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THz-wave generation and applications

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1. Introduction

After more than a dozen years of basic research into the submillimeter and far infrared range, terahertz (THz) wave research has finally come into its own, and is recognized by the world scientific community as a new frontier. While femtosecond laser pumped THz wave sources have opened up a new vista in applied research, the ideal THz wave source will likely require high coherence and wide tunability. When this level of quality is finally made available in a user-friendly device, there is little doubt that applied research efforts into the THz region will enjoy a true renaissance. In this direction we have developed a widely tunable injection seeded THz-wave parametric generator (is-TPG) that operates at room temperature. The spectral resolution is the Fourier transform limit of the nanosecond THz wave pulses. In our laboratory, THz-waves continue to broaden their range of applications as following. We have developed a basic technology for THz imaging which allows detection and identification of drugs concealed in envelopes by introducing the component spatial pattern analysis. On the other hand, for inspecting electrical failures in large scale integration circuit, we developed the laser-THz emission microscope, which records the map of THz emission amplitude in a sample upon excitation with fs laser pulses.

There are two key points around which much of the terahertz research and applications turn: 1) Spectral specificity: Most chemical substances present characteristic absorption features in the THz range. Such features are almost absent under 0.5 THz, in the millimeter and microwave region. 2) Transmission properties: A wide range of materials are transparent or partially transparent to THz waves. These materials generally become opaque as you go beyond 3 THz into the far-infrared. The combination of these two properties is what makes THz radiation so interesting and unique for noninvasive inspection[1]. You can see through packaging and identify the contents. The ability of the terahertz radiation to pass through many packaging materials, such as paper and cardboard, textiles, plastics, wood, ceramics, semiconductors, dried or frozen materials, and so on, will allow the nondestructive and noninvasive inspection of mail packages in post offices, luggage and personal belongings in airports and border crossing points, and others.

2. THz wave parametric sources

There are three basic types of parametric sources: the THz-wave parametric generator (TPG), the THz-wave parametric oscillator (TPO), and the injection-seeded TPG (is-TPG)[2]. They are all compact and operate at room temperature, which makes them suitable as practical sources. The principle of operation of the parametric sources is as follows. When an intense laser beam propagates through a nonlinear crystal, the photon and phonon transverse wave fields are coupled, and behave as new mixed photon-phonon states, called polaritons. The generation of the THz radiation results from the efficient parametric scattering of laser light via a polariton, that is, stimulated polariton scattering. The scattering process involves both second- and third-order nonlinear processes. Thus, strong interaction occurs among the pump beam, the idler beam, and the polariton (THz) waves.

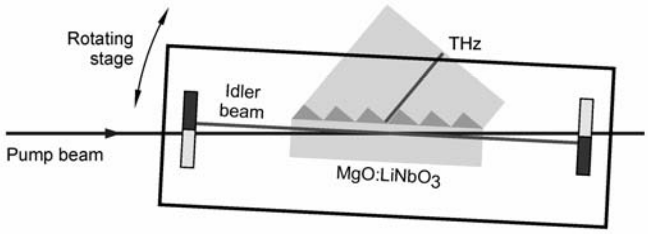

Figure 1. The TPO configuration.

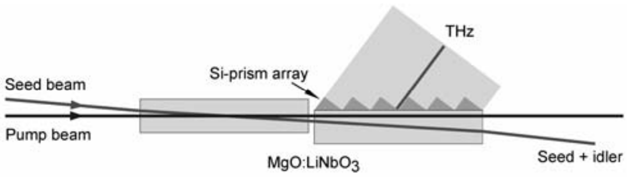

Figure 2. Experimental setup of the is-TPG.

A primitive TPG uses just a nonlinear crystal placed in the pump beam. The output of such a device contains a wide range of THz frequencies as there is no frequency selector in place. For an efficient extraction of the THz wave from inside the crystal several techniques have been tried, and the one presented in the figure, making use of an array of small silicon prisms, seems to be most suitable. The prism array covers the whole lateral surface of the crystal, increasing the collection efficiency, and minimizing the diffraction effects.

Coherent tunable THz waves can be generated by realizing a resonant cavity for the idler wave. This is the basic configuration of a TPO, and consists of a Q-switched Nd:YAG laser, the nonlinear crystal, and a resonator, as shown in figure 1. The idler wave is amplified in the resonator consisting of a pair of flat mirrors with a half-area HR coating. The mirrors and crystal are installed on a computer-controlled rotating stage for precise tuning. With the slight variation in the phase-matching condition, the wavelength of the THz-wave is tuned between 330 and 100 µm (in frequency from 0.9 to 3.0 THz); the corresponding idler wavelength changes from 1.075 down to 1.067 µm.

