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Highly sensitive multi-stage terahertz parametric upconversion detection based on $RbTiOPO_4$ crystal

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Abstract: Highly sensitive terahertz frequency upconversion detection was demonstrated with a $RbTiOPO_4$ crystal. The detectable THz frequency ranges were 3.6-4.0, and 5.4-5.7 THz. The minimum detectable terahertz energy at 5.6 THz was about 0.2 fJ.

1. Introduction

Terahertz (THz) wave is the electromagnetic radiation whose frequency is located between the microwave region and the infrared region. It has wide applications in drug and food inspection, imaging, non-destructive testing, biomedicine, security checking, etc[1-3]. The highly sensitive, room-temperature THz detectors play an important role in the development of THz technologies. THz frequency upconversion detection, which uses a nonlinear crystal to convert the THz wave to near infrared or visible light, is an important subject in the field of THz measurement for it has the advantages of room-temperature operation, fast response, high sensitivity, and high dynamic range[4].

In the past 10 years, DAST, $MgO:LiNbO_3$ and $KTiOPO_4$ (KTP) have been used as the practical nonlinear crystal for difference frequency generation (DFG) and THz parametric process with stimulated polariton scattering (SPS) in frequency upconversion detection, and realized effective THz-wave detection[4-6]. Rubidium Titanyle Phosphate ($RbTiOPO_4$, RTP) is a highly efficient nonlinear optical crystal. It has been used in electro-optical and frequency conversion fields based on its excellent qualities such as high nonlinear coefficient and high damage threshold[7-8]. Based on the stimulated polariton scattering in it, a terahertz parametric oscillator (TPO) was constructed and the intermittently tunable THz waves from 3.01 to 3.09 THz, from 3.53 to 4.17 THz, from 4.54 to 4.66 THz, and from 5.35 to 5.89 THz were obtained[9]. Considering that the RTP crystal with excellent optical properties is beneficial to nonlinear conversion, it is interesting to study the THz detection based on the RTP parametric upconversion process.

In this study, we demonstrate highly sensitive multi-stage terahertz parametric upconversion detection from 3.6 to 4.0 THz and from 5.4 to 5.7 THz based on $RbTiOPO_4$ crystal. The minimum detectable energy of about 0.2 fJ at 5.6 THz is realized with a dynamic range of 65 dB.

2. The experimental setup of the multi-stage THz parametric upconversion detector based on RTP crystal

The experimental setup of the multi-stage THz parametric upconversion detection based on RTP crystal is shown in Figure 1. It is mainly composed of four parts: the pump source, the THz parametric generator, the THz parametric upconversion detector, and the Stokes parametric amplifier.

The pump laser was a pulsed 1064.1 nm laser with a repetition rate of 1 Hz and a pulse width of 420 ps. A telescope system was used to shrink the pump beam size to 4.0 mm. The pump laser was divided into three beams by the combination of a half wave plate (HWP) and a polarizing beam splitter (PBS), which were successively called as Pump 1, Pump 2, and Pump 3. Pump1 was used to generate broadband THz waves using a terahertz parametric generator (TPG). Pump2 was used to realize THz parametric upconversion detection, and Pump3 was used to realize Stokes parametric amplifying (SPA).

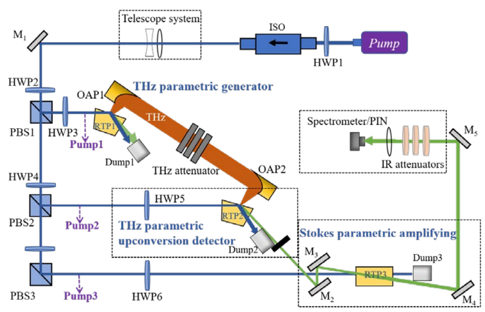

Fig. 1 The experimental setup of the multi-stage THz parametric upconversion detection based on RTP crystal.

Three RTP crystals were used in the experiment. The two RTP crystals were cut into isosceles trapezoid, in which the angle between the base and the waist was 58°. One crystal (labelled as RTP1) was used as the THz generator to generate THz waves. Another crystal (labelled as RTP2) was used to realize frequency upconversion detection by deference frequency generation between the pumping and terahertz waves. The generated THz wave can be emitted nearly vertically from the RTP1 crystal without any other couplers, and the pumping beam and the generated Stokes beam could propagate nearly vertically to the incident and exit surfaces. The THz wave was focused and injected into the RTP2 crystal through two off-axis parabolic mirrors (OAP1 and OAP2). The THz energy was attenuated by adding black polyethylene terephthalate (PET) plates between OAP1 and OAP2. The Stokes beam was further amplified in RTP3 ($4 \times 4 \times 30$ mm^3) based on optical parametric amplifying process with non-collinear phase matching. The HWP before each RTP crystal was used to guarantee that the polarization of the pumping beam to be along z axis of the nonlinear crystal.

