Research on Terahertz Generation Based on Cherenkov-Type Difference Frequency

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Abstract: In this paper, we report a new method of highly efficient terahertz generation based on Cherenkov-type cavity phase matching cascade difference frequency. The influence of different temperature, crystal length, pump light inversion times and reflectivity on the power conversion efficiency of terahertz wave emitted along Cherenkov angle is analyzed. Our theoretical calculation shows that the highest terahertz photon conversion efficiency reach to 443.6%. Compared with the cavity phase matching technology, the Cherenkov effect introduced in the preparation of terahertz sources is a new idea, which is expected to develop efficient terahertz sources.

1 INTRODUCTION

Terahertz wave is an electromagnetic wave with a wavelength ranging from 0.03 to 3 mm. It contains rich physical and chemical information when interacting with substances. In recent years, terahertz sources have been widely used in radar, medical diagnosis, safety inspection, broadband communication, electromagnetic weapons, non-destructive testing and other fields (Wang R-H. Tanoto). Among many methods of generating terahertz source wave, nonlinear optical method has the advantages of wide tuning, compact structure, no threshold and easy realization, which has attracted more and more attention (He Y-Ravi K).Using two infrared lasers with similar wavelengths to conduct frequency difference in nonlinear crystals is a common method to obtain terahertz wave radiation sources. As early as 1965, since the birth of the laser, Zernike and Berman (F. Zernike, 1965) have started to use neodymium glass lasers to conduct frequency difference through quartz crystals to obtain terahertz wave output with a frequency of 3 THz (100 μ m), but the output efficiency at that time was extremely low. In 2005, S.Y. Tochisky et al. used a CO_2 laser with a pulse width of 250 ps to conduct non-collinear frequency difference on GaAs crystal (S. Y. Tochitsky, 2005).In 2007, they used a CO_2 laser with a pulse width of 200 ns to conduct non-collinear differential frequency on GaAs crystals at room temperature, and obtained terahertz wave output in the range of 0.5-3.0 THz, with a peak power of 2 kW (S. Y. Tochitsky, 2007) .In 2008, Stokes light and anti Stokes light were detected in the experiment, confirming the cascade process (Schaar J E, 2008).In 2011, the team of Tianjin University pumped the periodically inverted GaAs crystal by picosecond pulse, generated narrowband THz wave by differential frequency technology, and analyzed the coupling distance of pump light in GaAs crystal and the data under different parameters of the optimal inversion period length of nonlinear crystal (Zhang Chengguo, 2011).In 2011, Vodopyanov K. L. et al. used 11 and 15 layers of GaAs chips to form a "period reversal chip stack", and achieved terahertz wave output with an average power of 200 μw in the ring resonator v (Vodopyanov K L, 2011).In 2015, Kyosuke Saito et al. described a method for efficient terahertz generation, which uses the total reflection of the laser at both ends of the sheet Fabry Perot (F-P) microcavity to compensate for phase mismatch, known as "cavity phase matching" (CPM) (SAITO K, 2015).

In recent years, the Cherenkov phase matching method in terahertz radiation sources has been proposed. Cherenkov phase matching has high conversion efficiency and wide tuning, which can automatically realize phase matching and effectively overcome the frequency difference of nonlinear crystals in optical and terahertz bands. The phase matching condition satisfies any angle of the pump light path (P. A. Cherenkov, 1934). Koji Suizu et al. demonstrated the generation of Cherenkov type

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terahertz wave using organic DAST crystal and Si prism coupler prism coupling (Suizu K, 2021). In 2012, Karun et al. reported the method of generating terahertz radiation using dual-wavelength quantum cascade lasers (QCL) based on Cherenkov phase matching at room temperature (Vijayraghavan K, 2012). At present, the method of realizing terahertz wave source based on Cherenkov phase matching needs to be further explored, and there is still much room for development of this method to generate terahertz radiation (Juntao Huang, 2019).

