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Asian Journal of Physics Vol. 24, No 3 (2015) 00-00

High power terahertz wave generation via non-linear optical processes

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In this paper, we present state-of-the art technologies for the emission of terahertz (THz) wave based on non-linear optical processes. First, we introduce high power terahertz wave emission scheme via optical rectification of femtosecond pulses in non-linear optical crystal known as 4-N,N-dimethylamino-4'-N'-methyl-4-stilbazoliumtosylate (DAST). Second, we demonstrate THz wave emission and amplification in magnesium oxide doped lithium niobate ($MgO:LiNbO_3$) crystal based on optical parametric process.

Keywords: Terahertz wave, THz sources, THz spectroscopy, DAST, Lithium Niobate

1 Introduction

Electromagnetic waves which lie between the microwave and infrared regions in the electromagnetic spectrum with a frequency extending from a few hundreds of gigahertz (GHz) to a few terahertz (THz) are known as terahertz waves. These waves possess excellent properties such as higher penetrability than infrared waves and better spatial resolution compared to microwaves. Moreover, the photon energy of THz wave (~meV) is much smaller in comparison to X-ray (~keV), these waves are considered safe for human being. Owing to these characteristics, THz waves have widely been used in various applications such as material characterization [1], information and communication technology [2], biomedicine [3], homeland security [4], non-destructive testing and analysis [5,6] and scientific studies [7]. High power and broadband THz wave is essential to further expand the applications of THz technology. In the past, there have been large numbers of reports on high power THz wave generation using different methods such as optical parametric generation [8], quantum cascade laser [9], laser plasma interaction [10]. All these sources produce THz radiation which can fulfill the requirements for experimental research at a laboratory level. However, because of the complexity and need to use sophisticated optics, alternative high-power THz sources that are robust, portable, and compact are in strong demand. In this paper, we report on high power THz wave generation scheme based on optical rectification of femtosecond pulses in DAST crystal and THz wave emission and amplification method based on parametric processes.

2 High power THz wave emission using DAST crystal

THz wave generation using non-linear optical methods have shown very good potential to generate broadband THz waves. One of the non-linear organic crystals, known as 4-N,N-dimethylamino-4'-N'-methyl-4-stilbazolium tosylate (DAST) has widely used to produce terahertz waves via optical rectification of femtosecond pulses. This crystal has excellent characteristics such as large second order optical non-linearity and low THz wave absorption [11]. Besides this, it has high melting point and high power tolerance towards incident laser due to the presence of ionic bonds. Owing to such excellent properties, DAST is widely used to generate THz radiation using various methods such as difference frequency generation [12, 13] and optical rectification [14, 15].

In optical rectification, the intensity of THz waves generated via optical rectification of femtosecond pulses in a nonlinear crystal is proportional to the square of the excitation pulse intensity, high-power THz radiation is expected from a DAST crystal when it is pumped by a high-power femtosecond laser. In this work, we used a 1610 nm fiber laser with a repetition rate of 67.1MHz, producing an average power of about 300mW to irradiate the crystal. We successfully detected the THz radiation using room temperature, calibrated pyroelectric sensor.

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2.1 Experiment and Results

The experimental setup to measure the THz output from the DAST crystal is shown in Fig 1. The as grown DAST crystal with the size of 5 mm × 5 mm and the thickness of 0.49 mm was used as an emitter. We used femtosecond fiber laser (IMRA, HFX-400, footprint = 20cm × 19cm × 7cm) which could emit fs pulses with three different wavelengths such as 805nm, 1560nm, 1610nm with their respective pulse width of 130 fs, 65 fs, 65 fs. The repetition rate was 67.1 MHz. The fs pulse produced by laser was focused on the DAST crystal to a spot diameter of 60μm using the lens with the focal length of 25.4 mm. The polarization of laser is aligned to a-axis of the DAST crystal using λ/2 plate. The residual laser is blocked by lowpass filter (BPE). The emitted THz radiation was first collimated and then focused to the detector using parabolic mirrors as shown in figure. We used calibrated pyroelectric sensor (Gentec, SPI-A-65THz) to measure the THz output power. The pump beam was modulated by a chopper with the frequency of 5 Hz.