In the is-TPG, the THz spectrum specific to a TPG source is narrowed to the Fourier transform limit imposed by the pulse length by introducing the injection seeding for the idler wave. Figure 2 shows our experimental setup of the is-TPG. The purity of the THz-wave frequency was dramatically improved. Simultaneously, the output power obtained is several hundred times higher than that of a conventional TPG. It was possible to tune the THz wavelength using an external cavity laser diode as a tunable seeder. A wide tunability, from 115 to 460 µm (0.6 to 2.6 THz), was achieved by changing simultaneously the seed wavelength and the seed incident angle.

We have also developed two kinds of terahertz-wave parametric generators (TPG) by using compact pump sources[3]. One TPG generates high energy and broadband THz-waves with high stability, the other has a potential to be a narrow-linewidth injection-seeded TPG. The experimental apparatus consists of a pump source and two nonlinear crystals.

About energy enhancement version, we used compact Q-sw. Nd:YAG laser as a pump source. All components, except for the detector, can be mounted on a 12 × 22 cm breadboard. The pump beam is collimated by a lens at the output of the source and reflected by mirrors for downsizing of a source. It has a top-hat profile with a beam diameter of 1.3 mm (FWHM) on the first crystal. We used two 65-mm-long nonlinear $MgO:LiNbO_3$ crystals. A Si-prism array placed on the y surface of the second crystal acts as an efficient output coupler for the THz-waves to avoid the total internal reflection of the THz-waves on the crystal output side. For an efficient THz-wave emission, the pumped region within the second crystal must be as close as possible to the Si-prism array, because of the large absorption coefficient of the $MgO:LiNbO_3$ crystal in the 1 ~ 3 THz range (10 ~ 100 cm^{-1}). A top-hat beam profile is suitable for this purpose, since the high intensity region of the pump beam is closer to the y surface than in the case of a Gaussian beam. The distance between the y surface and the beam center was precisely adjusted to obtain a maximum THz-wave output, and it was approximately equal to the pump beam radius. The THz-wave output extracted through the Si-prism array was measured using a 4.2 K Si bolometer, while the idler-wave energy was measured using a pyroelectric detector.

About another source for narrow linewidth, we replace pump source to microchip laser[4]. All components except for the detector can be mounted within an area of 25 × 5 cm^2. This pump source is a diode end-pumped single-mode microchip Nd^{3+}:YAG laser passively Q-sw. by Cr^{4+}:YAG saturable absorber. This microchip configuration enables the low order axial and transverse mode laser oscillation, which linewidth is below 0.009 nm. The laser delivers 1.8 MW peak power pulses (750 µJ/pulse) with 420 ps pulse width at 100 Hz repetition rate with a M^2 factor of 1.09. This laser is free from the electric noise compared with active Q-sw. lasers. Additionally, this kind fixed passively Q-switching allows us the stabilized peak power, less than +/- 2% power jitter. The pump beam diameter on the first crystal is 0.3 mm (FWMH). We used a pyroelectric sensor to detect both the THz-wave and the idler-wave.

3. THz wave applications

The ability of the THz wave to pass through many packaging materials, such as paper and cardboard, textiles, plastics, wood, ceramics, semiconductors, dried or frozen materials, and so on, will allow the nondestructive and noninvasive inspections. Our group has been conducting research activities in several directions within the THz field. We introduced the THz-wave parametric generator as a widely tunable source1, and we suggested a whole range of real-life applications. Among our research activities we can mention: i) Noninvasive detection of illicit drugs using spectral fingerprints[5]; ii) Laser-THz emission microscope for semiconductor device inspection[6]; iii) Metal mesh sensor for bio chip[7]; iv) Terahertz tomography[8,9].

Detailed information will be presented at the conference.

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References

[1] A. Dobroiu, C. Otani, K. Kawase, Meas. Sci. Tech. 17, R161 (2006).

[2] K. Suizu and K. Kawase, IEEE J. Sel. Top. Quantum Electron. 14, 295 (2008).

[3] S. Hayashi, H. Minamide, T. Ikari, Y. Ogawa, J. Shikata, H. Ito, C. Otani, and K. Kawase, Appl. Opt. 46, 117 (2007).

[4] N. Pavel, J. Saikawa, S. Kurimura, T. Taira, Jpn. J. Appl. Phys. 40 1253 (2001).

[5] K. Kawase, Y. Ogawa, Y. Watanabe and H. Inoue, Opt. Exp. 11, 2549 (2003).

[6] M. Yamashita, K. Kawase, C. Otani, T. Kiwa and M. Tonouchi, Opt. Exp. 13, 115 (2005).

[7] H. Yoshida, Y. Ogawa, Y. Kawai, S. Hayashi, A. Hayashi, C. Otani, E. Kato, F. Miyamaru, and K. Kawase, Appl. Phys. Lett. 91, 253901 (2007).

[8] J. Takayanagi, et.al., IRMMW/THz2008, California, USA (Sept. 15-19, 2008).

[9] L. Cheng, S. Hayashi, C. Otani, K. Kawase, T. Miyazawa, and Y. Ogawa, Appl. Phys. Lett. 92, 181104 (2008).