TITLE: Continuously Tunable THz-Wave Generation from GaP Crystal by Difference Frequency Mixing with a Dual-Wavelength KTP-OPO

Continuously Tunable THz-Wave Generation from GaP Crystal by Difference Frequency Mixing with a Dual-Wavelength KTP-OPO

Tetsuo Taniuchi, Jun-ichi Shikata, and Hiromasa Ito

Abstract- **Tunable terahertz (THz)-wave generation has been achieved by difference frequency generation (DFG) in a GaP crystal, with a $KTiOPO_4$ (KTP) optical parametric oscillator (OPO). We have developed a dual signal-wave OPO with two KTP crystals of $\phi = 55°$ to oscillate wavelengths from 980 nm to 990 nm, corresponding to the phase matching wavelength for DFG in GaP. Continuously tunable THz-waves were successfully generated in the 0.5 - 2.0 THz region, with the angle-tuning of the KTP crystal in the OPO cavity. The maximum power of 1.4 mW at the peak was achieved at 1.4 THz.**

Index Term- **terahertz-wave, optical parametric oscillator, difference frequency generation**

I. INTRODUCTION:

A coherent tunable terahertz (THz) wave can be generated by difference frequency generation (DFG) or parametric oscillation in nonlinear-optic crystals. THz-wave (far infrared) generation by DFG has been reported by mixing two CO_2 lasers using GaAs [1], and two dye lasers using ZnTe [2] and $LiNbO_3$ [3]. THz waves have also been generated by THz parametric oscillation (TPO) in $LiNbO_3$ pumped by a Q-switched Nd:YAG laser [4], based on stimulated polariton scattering. Recently we successfully generated THz waves tunable from 1 to 3 THz in MgO doped $LiNbO_3$, and we found that THz-wave output was nearly five times larger, compared to undoped $LiNbO_3$ [5]. The TPO has an advantage that it requires only one pump laser with a fixed wavelength, however, it has a threshold energy large than 10 mJ.

On the other hand, DFG has no threshold, and it potentially has wider tunability than TPO by selecting the DFG crystal and input wavelengths. The light sources for DFG must have slightly different wavelengths, with a separation of 0-10 nm, corresponding to the THz frequency.

Recently we have demonstrated THz-wave DFG in 4-N,N-dimethylamino-4'-N'-methyl-stilbazolium tosylate (DAST) [6] crystal using a type II $KTiOPO_4$ (KTP) optical parametric oscillator (OPO) with dual wavelengths near 1064 nm [7]. The organic crystal DAST has a large nonlinear-optic coefficient of d_{11}=290pm/V [8], which is 10 times larger than that of $LiNbO_3$, and phase matching wavelength for collinear DFG is in the range of 1 -1.15 μm. DAST is an effective material for generation of sub-THz-waves below 1THz, however, there is a large absorption band near 1.1THz, so that frequency range of DFG was limited to 0.2 - 1.2THz region.

To generate frequencies higher than 1 THz, low-loss crystals in the THz-wave region, such as GaP, ZnTe, or GaAs are useful for DFG interaction. Also, the nonlinear crystal is required to possess a large nonlinear coefficient at the two input optical frequencies. Therefore, GaP crystal is an attractive material for nonlinear interaction between optical wave and THz-wave due to wide transmission range of optical and THz waves [9,10]. In addition, we can easily obtain a large high quality GaP crystal with 2 inches diameter. The phase-matching for THz-DFG can be achieved in the wavelength range of 980-1000 nm in GaP crystal [11].

In this paper, we developed a dual signal-wave OPO using two KTP crystals in the same cavity as a source for THz-wave DFG with GaP. Using $\phi = 55°$, $\theta = 90°$ cut KTP crystals, we can easily obtain dual wavelengths with separation of 0-10 nm in the range 980 to 990 nm by angle-tuning the KTP crystals. Continuously tunable THz-wave generation in the range of 0.5 to 2.0 THz is demonstrated by tuning the angle of KTP.

II. DFG CHARACTERISTICS

Fig.1 shows a schematic diagram for generating THz waves by mixing two light waves from OPO, with slightly different wavelengths. For efficient DFG, the phase matching conditions in GaP is important, and they are given by;

$$\textit{energy conservation}: \frac{1}{\lambda_1} - \frac{1}{\lambda_2} = \frac{1}{\lambda_3}$$

$$\textit{momentum conservation}: \frac{n_1}{\lambda_1} - \frac{n_2}{\lambda_2} = \frac{n_3}{\lambda_3}$$

where λ_1 and λ_2 are the input wavelengths, λ_3 is the DFG wavelength, and n_1, n_2, n_3 are the refractive indices at each wavelength.