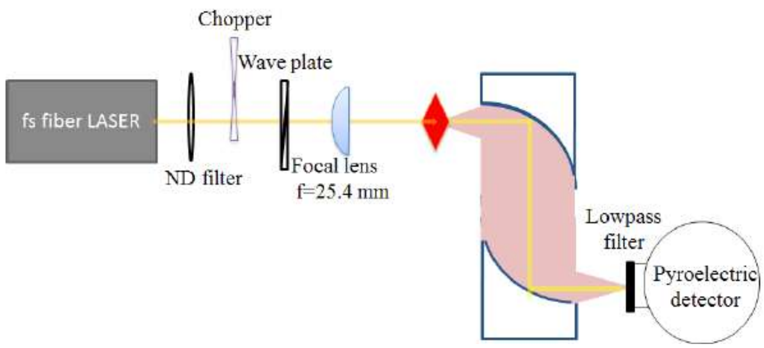

Fig. 1. Experimental setup

In order to observe THz electric field and its spectral content, we constructed the THz time domain spectrometer using dipole type photoconductive (PC) antenna (Hamamatsu Photonics.) as a detector and 0.49 mm thick DAST crystal as THz emitter. In this case, two wavelength (λ=805 nm, λ=1560 nm) fs laser was emitted from the laser, which was divided by dichroic filter and DAST crystal and PC antenna were excited separately with 1560 nm and 805 nm laser respectively. Finally, the temporal profile of electric field was recorded as a function of time delay between THz wave and optical probe pulse as shown in Fig 2(a). We obtained the near single pulse with the pulse duration of 0.15 ps and THz spectrum reaches beyond 7 THz with the maximum intensity at 2.1 THz as shown in Fig. 2(b).

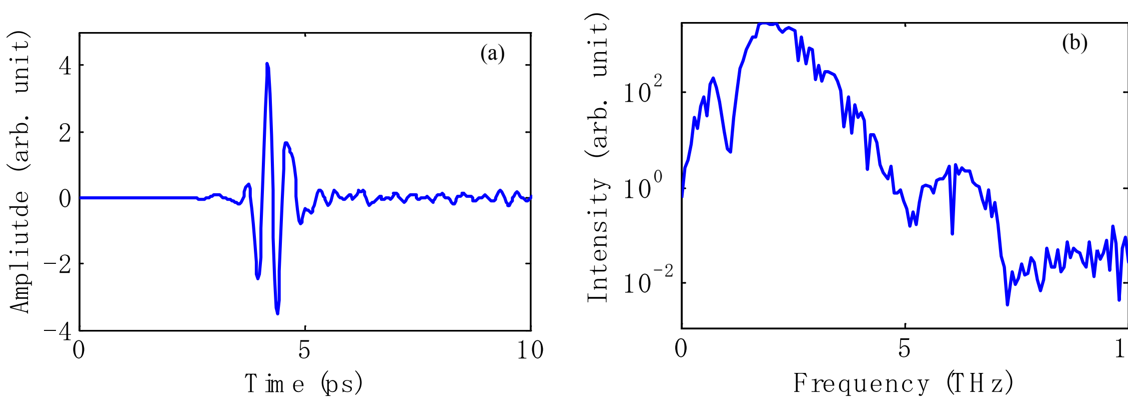

Fig 2: (a) THz electric field (b) Intensity spectrum

We used the experimental setup shown in Fig. 1 to measure the average power obtained from the

DAST emitter. Figure 3 shows the THz wave output average power dependence on the input average pump power and it shows that the output power increases quadratically with the input power. We obtained the maximum output power of 18 μW when the input power is 280 mW, which yields the optical to terahertz power conversion factor of 6×10^{-5}. Within the measured input average power of laser light, we did not observe saturation. Moreover, any damage due to laser intensity in the crystal was also not observed. These results indicate that the higher THz power can be expected with the increase in laser power. Simultaneously, we can obtain the higher conversion efficiency as it has linear relationship with the input power in the case of optical rectification.

