Compact high-repetition-rate terahertz source based on difference frequency generation from an efficient 2-μm dual-wavelength KTP OPO

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ABSTRACT

A compact optical terahertz (THz) source was demonstrated based on an efficient high-repetition-rate doubly resonant optical parametric oscillator (OPO) around 2 μm with two type-II phase-matched KTP crystals in the walk-off compensated configuration. The KTP OPO was intracavity pumped by an acousto-optical (AO) Q-switched $Nd:YVO_4$ laser and emitted two tunable wavelengths near degeneracy. The tuning range extended continuously from 2.068 μm to 2.191 μm with a maximum output power of 3.29 W at 24 kHz, corresponding to an optical-optical conversion efficiency (from 808 nm to 2 μm) of 20.69%. The stable pulsed dual-wavelength operation provided an ideal pump source for generating terahertz wave of micro-watt level by the difference frequency generation (DFG) method. A 7.84-mm-long periodically inverted quasi-phase-matched (QPM) GaAs crystal with 6 periods was used to generate a terahertz wave, the maximum voltage of 180 mV at 1.244 THz was acquired by a 4.2-K Si bolometer, corresponding to average output power of 0.6 μW and DFG conversion efficiency of 4.32×10^{-7}. The acceptance bandwidth was found to be larger than 0.35 THz (FWHM). As to the 15-mm-long GaSe crystal used in the type-II collinear DFG, a tunable THz source ranging from 0.503 THz to 3.63 THz with the maximum output voltage of 268 mV at 1.65 THz had been achieved, and the corresponding average output power and DFG conversion efficiency were 0.9 μW and 5.86×10^{-7} respectively. This provides a potential practical palm-top tunable THz sources for portable applications.

Keywords: Terahertz (THz), optical parametric oscillator (OPO), difference frequency generation (DFG), gallium arsenide (GaAs), gallium selenide (GaSe)

1. INTRODUCTION

The terahertz (THz) frequency range (0.1–10 THz) is extremely attractive for many applications such as spectroscopy, imaging, communication, biomedical analysis, radar, etc. As to the THz systems that applied to the above fields, THz source with high power, narrow bandwidth and continuously tuning range is a core component. Difference frequency generation (DFG) was proposed in 1960s and developed in recent decades. The main advantages of the DFG method are simple experimental setup, wide tuning range, high peak powers, room-temperature operation, and others.

A multitude of nonlinear optical (NLO) crystals have been used such as $LiNbO_3$, PPLN, GaP, GaSe, DAST[1,2,3,4,5], in which GaSe has the high nonlinear susceptibility and low THz absorption, indicating its better fit for optical THz sources based on the DFG process. Also, microstructured NLO crystals like PPLN, periodically inverted GaP and GaAs were employed for quasi-phase-matching (QPM), and milliwatt-level THz sources were achieved, benefiting from their high nonlinear coefficients and good physical and optical characteristics. Among these crystals, periodically inverted GaAs has been recognized for some time to play an important role employed to generate coherent and tunable THz radiation because of its superior properties. Dual-wavelength ns optical parametric oscillators (OPOs) operating around 1.06 μm, 1.55 μm, 2 μm, and 10 μm have been applied into the DFG process to achieve THz sources, and in consideration of the compactness, high quantum efficiency, high average power, wide tuning range and low cost, 2 μm OPO is the best choice. In 2000, Wu *et al.*[6] demonstrated a compact 21-W 2 μm doubly resonant intracavity KTP optical parametric oscillator pumped by a linearly polarized Nd:YALO laser with a beam quality factor of M^2~18 and the efficiency from 1 μm to 2 μm of 0.037%. In 2014, Qianjin Cui *et al.*[7] reported a high-power intracavity pumped doubly resonant OPO at

Infrared, Millimeter-Wave, and Terahertz Technologies IV, edited by Cunlin Zhang, Xi-Cheng Zhang, Masahiko Tani, Proc. of SPIE Vol. 10030, 100301Q · © 2016 SPIE
CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2245692

2 μm with single-type II phase-matched KTP, average output power of 70-W with the repetition rate of 5 kHz, the efficiency from 1 μm to 2 μm of 10%. And walk-off compensated dual-wavelength KTP OPO near the degenerate point of 2.128 μm pumped by a Nd:YAG pulsed laser has been employed as the pump for THz source based on DFG[8] which was modulated by an electro-optic Q-switch.