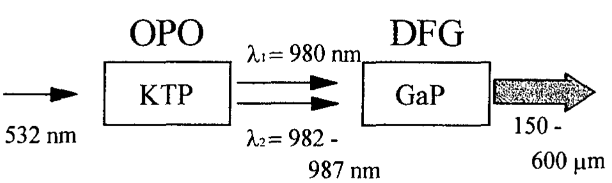

Fig. 1 THz-wave generation using a dual-wavelength OPO

T. Taniuchi, J. Shikata, and H. Ito are affiliated with the Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan

The refractive indices n_1, n_2 and n_3 of GaP in the optical and THz region were calculated using the Sellmeier equation [12].

$$n^2 = 2.81479 + \frac{6.27677\lambda^2}{\lambda^2 - 0.09116} + \frac{2.05549\lambda^2}{\lambda^2 - 762.1311}$$

Fig.2 shows measured refractive indices [13] and the calculation from the Sellmeier equation. The transmittance of GaP in the THz region is also shown in Fig.2. The GaP crystal is transparent below 2.7THz.

The coherence length L_c for DFG is obtained by:

$$L_c = \frac{1}{2\left|\frac{n_1}{\lambda_1} - \frac{n_2}{\lambda_2} - \frac{n_3}{\lambda_3}\right|}$$

Fig. 3 shows the coherence length L_c as a function of the input wavelength λ_1, calculated using the above equation. It shows that the collinear phase-matching can be achieved with input wavelengths near 980 - 990 nm in order to generate 0.5 to 2 THz frequencies. For example, 1.5 THz (λ_3 = 200 μm) can be generated with input wavelengths of 980 nm (λ_1) and 985 nm (λ_2).

III. EXPERIMENT

Fig. 4 shows a schematic diagram of the experimental arrangement for THz- wave generation in GaP by mixing dual wavelengths of KTP-OPO, which has two KTP crystals in the same cavity. The oscillating wavelengths can be independently controlled by the angle-tuning of KTP.

The pump source for the OPO was a frequency-doubled Q-switched Nd:YAG laser, with a pulse duration of 10 ns and 20 Hz-repetition rate. The OPO cavity was 150-mm long, which consisted of two 15mm-long KTP crystals and two highly reflective flat mirrors with 98% (input) and 82% (output). The threshold energy of the KTP-OPO was 3 mJ, and an output energy of 0.3 mJ was obtained with a pump energy of 4 mJ. In the KTP-OPO, it is possible to generate signal waves with relatively narrow bandwidths in the range of 980 to 990 nm by the angle-tuning from ϕ= 55 to 59° as shown in Fig.5.

Fig. 6 shows typical output spectrum of generated signal waves. P_1 and P_2 are obtained power at λ_1 and λ_2. P_2 is slightly lower than P_1 because of the pump depletion. The output power and the spectral bandwidth (0.2 nm) did not change throughout the tuning range.