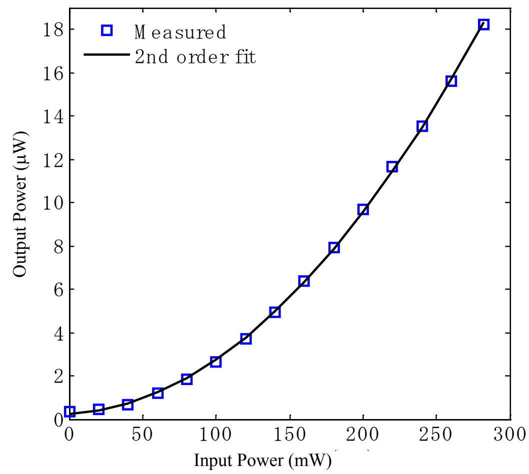

Fig 3. Dependence of THz average power on laser input power

3 High power THz wave emission and amplification using Lithium Niobate crystal based on optical parametric process

Emission of high power terahertz wave has received much recent research attention and various methods including optical rectification of femtosecond pulses in non-linear organic and inorganic crystals, such as DAST and Lithium Niobate have been reported. Such sources have been applied in wide range of research fields, including THz imaging and spectroscopy. Despite the improved performance, it remains difficult to obtain THz spectra and transmission-based images of samples with a large absorption coefficient. In order to overcome such problems, it is necessary to either increase the power of the THz wave or to improve the sensitivity of the THz sensors. One approach to overcoming these limitations is to amplify the THz wave that has been transmitted through the sample. This allows us to easily detect the transmitted THz wave using a conventional room-temperature THz sensor, such as a pyroelectric detector. In this section, we demonstrate a method to amplify single longitudinal mode, pulsed THz wave emitted from an injection-seeded THz wave parametric generator. The emitted THz wave was amplified in a nonlinear crystal by means of an optical parametric process.

Parametric generation and amplification of THz wave is based on both second and third order optical nonlinear processes. In our experiment, we selected $LiNbO_3$ crystal because of its excellent characteristics such as large non-linear coefficient (d_{33} = 25.2 pm/V at λ = 1064 nm), high figure of merit and high transparency over a wide frequency range. Besides this, the damage threshold due to laser power is high, making it possible to use higher peak power pump sources without damage to the crystal. Previously, we have demonstrated THz wave generation using a parametric oscillator [16] and an injection-seeded THz wave parametric generator (is-TPG) [17]. Recently, we demonstrated a high dynamic range, frequency tunable THz wave spectrometer where both emission and detection of THz waves have been achieved by non-linear parametric processes in Lithium Niobate crystal [18]. Based on the fundamental principle of is-TPG, in this section we demonstrate the amplification of THz wave via parametric processes in Magnesium Oxide doped Lithium Niobate (MgO: $LiNbO_3$) crystal.

3.1 *Experiment and Result*

The experimental setup of THz wave amplification system is shown in Fig. 4. The system mainly consists of two major parts. First, a THz wave emission section that comprises a pump laser, laser amplifier, seed laser and non-linear crystal. The second part is a THz amplifier section, which comprises of a pair of non-linear crystal and a pyroelectric detector to measure the emitted THz power. We used microchip Nd:YAG laser (λ = 1064 nm, pump energy = 700 μJ/pulse, pulse width = 420 ps, repetation rate = 100 Hz) as a pump source. This laser is free from noise and the power fluctuation of this laser is comparatively better than the other Q-switched laser. The output of the laser was amplified usingtwo optical amplifiers in a double-path configuration. The amplified beam was extracted using a polarizing beam splitter (PBS). We used a continuous-wave (CW) tunable external cavity diode laser (ECDL) (Velocity 6300, New Focus Inc.) with an average power of 5.5 mW as an injection seed for the idler beam. Both pump beam and seed beam are irradiated to the MgO:$LiNbO_3$ crystal with a certain angle as shown in Fig 4.

