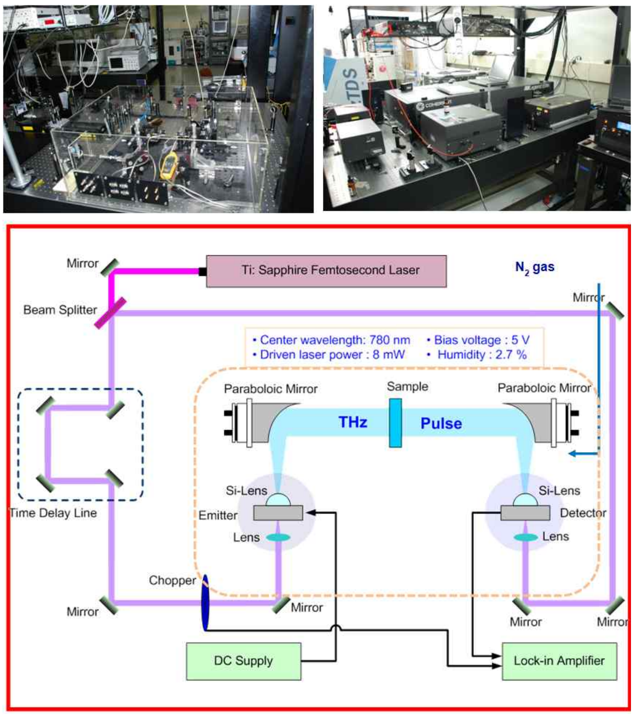

Fig. 1. ETRI lab. scale THz-TDS system(top-left), the femtosecond laser set(top-right), and the schematic diagram of the system(bottom).

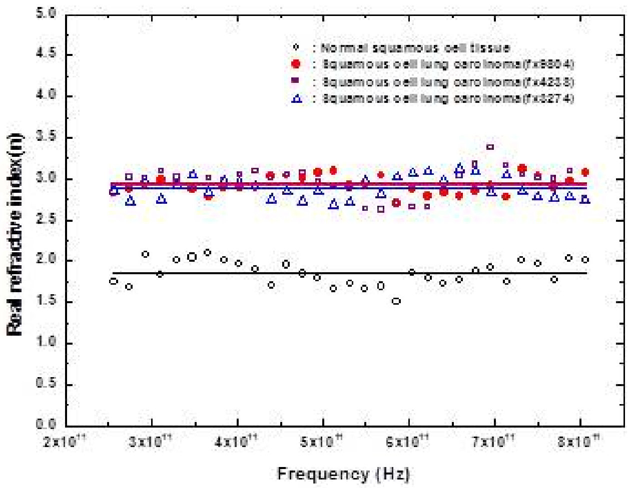

Fig. 2. Difference between real refractive indices of normal squamous tissue and squamous cell lung carcinomas in the frequency range from 0.2 to 0.8 THz measured by ETRI THz-TDS system.

of 780 nm wavelength and LT poly-GaAs based photoconductive Tx/Rx antenna devices. A single-axis piezoelectric linear stage was employed for the optical delay line, and a double-axis piezoelectric linear stage was employed for the sample scanning module. The spatial resolution of the T-ray images acquired by using this system is less than 300 μm as shown in Fig. 3(right), which is the diffraction limit of the terahertz wave. An optical image of a surgeon's knife and the correspon-

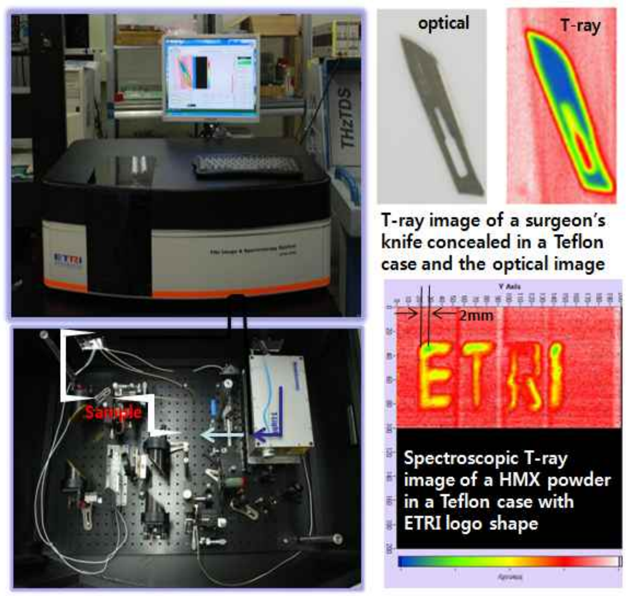

Fig. 3. Table-top scale THz-TDS/T-ray imaging system(left), an optical and a T-ray image of a surgeon's knife(top-right) concealed in a Teflon case, and an explosive HMX(top-bottom) packaged in a Teflon case.