This paper studies the process of generating efficient terahertz wave by cavity phase matching difference frequency of GaAs cavity based on Cherenkov-type. The angle between the generated terahertz wave direction and the cavity phase matching generated terahertz wave direction is Cherenkov angle. The formula of power conversion efficiency of terahertz wave emitted along Cherenkov angle is obtained through calculation. Considering the influence of temperature, pump inversion times, crystal length and reflectivity, terahertz photon conversion efficiency is compared by numerical simulations. The terahertz source prepared by this method is simple and efficient, and will have great application prospects.

2 CASCADE FREQUENCY DIFFERENCE PRINCIPLE OF CHERENKOV EFFECT CAVITY PHASE MATCHING

The frequency difference process is influenced by many factors. Such as working conditions, working temperature, pump photon energy, and crystal body growth technology, etc. The schematic diagram of cascade frequency difference method is shown in the figure 1.

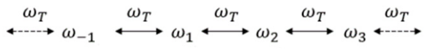

Fig. 1. Schematic of cascade DFG.

The cascade process includes Stokes light and anti Stokes light. High-frequency pump light ω_1 is consumed while low-frequency pump light ω_2 interaction is amplified to generate terahertz photons frequencyω_T. This process is called Stokes process, which will generate Stokes light. The amplified low-frequency pump light ω_2 acts as the high-frequency pump light of the second differential frequency, and it interacts with the terahertz photon differential frequency to produce the low-frequency pump light ω_3 in the second differential frequency process. By analogy, the cascade frequency difference process can generate multiple terahertz photons. At the same time, the anti Stokes process consumes terahertz photons to generate high-frequency pump light ω_{-1}. Each Stokes process will produce terahertz photons, while the anti Stokes process will also consume terahertz photons. However, the anti Stokes process is always weaker than the Stokes process, which eventually leads to the generation of terahertz waves.

Cherenkov phase matching is a method with high energy output efficiency and wide tunability. The phase matching conditions during the Cherenkov phase matching process automatically meet any angle of the pump laser path. The structure diagram of THz wave generation based on Cherenkov effect cavity phase matching cascade differential frequency is shown in Fig. 2.

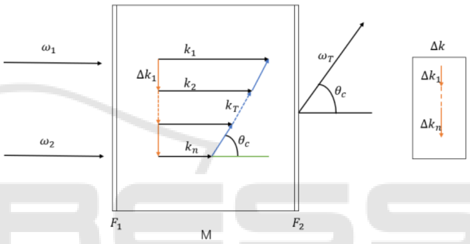

Fig. 2. Schematic of terahertz generation by cascade DFG based on Cherenkov effect CPM.

F1 and F2 are two optical dielectric mirrors, and M is the working medium. The collinear pump light frequency ω_1 and ω_2 enter the cavity from the left cavity mirror F1, and performs cascade differential frequency through M to generate terahertz wave and propagate to the right cavity mirror F2.In this paper, Cherenkov angle θ_c is introduced based on the principle of Cherenkov effect cavity phase matching cascade frequency difference.

3 THEORETICAL ANALYSIS OF TERAHERTZ CONVERSION EFFICIENCY

Terahertz wave generated by cascade frequency difference is accumulated and emitted in the direction of angle θ_c and automatically meets the phase matching condition.The three wave coupling equation as follow (Zhi-ming Rao, 2011).

$$\frac{dE_1}{dx} = \frac{i\omega_1}{cn_1}\frac{d_{eff}}{2\varepsilon_0}E_2E_Te^{(-i\Delta Kx)} \tag{1}$$

$$\frac{dE_2}{dx} = \frac{i\omega_2}{cn_2}\frac{d_{eff}}{2\varepsilon_0}E_1E_T{}^*e^{(i\Delta Kx)} \tag{2}$$

$$\frac{dE_T}{dx} = \frac{i\omega_3}{cn_3}\frac{d_{eff}}{2\varepsilon_0}E_1E_2{}^*e^{(i\Delta Kx)} \tag{3}$$