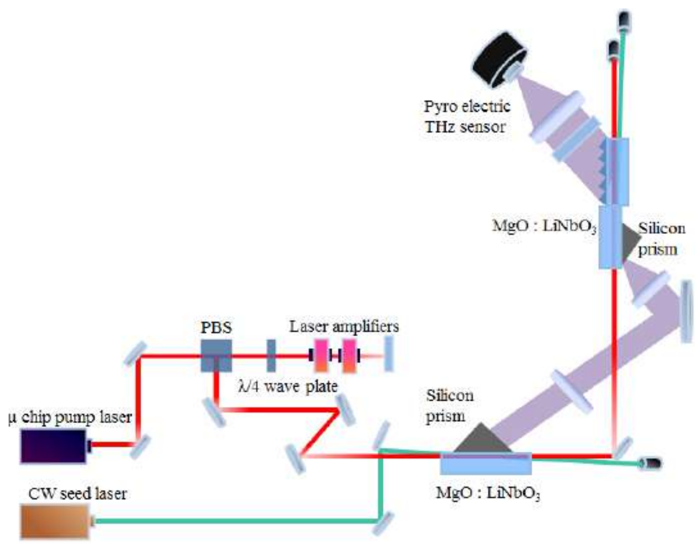

Fig 4. Experimental setup for emission and amplification of THz waves

We used a 50 mm long crystal with an anti reflection coating for a wavelength of1064 nm. The polarization orientation of the pump, seed, idler, and THz waves are all parallel to the z axis of the crystal. Since the maximum gain coefficient of $LiNbO_3$ occurs at approximately 2 THz, we optimized our system for the frequency of 2.01 THz by tuning the seed beam wavelength to 1072.36 nm. The emitted THz waves has a pulse energy of 12.1 nJ, pulse width of 100ps. The emitted THz wave was collimated using a cylindrical lens and coupled to another MgO:$LiNbO_3$ crystal using a silicon prism. The THz wave was focused using a lens of 100 mm and was incident on the amplifier crystal with the appropriate phase-matching angle, which is an important criterion for efficient THz wave amplification. Moreover, the THz wave and pump laser were temporally overlaid by adjusting the optical path lengths. These crystals used for amplification are pumped by the Nd:YAG laser beam after it was transmitted through the emitter crystal. This recycling of the pump laser makes the system physically far more compact. The energy of the pump beam in this second stage is about 7.2 mJ/pulse. During this process, the THz wave that was incident on the crystal acts as a seed beam, and, due to the parametric interaction between the THz wave and the intense pump beam in the non-linear crystal, the THz wave was amplified [19]. We used a Si prism to out-couple the THz wave, and the energy of the amplified THz wave was measured using a calibrated pyroelectric sensor.

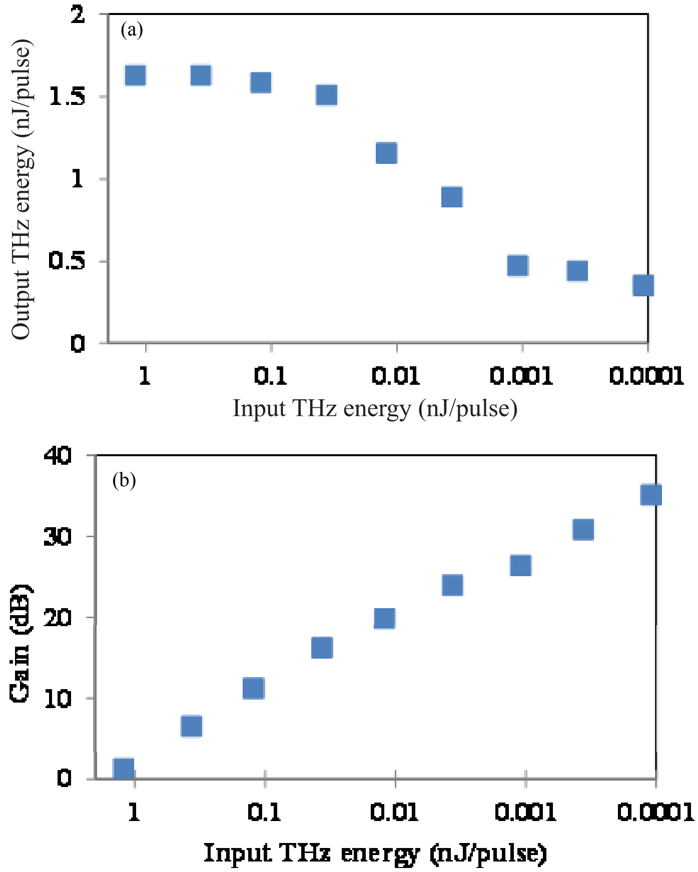

Fig 5: (a) Input–output characteristics of the THz wave amplifier. (b) Gain of the THz amplification system

Figure 5(a) shows how the output pulse energy of theTHz amplification system varies as a function of the input pulse energy. Both input and output THz energy were measured using the pyroelectric detector with the input energy ranging from 1 nJ⁄pulse to 0.1pJ⁄pulse. The input THz energy was varied using the THz wave attenuators (TFA-4; CDPCorp) with transmittances of 1%, 3%, 10% and 30%.In order to better visualize the results, we plot the gain as a function of input pulse energy in Fig. 5(b). The gain was calculated as G =10log10(E_{out}/E_{in}), where E_{in} and E_{out} are the input and output THz energy. We obtained a system gain in excess of 30 dB with low values of input energy per pulse (0.1pJ⁄pulse). The gain varies inversely with input THz pulse energy. Gain falls almost to unity when the input THz pulse energy is higher than 1 nJ. We attribute this to saturation of the parametric gain of the nonlinear crystal. It is satisfying to note that our system generates THz pulse energies at levels that are easily detected by commercially available room temperature THz detectors. In our system, the gain saturates when the input pulse energy is more than 1 nJ⁄pulse. However, commercially available THz detectors are capable of detecting 1 nJ pulses with good signal-to-noise ratio, so amplification beyond this level is not crucial. However, when the THz energy is less than 1 nJ⁄pulse, our amplifier demonstrates an unprecedented ability to amplify such weak signal. Recently, we succeeded in the enhancement of the gain of the system, where we pumped the emitter and amplifier crystals separately, which enables us to increase the gain of our system to 55 dB [20].