ding T-ray image of the knife concealed in a Teflon case are displayed for comparison. The Teflon box is transparent to terahertz beam and the knife metal reflects all of terahertz wave. AT-ray image of an explosive powder HMX packaged in a Teflon case with the shape of the ETRI logo represents the spectroscopic T-ray image. The table-top THz-TDS system is movable and easy to carry, so it is suitable for outdoor applications in areas such as earth science and the inspection of illegal drugs and weapons.

2-2 Polycrystalline GaAs Thin Films

Low temperature grown epitaxial GaAs thin films(LT-GaAs) are the most efficiently employed material for the generation and detection of the pulse and continuous terahertz waves by photoconductive antennas and photomixing devices. LT GaAs has high mobility electrical properties, a short carrier lifetime, and a low dark resistivity, which are necessary for terahertz generation and detection. Many point defects generated and distributed in the LT-GaAs films during the epitaxial process play a role in capturing sites of electron-hole charge carriers generated by a femtosecond laser beam incidence. These defects shorten the lifetime of the carriers.

However, we have developed polycrystalline GaAs (poly-GaAs) thin films rather than epitaxial LT-GaAs films[7]. Poly-GaAs has not been studied for terahertz applications so far, because it is difficult to control the electrical and structural properties of the polycrystalline films due to the irregular shape and orientation of the grain boundaries. However, the LT poly-GaAs films also have high mobility, high breakdown voltage, and a short carrier life-time compared with those of the epitaxial LT-GaAs films. These results encouraged us to apply poly-GaAs to Tx/Rx devices instead of the epitaxial GaAs films. Poly-GaAsfilms can grow not only on GaAs substrates but also on the other substrates such as silicon, sapphire, and quartz. Fig. 4 shows cross section transmission electron micrographs of the poly-GaAs films grown on SI-GaAs, sapphire, and high resistivity(HR) silicon substrates. Corresponding time domain and frequency domain terahertz spectra obtained by using the same materials are also shown in Fig. 4. As shown in Fig. 4, all poly-GaAs films on various substrates revealed high SNR terahertz wave emission/detection properties. The highest SNR was measured when we used the poly-GaAs films on HR silicon substrates[7].

2-3 Ferroelectric BSTO Films

High-permittivity ferroelectric $Ba_xSr_{1-x}TiO_3$ thin films have attracted considerable attention as a promising ma-

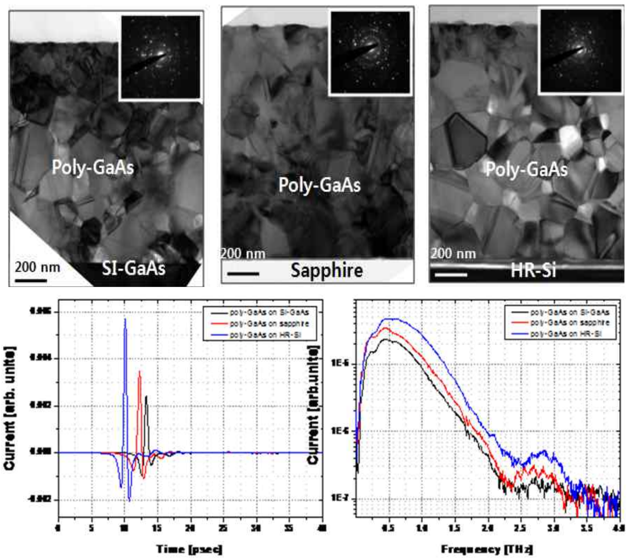

Fig. 4. Cross section transmission electron micrographs and the diffraction patterns of poly-GaAs films on various substrates, and the corresponding time domain and frequency domain THz spectra.