In this letter, a compact high efficiency 2 μm laser at the repetition rate of 24 kHz was obtained from a doubly resonant KTP OPO which intracavity pumped by a linearly polarized Q-switched $Nd:YVO_4$ laser. The output power can reach 3.29 W with the efficiency of 20.69% when increasing the 808 nm pump power to 15.9 W, corresponding pulse width is 4.6 ns. The efficiency of 25.49% obtained is the highest ever achieved from 808 nm to 2 μm within KTP OPO so far as we know, when the pump power of 8.5 W and the average output power of 2.167 W. When using QPM-GaAs, the terahertz frequency can cover the range of 1.006-1.456 THz with the maximum output THz voltage of 180 mV at 1.244 THz, corresponding to average output power of 0.6 μW and DFG conversion efficiency of 4.32×10^{-7}. As to the 15-mm-long GaSe crystal used in the type-II collinear DFG, a tunable THz source ranging from 0.503 THz to 3.63 THz with the maximum output voltage of 268 mV at 1.657 THz had been achieved, and the corresponding average output power and DFG conversion efficiency were 0.9 μW and 5.86×10^{-7} respectively.

2. EXPERIMENTAL SETUP AND RESULTS

2.1 Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup. Seeing in the Fig. 1(a), 808 nm laser diode (LD) used as the fundamental pump laser that was focused into a $Nd:YVO_4$ crystal by a 1:1 coupling lens. The laser cavity is formed by a $Nd:YVO_4$ crystal (3mm×3 mm×10mm in size), an acoustic-optical Q-switch, a plane-concave (300 mm radius of curvature) input mirror M1 and a flat mirror M3. Both side surfaces of the $Nd:YVO_4$ crystal are flat and anti-reflection (AR) coated at 1064 nm with 808 nm. The input mirror M1 is coated for anti-reflectivity of 808 nm and high reflectivity of 1064nm on its each side face. Twin KTP crystals are mounted inside an OPO resonator with mirrors M2 and M3. Mirrors M1, M2 and M3 are all the same size of Dia. $20\times3mm^3$. One side surface of M2 is anti-reflection coated at 1064 nm (R<0.2%), the other is high-reflection (HR) coated at 2000 nm~2300 nm (R>99.5%) and anti-reflection coated at 1064 nm (T>95%). Output coupler M3 is a sapphire mirror with reflectivity of 99.8% at 1064 nm and transmittance of 25+/-5% in the range of 2000~2300 nm. The KTP crystals with the same dimensions 7mm×8mm×15mm have a cut angle of θ=51.5° and φ=0°, which are antireflection coated on both faces for 2000~2300nm and tuned in the x-y plane to achieve type-II (o→e+o) phase matching. The laser and OPO cavity are only 153 mm and 73 mm in length respectively.