4 Conclusion

In this article, we introduced two methods to enhance the power the THz waves. First, we demonstrated a high-power THz wave source based on optical rectification of a femtosecond laser using a DAST crystal. We produced a THz wave with an average power of 18 μW and a maximum spectral intensity at 2 THz. The majority of the spectral energy lay between1.1 and 7 THz. Our results demonstrated that a high conversion ratio and hence high power could be expected as the laser power increases. Because the emitted THz wave can be easily detected by room-temperature detectors such as a pyroelectric sensor, our sources could find applications in THz imaging based on direct detection. In the second section, we demonstrated THz wave amplification viaa parametric process in MgO:$LiNbO_3$ crystals with a gain of30 dB. The system operates at room temperature. We believe that the methods presented here will enable an extension of the applications of THz wave and represents a significant advance in the state of the art of THz technology.

References

1. Naftaly M, Miles R E, *Proc IEEE*, 95(2007)1658.
2. Koenig S, Lopez-Diaz D, Antes J, Boes F, Henneberger R, Leuther A, Tessmann A, Schmogrow R, Hillerkuss D, Palmer R, Zwick T, Koos C, Freude W, Ambacher O, Leuthold J, Kallfass I, *Nat Photon*, 7(2013)977.
3. Wilmink G J, Grundt J E, *J Infrared Millim Terahertz Waves*, 32 (2011)1074.
4. Federici, J F, Schulkin B, Huang F, Gary D, Barat R, Oliveira F, Zimdars D *Semcond Sci Technol*, 20 (2005)S266.
5. Kawase K, Ogawa Y, Watanabe Y and Inoue H, *Opt Express*, 11(2003)2549.
6. TripathiS R, Ogura H, Kawagoe H, Inoue H, Hasegawa T, Takeya K, Kawase K, *Corrosion Science*, 62 (2013)5.
7. Hirori H, Tanaka K, *IEEE Trans Sel Quant Elec*, 19(2013)8401110.
8. Hayashi S, Nawata K, Sakai H, Taira T, Minamide H, Kawase K, *Opt Exp*, 20(2012)2881.
9. Williams B S, Kumar S, Hu Q, Reno J L, *Electron Lett*, 42 (2006)89.
10. Hamster H, Sullivan A, Gordon S, White W, Falcone R W, *Phys Rev Lett*, 71(1993)2725.
11. Walther M, Jensby K, Keiding S R, Takahashi H, Ito H, *Opt Lett*, 25(2000) 911.
12. Kawase K, Mizuno M, Sohma S, Takahashi H, Taniuchi T, Urata Y, Wada S, Tashiro H, Ito H, *Opt Lett*, 24(1999)1065.
13. Dixit N, Farroqui M, Mishra A, Kumar V, Gupta A K, *Asian J Phys*, 23(2014)573.
14. Tripathi S R, Murate K, Uchida H, Takeya K, Kawase K, *App Phys Exp*, 6(2013)072703-1.
15. Schneider A, Neis M, Stillhart M, Ruiz B, Khan R A, Gunter P, *J Opt Soc Am* B, 23(2006)1822.
16. Kawase K, Sato M, Taniuchi T, Ito H, *Appl Phys Lett*, 68(1996)2483.
17. Kawase K, Minamide H, Imai K, Shikata J, Ito H, *Appl Phys Lett*, 80 (2002)195.
18. Murate K, Taira Y, Tripathi S R, Hayashi S, Nawata K, Minamide H, Kawase K, *IEEE Trans THz Sci Tech*, 4 (2014)523
19. Tripathi S R, TairaY, Hayashi S, Nawata K, Murate K, Minamide H, Kawase K, *Opt Lett*, 39(2014) 1649
20. Taira Y, Tripathi S R, Murate K, Hayashi S, Nawata K, Minamide H, Kawase K, to be published in *IEEE Trans THz Sci Tech*, 4(2014)753.

[*Received*: ....; *accepted*: 26.10.2014]