Effective nonlinear coefficient d_{eff} as follow (Z.D.Xie, 2011),

$$d_{eff} = d \cdot \left|\sin\left(\frac{\pi}{2}\frac{l_{cav}}{l_{coh}}\right)/\left(\frac{\pi}{2}\frac{l_{cav}}{l_{coh}}\right)\right| \tag{4}$$

Where c is the speed of light, E_1, E_2, E_T are electric field intensity of pump light frequency ω_1 and ω_2, and THz wave respectively.d is the second-order nonlinear coefficient of the nonlinear working medium M , $l_{coh}$is Coherent length, ε_0 is vacuum dielectric constant, n_1, n_2, n_T are refractive index on working medium M of pump light frequency ω_1 and ω_2, and THz wave respectively.

Cherenkov angle θ_c meets the conditions (Juntao Huang, 2019),

$$\cos\theta_c = \frac{\lambda_T(k_1-k_2)}{2\pi n_T} \tag{5}$$

where nT is the refractive index in the THz range and λT is the wavelength of the THz wave in the DFG process.

When there is no cascade, consider the destructive interference between the pump light outside the left side cavity. The pump energy is expected to be retained in the cavity by considering the destructive interference that can be expressed by (Shijia Z, 2020):

$$\sqrt{R_1}E_{01} - \sqrt{T_1}\sqrt{\frac{n_1}{n_{01}}}E_1 = 0 \tag{6}$$

$$\sqrt{R_2}E_{02} - \sqrt{T_2}\sqrt{\frac{n_2}{n_{02}}}E_2 = 0 \tag{7}$$

Where, $E_{01}$and E_{02} are the amplitudes of the two pump beams outside the cavity respectively. Rj and Tj (j = 1,2) are, respectively, the reflectances and transmittances of F1 for the two pump lasers. n1and n2 are the refractive index of crystal in the cavity for frequency ω_1 and ω_2, respectively. n01 and n02 are, respectively, the refractive index of frequency ω_1 and ω_2 in the air. According to wave equation,

$$\nabla^2\overrightarrow{E_T} + (k_3{}^2)\overrightarrow{E_T} = \frac{1}{\varepsilon_0 c^2}\frac{\partial^2}{\partial t^2}\left(2\varepsilon_0 d_{eff}E_1e^{-i(k_1x-\omega_1t)}.E_2e^{-i(k_2x-\omega_2t)}\right) \tag{8}$$

Replace E_T with,

$$\overrightarrow{E_T} = E_B.e^{-i(\Delta k_1)x} \tag{9}$$

Phase mismatch $\Delta k_1$is given by,

$$\Delta k_1 = k_1 - k_2 - k_T \cdot \cos\theta_c - \frac{\pi}{L_c}. \tag{10}$$

Amplitude E_B of THz wave generated by difference frequency as follow,

$$E_B = -\frac{2\mu_0\varepsilon_0\omega_3^2d_{eff}}{k_T^2-(\Delta k)^2}\cdot E_1E_2 \tag{11}$$

According to the boundary conditions observed in the waveguide propagation process,

$$\begin{cases} E_{T1} + E_B = -(E_{T2} + E_B) \\ E_{T2}e^{-ik_TL} + E_Be^{-ik_BL} = -\sqrt{R_T}(E_{T1}e^{ik_TL} + E_Be^{ik_BL}) \end{cases}. \tag{12}$$

Where, $k_B = k_1 - k_2$,

$$E_{1T} = -\frac{2\mu_0\varepsilon_0\omega_T^2d_{eff}}{k_T^2-(\Delta k_1)^2}\cdot E_1E_2\cdot\frac{2e^{i\Delta k_1L}-1-e^{i2\Delta k_1L}}{e^{i\Delta k_1L}(\sqrt{R_T}-1)}. \tag{13}$$