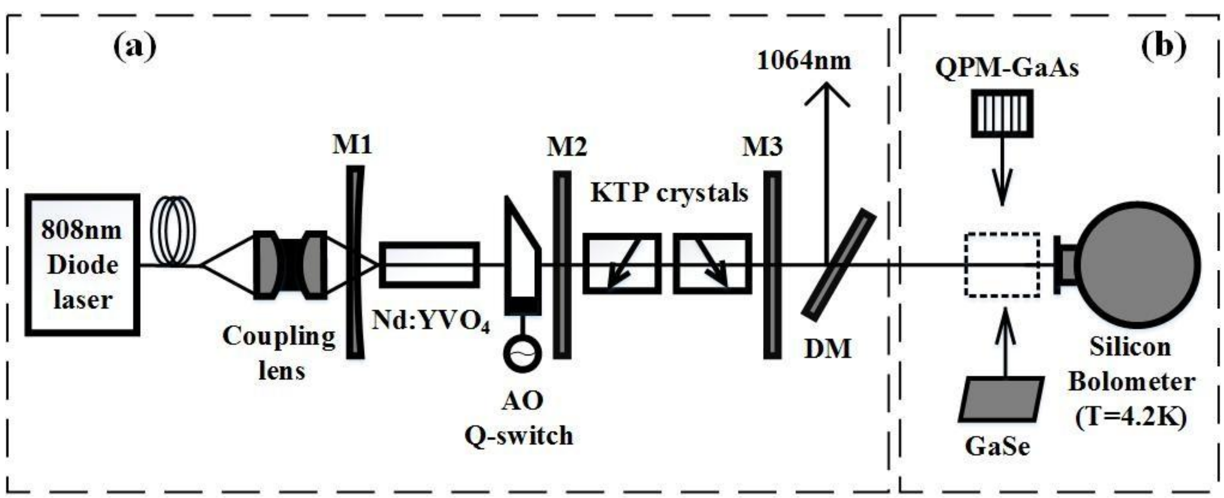

Figure 1. Experimental setup for THz DFG system. (a) is the part of dual-wavelength KTP OPO and (b) is the part of THz generation based on QPM-GaAs/GaSe crystals.

A dichromatic mirror DM (HR at 1.06 μm and AR at 2.0-2.3μm) was used to filter the residual fundamental laser, and the dual-wavelength laser was incident into QPM-GaAs/GaSe crystals for DFG without focusing. The QPM-GaAs was 7.84-mm long with 6 periods, manufactured from 12 (110) plates alternately rotated one by one, stacked and diffusion-bonded together. Comparing to our previous work, a longer GaSe crystal with 15 mm was used. The generated THz wave was detected by a 4.2-K Si bolometer (calibrated to 2.89×10^5 V/W) after an optical chopper.

2.2 KTP OPO

We have invested the properties of the Nd:YVO_4 laser and KTP OPO, and characteristics of the 1.06 μm and 2 μm lasers were illustrated in Fig. 2. If remove the mirror M3, KTP crystals, and replace the mirror M2 by a 12.4% output coupler (OC) at 1064 nm, the average output power of Nd:YVO_4 laser could reach to 9.59 W and 6.41 W, corresponding to the continuous wave (cw) and pulse wave respectively. Benefiting from the Nd:YVO_4 crystal, the fundamental laser was polarized along the vertical direction and can be applied to the type-oeo OPO. Seeing in Fig. 2, the OPO threshold almost coincides with the laser threshold. Two KTP crystals can compensate the walk-off effect and increase the acceptance angle for the non-linear interaction, and symmetrically angle-tuning of the double KTP crystals can establish different phase matching (PM) leads to the continuously changing of wavelengths at 2 μm. The maximum output power of 2 μm laser could reach to 3.29 W with efficiency of 20.69%. Under consideration of peak power, average power, optical-optical conversion efficiency and beam quality, we chose 24 kHz as the optimal repetition rate. The highest efficiency of 25.49% obtained when the 808 nm pump power increased to 8.5 W and the output power of 2.167 W. When normal incident into KTP crystals without angle tuning (θ=51.5° and φ=0°), the acquired signal wavelength (2162 nm) and idler wavelength (2096 nm) were polarized along horizontal and vertical direction respectively. Symmetrically tuning the PM angle of the two KTPs from 50.79° to 51.95° (internal PM angle), the dual-wavelength laser could be tuned to cover the range from 2.068 μm to 2.191 μm, in frequency intervals from 0 to 8 THz. Degeneracy occurred at a PM angle of 50.98°. The temporal pulse shape of the KTP OPO was detected by a fast response InGaAs PIN detector (EOT ET-5000), and the pulse width was found to be around 4.6 ns, much narrower than that of the fundamental laser of 24 ns. As the two wavelengths are close to each other and came from the same DRO cavity, the timing jitter of the dual-wavelength laser was negligible. The M^2 values of 3.1797 (vertical) and 6.4117 (horizontal) were measured by using the knife-edge method, and corresponding beam waist radius are 1.1194 mm and 1.8426 mm.