terial for various microelectronic applications. Because of a large dielectric constant, a low dielectric loss and a good tunability under external electric fields, microwave/millimeter wave devices such as phase shifters, varactors and tunable filters based on $Ba_xSr_{1-x}TiO_3$ thin films operating at room temperature are an active area of research. Among the various compositions of $Ba_xSr_{1-x}TiO_3$(BSTO) with different Ba/Sr ratios, $Ba_{0.6}Sr_{0.4}TiO_3$ thin film has the highest dielectric constant and highest room temperature dielectric tunability. Due to the ever increasing operation frequency of electronic devices and communication application, it is imperative to explore the consistent measurements and characterizations of the dielectric response of ferroelectric thin-films at the terahertz frequency range. The THz-TDS method can extract both real and imaginary parts of the dielectric property of materials by measuring the temporal electric field of terahertz waves transmitted through the sample materials.

Experimental characterization of complex dielectric properties of ferroelectric $Ba_{0.6}Sr_{0.4}TiO_3$ thin films with(110) and (100) planes orientation by THz-TDS in the frequency range of 0.2 to 2.0 THz was carried out and the frequency-dependent complex dielectric constants were obtained from a Fourier analysis of the reference and sample terahertz pulses. In order to obtain these constants, we also measured the complex refractive index of the substrates. Fig. 5 shows the measured data of the complex dielectric constants as a function of frequency varying from 0.2 to 2.0 THz[6]. The theoretical calculation of a pseudo-harmonic model fits well with the mea-

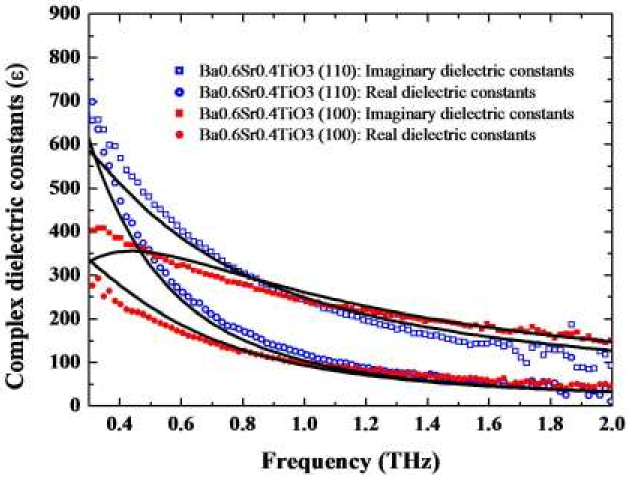

Fig. 5. Frequency-dependent complex dielectric functions of the $Ba_{0.6}Sr_{0.4}TiO_3$ thin films. The solid curves are the theoretical fit.

Table 1. Parameters to fit the experimental data.

Thin films	ε_0	ε_∞	$\omega_{TO}/2\pi$ (THz)	$\gamma/2\pi$ (THz)
$Ba_{0.6}Sr_{0.4}TiO_3$(100)	1,550	10	5.6	160
$Ba_{0.6}Sr_{0.4}TiO_3$(110)	510	10	11.5	360

sured data. Four parameters were used to fit the experimental data. The values of these parameters are listed in Table 1.

In Table 1, ε_∞, ε_0, ω_{TO}, and γ are the high-frequency dielectric constant, the low-frequency dielectric constant, the frequency of the TO phonon mode and the damping constant, respectively.

2-4 THz Tx/Rx Device Package Module

The THz-TDS system includes photoconductive switching antennas for both generation and detection of terahertz waves. Alignment of the photoconductive antenna devices to the femtosecond laser beam, the hyper-hemispheric silicon lens, and the terahertz optical components is an essential and time-consuming process for a good SNR of the terahertz wave. We have developed various types of terahertz Tx/Rx device package modules to improve the process of alignment and the exchange of the photoconductive antenna devices. Fig. 6 shows the package modules version(ver.) 2.0 and ver. 3.0 developed in 2008 and 2009, respectively. The all-in-one(AIO) Tx/Rx package module ver. 3.0, implemented in 2009, includes a nitrogen gas purge/discharge system, which can prevent the terahertz signal from absorption by water vapor in the air and degradation of the antenna materials. The package module can be applied to the THz-

Fig. 6. THz Tx/Rx package modules of ver. 2.0 and ver. 3.0.