Terahertz photon conversion efficiency η_{1T} as follow,

$$\eta_{1T} = \frac{P_{1T}}{P_1}. \tag{14}$$

$$\eta_{1T} = \frac{8(2\pi)^4d_{eff}{}^2L^4n_TR_1R_2n_{01}n_{02}P_2}{\varepsilon_0c\lambda_T{}^4T_1T_2n_1^2n_2^2(2n+1)^2\left(\sqrt{R_T}-1\right)^2A\cos^2\theta_c}. \tag{15}$$

When cascading effects generation, the horizontal forward propagation amplitude E_{nT} of the terahertz wave generated by the n-order connected differential frequency as follow,

$$E_{nT} = -\frac{2\mu_0\varepsilon_0\omega_T^2d_{eff}}{k_n^2-(\Delta k_n)^2}\cdot E_1E_2\cdot\frac{2e^{i\Delta k_nL}-1-e^{i2\Delta k_nL}}{e^{i\Delta k_nL}(\sqrt{R_T}-1)}. \tag{16}$$

Phase mismatch Δk_n is given by,

$$\Delta k_n = k_n - k_{n+1} - k_T\cdot\cos\theta_c - \frac{\pi}{L_c}. \tag{17}$$

Horizontal forward propagation amplitude of all cascaded THz waves is as follow,

$$E_{RT} = E_{1T} + \cdots + E_{nT}. \tag{18}$$

When cascading effects occur, n-order terahertz photon power conversion efficiency η_T is given by,

$$\eta_T = \eta_{1T} + \cdots\eta_{nT}. \tag{19}$$

4 FACTORS EFFECTING CONVERSION EFFICIENCY

The calculated results show that two CO2 laser lines (9.5524 μm(9P(20), λ_1), 9.7937 μm(9P(46), λ_2)) can approximately meet Eqs.(19) when $k_3L \approx 14\pi$. For two pump powers $P_1 = P_2 = 100kW$, and $A = 1mm^2$, the change curve of terahertz photon conversion efficiency under different parameters is as follows.

4.1 The Influence of Environment Temperature for the Conversion Efficiency

The refractive index of working medium GaAs is given by (Skauli T, 2003):

$$n^2(\lambda) = b + \frac{g_1}{b_1^{-2} - \lambda^{-2}} + \frac{g_2}{b_2^{-2} - \lambda^{-2}} + \frac{g_3}{b_3^{-2} - \lambda^{-2}}$$

where $\Delta T = T{-}22$ °C indicates the deviation of the actual temperature to the room temperature as used in the calculations above, and parameter values of GaAs dispersion equation is shown on table 1.

Table 1: parameter values of GaAs dispersion equation.

b	5.372514
b_1(μm)	$0.4431307+0.000050564\Delta T$
b_2(μm)	$0.8746453+0.0001913\Delta T-4.882\times10^{-7}\Delta T^2$
b_3(μm)	$36.9166-0.011622\Delta T$
g_1	27.83972
g_2	$0.031764+4.350\times10^{-5}\Delta T+4.664\times10^{-7}\Delta T^2$
g_3	0.00143436

The effect of changing temperature on the power conversion efficiency is illustrated in Fig. 3.

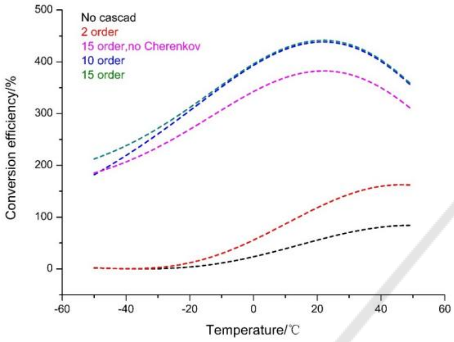

Fig. 3. Relationship between terahertz photon conversion efficiency and temperature.

It can be seen from Fig. 3 that with the increase of temperature, the terahertz photon conversion efficiency of the 10-order and 15-order couplets first increased and then gradually decreased, and the gap gradually narrowed. The 15-order couplets reached the maximum value of 443.6% at 22℃, while the terahertz photon conversion efficiency of the 15th class couplets without Cherenkov was only 382.5%.