The upconverted signal and the residual pump waves were separated by a copper garbage light collector and pieces of 1064 nm long pass edge filters. The upconverted signal spectral composition and intensity were detected by an optical spectrum analyzer (YOKOGAWA, AQ6315, 350-1750 nm) and a highly sensitive photodiode (Thorlabs, PDA05CF2), respectively.

3. Experimental results and discussion

When the energies of Pump1, Pump2 and Pump3 were 10.6 mJ, 3.0 mJ and 2.0 mJ, respectively, the generated upconverted signal spectrum could be detected by the spectrum analyzer. As shown in Figure 2(a), it included two bands: from 1078.1 to 1079.5 nm and from 1084.9 to 1086.2 nm. The center wavelengths of the two bands were 1078.8 nm and 1085.6 nm, respectively. By using a vertical slit placed in the THz optical path between OAP1 and OAP2, one wavelength could be selected.

According to the energy conservation law among the pumping, THz, and upconversion waves, the incident THz wave frequency ranges were calculated to be from 3.6 to 4.0 THz, and from 5.4 to 5.7 THz. The corresponding center frequencies were 3.8 THz and 5.6 THz, respectively.

Figure 2(b) shows the temporal profile of the upconverted signal measured by the photodiode and displayed on the oscilloscope. Due to the large sensitivity area of the detector, its response time was much larger than the pulse width, the displayed voltage would be proportional to the upconverted signal pulse energy. For different incident THz energies, the upconverted signal energies (shown as the equivalent voltage) could be calculated by using the real pulse height on the oscilloscope and the attenuation coefficient of the IR attenuator in front of the photodiode.

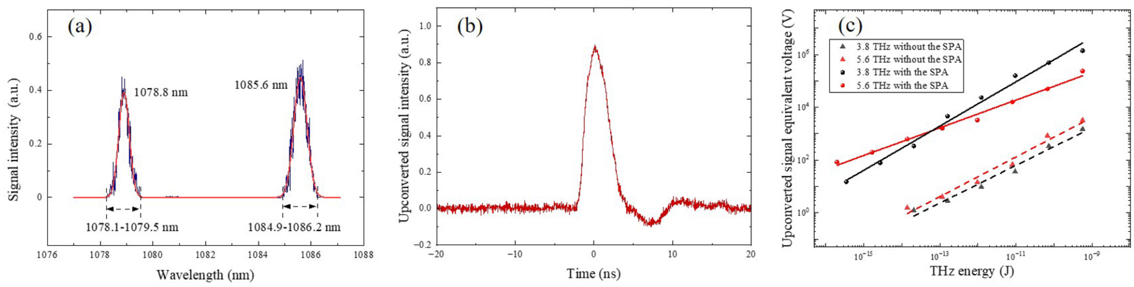

Fig. 2. (a) Spectrum of the generated upconversion signal. (b) Temporal profile of the detected upconverted signal. (c) Upconverted signal equivalent voltages as functions of the input THz energy at 4.1THz and 5.5 THz, respectively.

Figure 2(c) shows the upconverted signal equivalent voltages as functions of the input THz energy at 4.1 THz and 5.5 THz under two conditions: with and without the SPAs, respectively. The fitting curves conform to good linearity, which prove the reliability of parametric upconversion detection of the THz wave energy. Without the SPA, the detection signal beam generated from RTP2 crystal was measured, as shown in Fig. 1, the minimum detectable terahertz energy of 14 fJ at 5.5 THz was realized with the detection dynamic range of 45 dB. With the SPA, the minimum detectable terahertz energy was about 0.2 fJ, and the dynamic range reached 65 dB.

4. Summary

In conclusion, a high sensitivity multi-stage THz parametric upconversion detector based on the RTP crystal was demonstrated. The detectable THz frequency ranges were 3.6-4.0 THz and 5.4-5.7 THz. The minimum detected THz wave energy at 5.6 THz was about 0.2 fJ, and the dynamic range reached 65 dB.

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