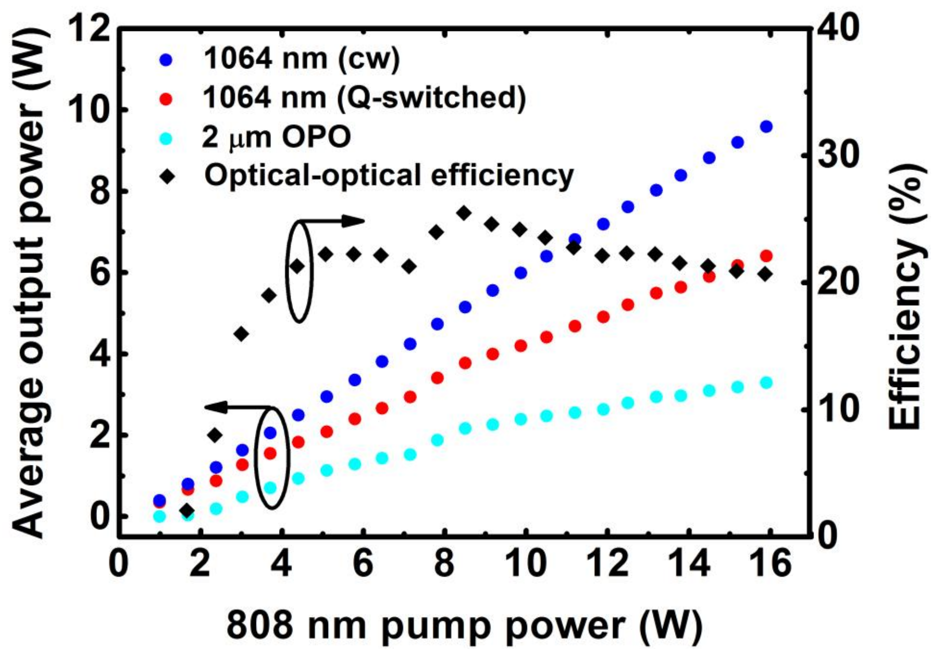

Figure 2. Output characteristics of the Nd:YVO_4 laser and KTP OPO

2.3 QPM-GaAs

We use this dual-wavelength KTP OPO to pump a QPM-GaAs crystal to generate THz in a difference frequency system (type oe→e), the configuration was shown in Fig. 1(b). A dichroic mirror (DM) high-reflection coated at 1064 nm and anti-reflection coated at 1.8~2.5μm is used to reflect off the 1064 nm wave before the dual-wavelength laser pulses are injected into the nonlinear crystal. Usually, there are three types of micro-structured GaAs involved in QPM condition: optically contacted, orientation-patterned (OP), and diffusion-boned (DB) GaAs. We use the diffusion-boned (DB) GaAs in the experiment. The DB-GaAs samples for the optical THz DFG with length of 7.84 mm and 6 periods. The liquid-helium-cooled silicon bolometer is placed close to QPM-GaAs crystal, and the residual pump beams at 2μm are blocked by a 1-mm-thick germanium (Ge) wafer with HR coatings from 2.0-2.3 μm and a 1-mm-thick black polyethylene (PE) wafer that were attached to the entrance window of the detector. An optical chopper (Stanford Research Systems, SR540) was used to modulate the high-repetition-rate signal to 40 Hz before detection. When the fundamental 1.06 μm laser beam was normal incident, that is KTP crystals with a cut angle of 51.5°, the signal wavelength of 2162 nm and idler wavelength of 2096 nm were acquired respectively. For the sake of acquiring the appropriate wavelengths involved in the DFG, the angle has to be tuned smaller. So the average pump power of 2 μm radiations could not reach 3.29 W when pumping QPM-GaAs crystal, because the increasing of Fresnel reflection loss and instability of the cavity caused by the angle tuning. The maximum output voltage of 180.8 mV was acquired at 1.244 THz (signal wavelength = 2138.4 nm, idler wavelength = 2119.6 nm). The full width half maximum (FWHM) frequency band was about 0.35 THz.