4.2 The Influence of Crystal Length for the Conversion Efficiency

The relationship between terahertz photon conversion efficiency and crystal length is shown in Fig. 4. The crystal length variation range is 700-800 μm. It can be seen from Fig. 4 that as the crystal length increases, the terahertz photon conversion efficiency increases to the highest point and then decreases. In this range, the maximum terahertz photon conversion efficiency of the 15-order junction can reach 443.6%. At this time, the crystal length is 758 μm. The maximum terahertz photon conversion efficiency of the 15-order junction without Cherenkov is 384.3%. The highest terahertz photon conversion efficiency is 81.3% when there is no cascade, and the 15 order cascade has increased 4.5 times compared with the cascade.

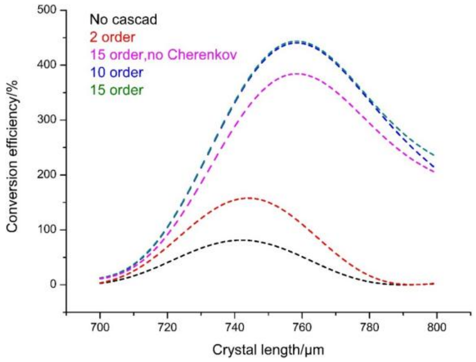

Fig. 4. Relationship between terahertz photon conversion efficiency and crystal length

5 CONCLUSION

In this paper, the process of generating high efficiency terahertz by using Cherenkov based GaAs cavity phase matching cascaded differential frequency is theoretically analyzed, and the principle of cavity phase matching based on Cherenkov is introduced. The two pumping beams frequency ω_1 and ω_2 act nonlinearly in the cavity, and each Stokes process will generate terahertz photons.

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REFERENCES

Wang R, Deng B, Qin Y, et al. Bistatic Terahertz Radar Azimuth-Elevation Imaging Based on Compressed Sensing. *IEEE Transactions on Terahertz Science & Technology*, 2017, 4(6):702-713.

Kai-Erik Peiponen, Prince Bawuah, Mousumi Chakraborty, Mikko Juuti, J. Axel Zeitler, Jarkko Ketolainen. Estimation of Young's modulus of pharmaceutical tablet obtained by terahertz time-delay measurement, *International Journal of Pharmaceutics*, 2015, 489: 100-105.

Liu. W, Li. C, Sun. ZY, Zhang, QY. Fang. GY, Three-dimensional sparse image reconstruction for terahertz surface layer holography with random step frequency, *Optics Letters*, 2015, 40(14):3384-3387.

N. V. Vvedenskii, A. L. Korytin, V. A. Kostin, A. A. Murzanev, A. A. Silaev, and A. N. Stepanov. Two-color

Laser-plasma generation of terahertz radiation using a frequency-tunable half harmonic of a femtosecond pulse. *Physical Review Letters*, 2014, 112: 055004.

Atsushi Nakanishi, Shohei Hayashi, Hiroshi Satozono and Kazuue Fujita. Spectroscopic Imaging with an Ultra-Broadband (1–4 THz) Compact Terahertz Difference-Frequency Generation Source. *Electronics*, 2021, 10, 336.

Nemec. H, Zajac. V, Kuzel. P, Maly. P, Gutsch. S, Hiller. D, Zacharias. M, Charge transport in silicon nanocrystal superlattices in the terahertz regime. *Phys. Rev. B*, 2015, 91:195443.

R.A. Motiyenko, B. Tercero, J. Cernicharo, L. Margul. Rotational spectrum of formamide up to 1 THz and first ISM detection of its vibrational state. *Astronomy and Astrophysics*, 2012, 548:A71.

H. Tanoto, J.H. Teng, Q.Y. Wu, et al. Greatly enhanced continuous-wave terahertz emission by nano-electrodes in a photoconductive photomixer. *Nature Photonics*, 2012, 6: 121-126.

He Y, Wang Y, Xu D , et al. High-energy and ultra-wideband tunable terahertz source with DAST crystal via difference frequency generation. *Applied Physics B*, 2018, 124(1):16.