TDS, T-ray imaging, and the terahertz photomixer systems. It consists of a LT poly-GaAs based photoconductive antenna device, a high resistivity silicon hyper hemispheric lens, and a large diameter focusing lens. A mini-USB interface is employed for the interconnection of an electrode to control the bias voltage and measure the photocurrent.

Ⅲ. Terahertz Continuous Wave System

3-1 Sub-THz CW System for Wireless Data Transfer

A sub-THz CW transmitter/receiver system for high data rate wireless communications and data transfer is being developed. In the near future, a data transfer rate of more than 10 Gbps for more than 7 channels of uncompressed and seamless HDTV images transmission by wireless communication would require sub-THz to several THz carrier frequencies. Although there have been various methods of generating sub-THz CW waves so far, we have chosen an optoelectronic technology because it enables high quality and low noise signal processing, and allows better tunability and high output power.

We are now investigating a sub-THz(120~200 GHz) CW generation system by using a photomixing method. We have employed a double side band suppressed carrier (DSB-SC) method to generate 120 GHz, and an amplitude shift keying(ASK) method to modulate the 10 Gbps signal. The DSB-SC method is an optical heterodyne technique having a simple structure and easy access to a desired frequency signal[8]~[10].The 120 GHz continuous wave is generated by photomixing of the double side bands(DSBs) ±60 GHz apart from central frequency 194.1 THz (1,546.9 nm wavelength) with a uni-traveling photodiode (UTC-PD). Fig. 7 displays a standard rack type (19" width) sub-THz CW generator and a measurement setup. It consists of a sub-THz CW generation

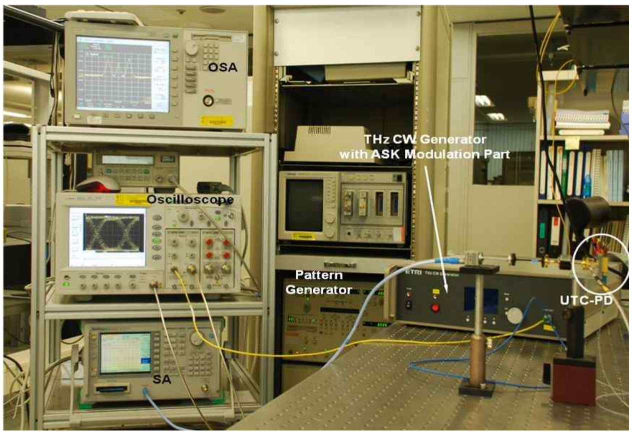

Fig. 7. Photograph of the standard rack(19 inch width) type THz CW generator and the measurement setup.

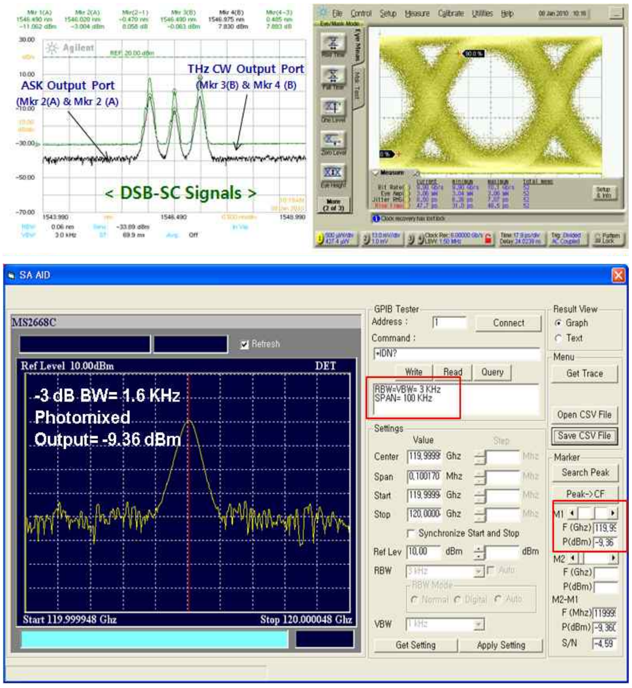

Fig. 8. The DSB-SC signal measured by optical spectrum analyzer(top-left) and the eye diagram of the ASK modulation with ~10 Gbps(top-right), and the output power of the THz wave generated by photomixing(bottom).

part and a 10 Gbps signal modulation part. Fig. 8 shows the DSB-SC signal observed by optical spectrum analyzer(left), the eye diagram of the ASK modulation with 10 Gbps(right), and THz CW signal generated by the photomixer UTC- PD(bottom). The power of the generated sub-THz CW was measured at −9.36 dBm, and the bandwidth was measured at −3 dB with a negligible frequency drift(~kHz).