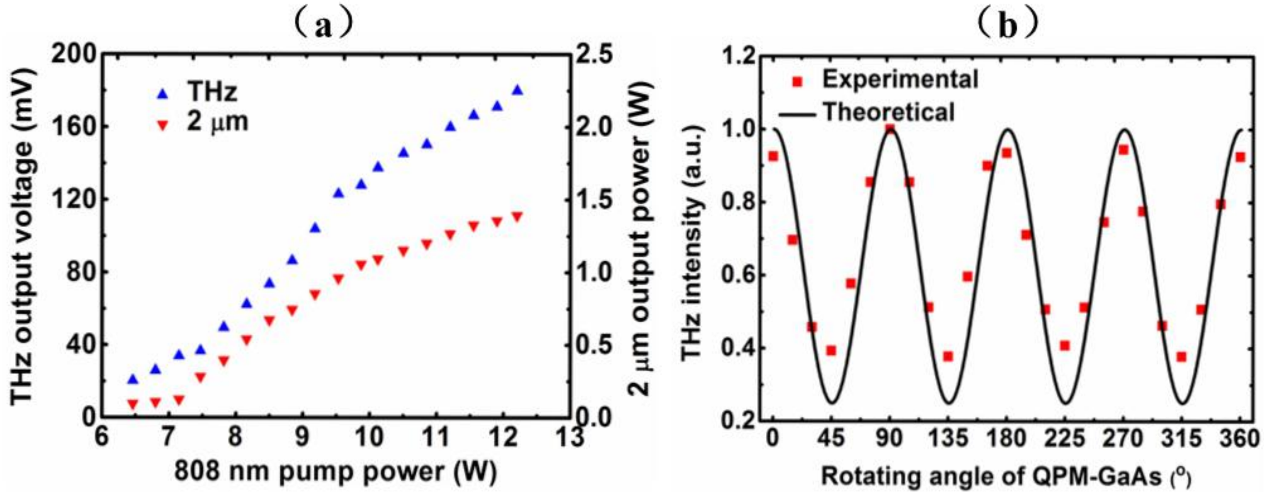

Figure 3. (a) THz output voltage and 2-μm output versus LD pump power; (b) Normalized THz output voltage while rotating QPM-GaAs in the (110) plane.

The output voltage of the bolometer along with the incident dual-wavelength power versus LD pump power at 808 nm is shown in Fig. 3(a). According to Ref. [9], the generated THz wave should be along the [001] direction. In other words, it should have the same polarization as the 2138.4-nm pump laser (or is perpendicular to the fundamental laser) to access the maximum effective nonlinear coefficient. For crystal rotation in the (110) plane, the generated THz field should vary with the azimuth angle between the [001] axis and the pump polarization of either of the two pump wavelengths. Therefore, the normalized DFG efficiency goes as $\cos(4\theta)$. The experimental results for normalized output voltage together with the theoretical calculation are shown in Fig. 3(b), demonstrating good agreement.

2.4 GaSe

Then based on the same configuration of 2 μm KTP OPO, a 15-mm-long GaSe crystal with an effective aperture about Ø=16 mm replaced QPM GaAs that was employed in the DFG process. Two surfaces of the GaSe crystal were uncoated with AR film. In order to use the maximum effective nonlinear coefficient, we set that $\varphi=0°$. When the dual-wavelength OPO was turned in the range of 2132.9-2156.6 (e-wave) and 2101.8-2125.3 nm (o-wave), we could rotate the GaSe crystal in the x-z plane to meet different PM conditions. The terahertz waves ranging from 82.7 μm (3.63 THz) to 596.5

μm (0.503 THz) was achieved under the type-oee collinear DFG. Comparing to the type-oeo, the type used in the experiment has a smaller walk-off angle. Fig. 4(a) shows the THz output voltage at different THz frequencies. The maximum output voltage of 268 mV at 1.657 THz was achieved, and the corresponding average output power and DFG conversion efficiency were 0.9 μW and 5.86×10^{-7} respectively. The THz frequency and wavelength versus the PM angle were also illustrated in Fig. 4(b).