Liu P, Zhang X, Chao Y, et al. Widely tunable and monochromatic terahertz difference frequency generation with organic.crystal 2-(3-(4-hydroxystyryl)-5, 5-dime-thylcyclohex-2-enylidene) malononitrile. *Applied Physics Letters*, 2016, 108(1): 621-629.

Ravi K, Schimpf D N, Franz X. Kärtner. Pulse sequences for efficient multi-cycle terahertz generation in periodically poled lithium niobate. *Optics Express*, 2016, 24(22):25582.

F. Zernike, P. R. Berman. Generation of Far Infrared as a Difference Frequency. Phys. Rev. Lett., 1965, 15(26): 999-1004

S.Y.Tochitsky, J.E.Ralph, C.Sung, et al. Generation of megawatt-power terahertz pulses by noncollinear difference-frequency mixing in GaAs. *J. Appl. Phys.*, 2005, 98(2): 26101

S. Y. Tochitsky, C. Sung, S. E. Trubnick, et al. High-power tunable, 0.5-3 THz radiation source based on nonlinear difference frequency mixing of CO$_2$ laser lines. *J. Opt. Soc. Am. B*, 2007, 24(9): 2509-2516

Schaar J E,Vodopyanov K L,Kuo P S,et al. Terahertz Sources Based on Intracavity Parametric Down-Conversion in Quasi-Phase-Matched Gallium Arsenide. *IEEE Journal of Selected Topics in Quantum Electronics*, 2008, 14(2): 354-362.

Zhang Chengguo, Study on terahertz radiation generated by optical difference frequency (D) Tianjin University, 2011

Vodopyanov K L, Hurlbut W C, Kozlov V G, Photonic THz generation in GaAs via resonantly enhanced intracavity multispectral mixing (J). *Appl.Phys. Lett.*2011, 99, 041104

SAITO K, TANABE T, OYAMA Y. Cascaded terahertz-wave generation efficiency in excess of the Manley–Rowe limit using a cavity phase-matched optical parametric oscillator. *Journal of the Optical Society of America B*, 2015, 32(4): 617-621.

P. A. Cherenkov. Visible glow of pure liquids under γ-irradiation. Dokl. *Akad. Nauk SSSR* 1934, 2, 451.

Suizu K, Shibuya T, Uchida H, et al. Prism-coupled Cherenkov phase-matched terahertz wave generation using a DAST crystal. *Optics Express*, 2010, 18(4):3338-3344.

Vijayraghavan K, Adams R W, Vizbaras A, et al. Terahertz sources based on Cherenkov difference-frequency generation in quantum cascade laser (J). *Appl.Phys. Lett.* 2012, 100, 2511044

Juntao Huang, Zhiming Rao, Fangsen Xie. Cascaded DFG via quasi-phase matching with Cherenkov-type PPLN for highly efficient terahertz generation, *Optics Express*, 2019, 27(12):17199-17208.

Zhi-ming Rao, Xin-bing Wang, Yan-Zhao Lu, et al. Two Schemes for Generating Efficient Terahertz Waves in Nonlinear Optical Crystals with a Mid-Infrared CO2 Laser(J).*Chin. Phys. Lett.*, 2011, 28(7).176-179

Z. D. Xie, X. J. Liu, Y. H. Liu, et al. Cavity phase matching via an optical parametric oscillator consisting of a dielectric nonlinear crystal sheet (J). *Physical Review Letters*, 2011, 106(8):083901.

Shijia Z, Zhiming R, Wenjiang T, et al. A cascaded difference frequency generation method combined with cavity phase matching and quasi phase matching for high-efficiency terahertz generation (J). *Laser Physics*, 2020, 30: 115401.

Skauli T, Kuo P S, Vodopyanov K L, et al. Improved dispersion relations for GaAs and applications to nonlinear optics (J). *Journal of Applied Physics*, 2003, 94(10): 6447-6455.