3-2 THz-CW T-ray Imaging System

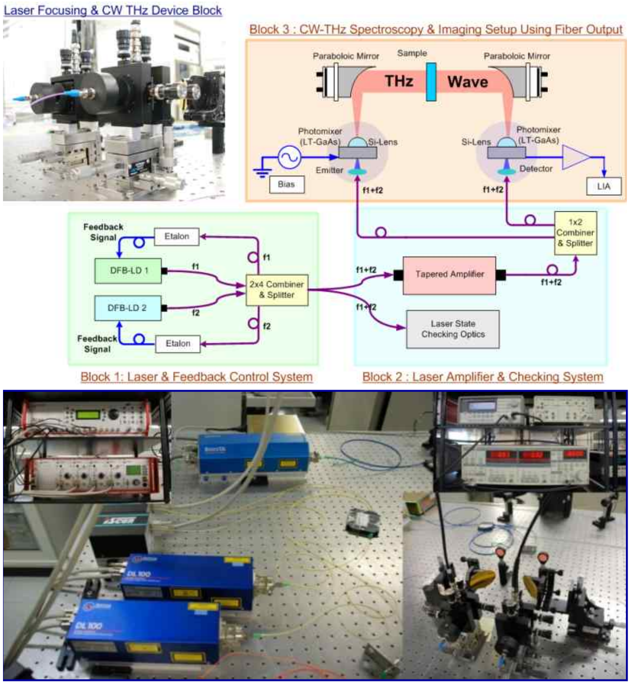

Fig. 9. Configuration diagram (top) and the photograph of the setup of the THz CW imaging system (bottom).

A THz CW imaging system using a photomixer has several merits including reduced construction costs, because it does not require a femtosecond laser. Moreover, with two tunable laser sources, we can obtain the T-ray images with specific terahertz frequencies. We have made a THz-CW imaging system with two tunable 850 nm DFB-LDs and a LT-GaAs based photoconductive antenna photomixer. Fig. 9 shows the configuration diagram and a corresponding photograph of the THz CW imaging system. For the high SNR CW imaging system, a feedback control system(FCS) with a laser and a Si semiconductor amplifier were connected by optical fiber instead of free space. The output of the optical fiber was focused to the photomixer device and the laser focusing components, and the photomixer was united to the block systems to avoid a shift in the focusing point during the alignment of the terahertz signal. Thus, the system can be divided into three blocks:

Block 1: Laser and feedback control system

Block 2: Laser and amplifier laser state checking system

Block 3: CW-THz spectroscopy and imaging setup using fiber output

We confirmed that two DFB-LDs and the feedback control system can generate 0~1,500 GHz stable output, and that the output power, when the beat frequency between two lasers is 0 GHz, yields double the power compared with a beat frequency of 100 GHz. Moreover, at 100 GHz beat frequency, the maximum output power emitted at the end of the optical fiber increases from 9 to 42 mW by raising the driving current of the semiconductor amplifier from 700 to 1,900 mA.

Ⅳ. Summary and Conclusion

We have reviewed the terahertz technologies research topics and the results of the ETR Iterahertz technologies laboratory experiment. The sensing systems for time domain spectroscopy and T-ray imaging have been set up and used for the research of variety of materials at THz frequency. By using the THz-TDS system, we have developed low temperature grown poly-GaAs films on SI GaAs substrates as photoconductive antenna materials for THz wave generation and detection, and investigated optical and dielectric properties of BSTO/MgO films, the chalcogenide glass system, and even human lung cancer tissues. The T-ray imager system has revealed the image of a concealed knife in a Teflon box and HMX powder in a Teflon package. Sub-THz(120 and 240 GHz) CW has been generated by using a photomixing method with a UTC-PD. We have employed the DSB-SC and the ASK methods for generation and modulation of 120 GHz waves. A THz CW system for T-ray imaging was set up and showed a stable output(9～42 mW) and good tunability from 0 to 1,500 GHz.

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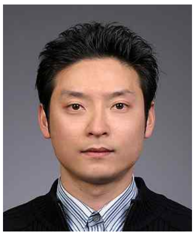

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