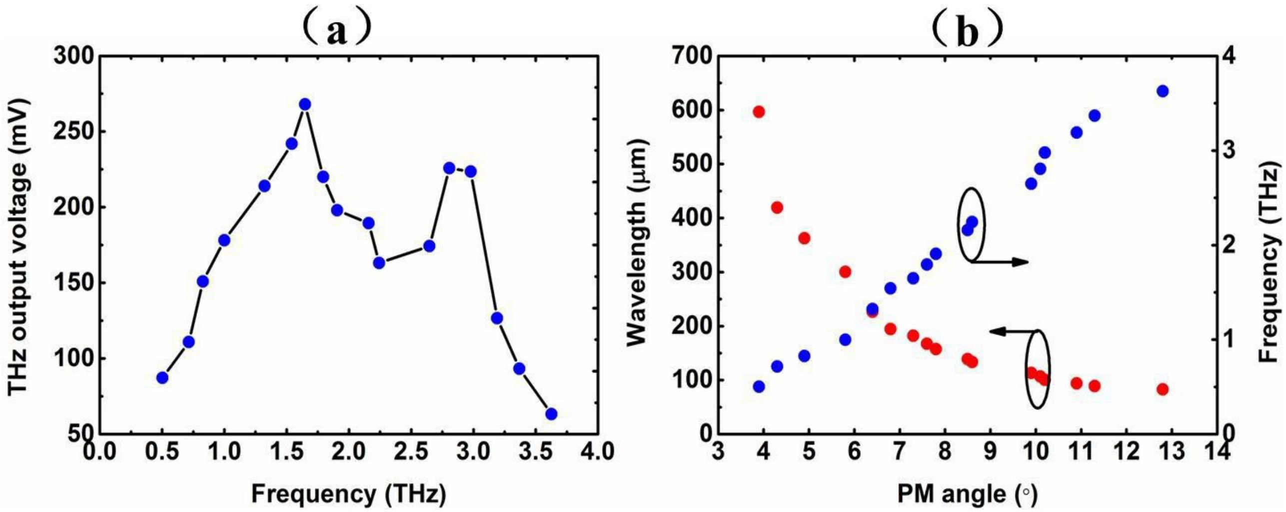

Figure 4. (a) THz output voltage at different frequencies; (b) THz wavelength and frequency versus the PM angle.

THz time-domain spectroscopy (TDS) was used to measure the properties of the 15-mm-long GaSe used in the experiment, and the absorption coefficient was shown in Fig. 5. Limited by the THz TDS system, the range of THz frequency can only cover the range from 0 THz to 2 THz. We can also see that absorption coefficient decreased around 1.65 THz which is consistent with experimental results.

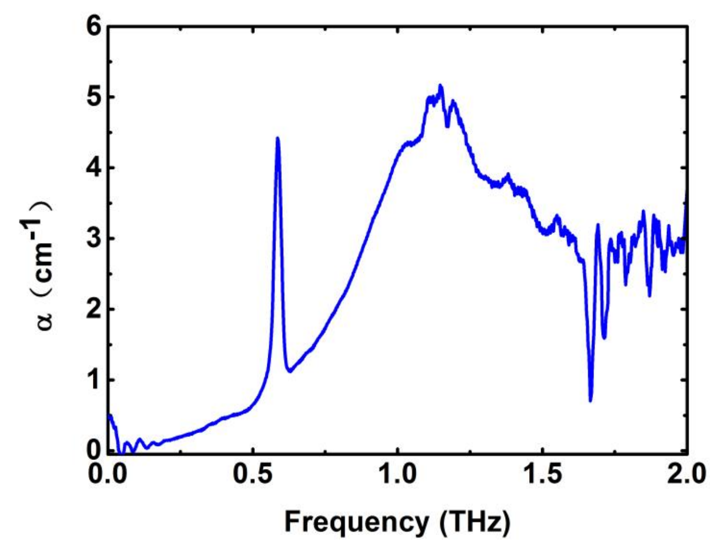

Figure 5. Absorption coefficient for the 15 mm-long GaSe crystal in the experiment

3. SUMMARY

In conclusion, we have demonstrated a THz difference frequency generation system based on QPM-GaAs/GaSe crystal by using a high efficiency degenerate intracavity 2 μm KTP OPO with the repetition rate of 24 kHz as the pump source. The tuning range extended continuously from 2.068 μm to 2.191 μm with a maximum output power of 3.29 W at 24 kHz, corresponding to an optical-optical conversion efficiency (from 808 nm to 2 μm) of 20.69 %. The highest efficiency of this dual-wavelength walk-off compensated 2μm KTP OPO can reach to 25.49% (average output power of 2.167 W and pump power of 8.5 W). The M^2 values for 2 μm are 3.1797 (vertical) and 6.4117 (horizontal). When using the QPM-GaAs, the maximum THz output voltage of 180.8 mV is obtained at signal wavelength of 2138.4 nm and idler wavelength of 2119.6 nm with narrow line-width (< 2 nm), the corresponding average power of 0.6 μW and DFG conversion efficiency of 4.32×10^{-7}. When replaced the QPM-GaAs by a 15-mm-long GaSe crystal, a tunable THz source ranging from 0.503 THz to 3.63 THz with the maximum output voltage of 268 mV at 1.65 THz was achieved, and the corresponding average output power and DFG conversion efficiency were 0.9 μW and 5.86×10^{-7} respectively. These compact high-repetition-rate tunable terahertz sources can be used in the portable applications, such as imaging and spectroscopy.

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