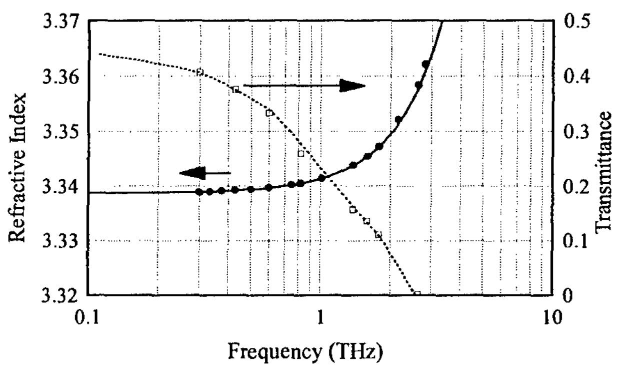

Fig.2 Characteristics of GaP in THz-wave region

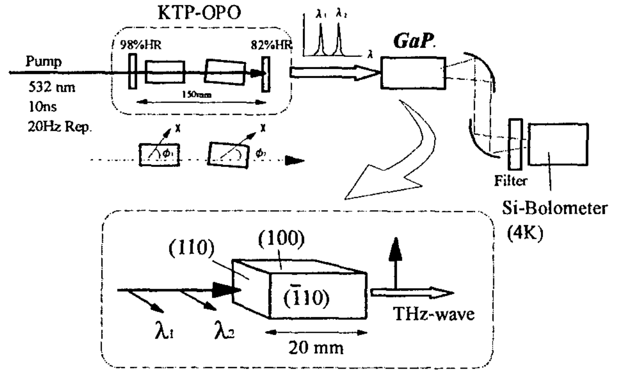

Fig. 4 Experimental arrangement for THz-DFG in GaP

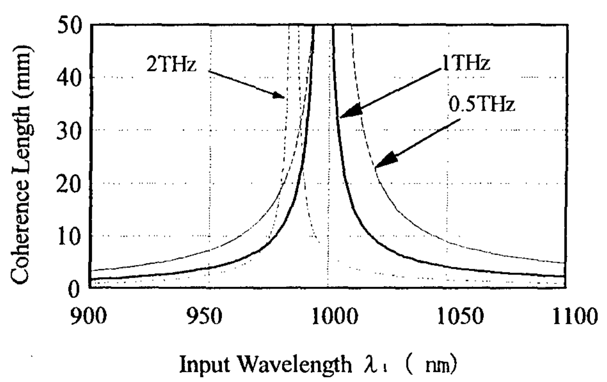

Fig.3 Coherence length for DFG vs input wavelength λ_1

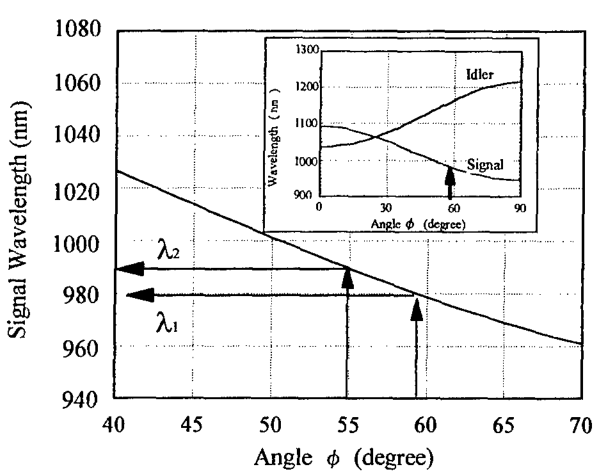

Fig.5 Signal wavelength vs KTP angle ϕ

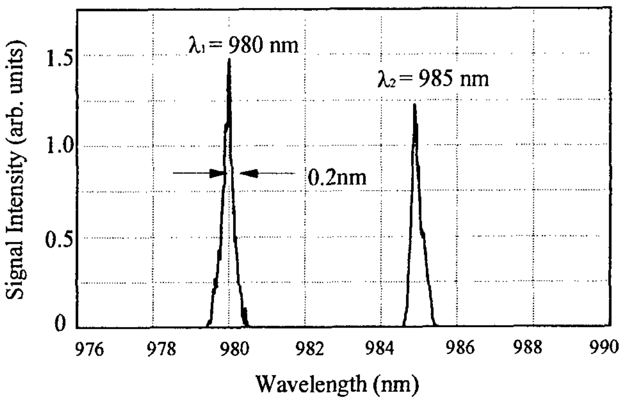

Fig.6 Signal spectrum of the dual signal-wave KTP-OPO

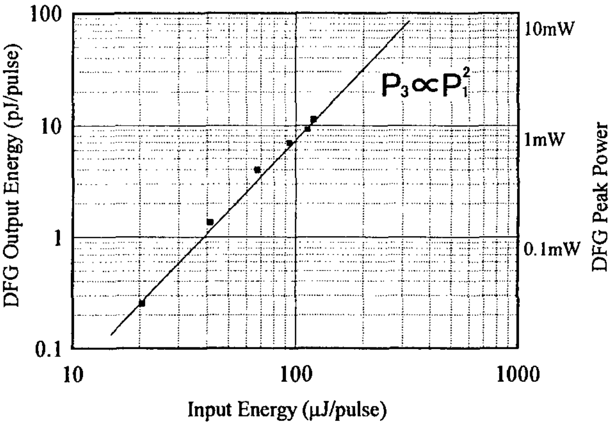

Fig.8 DFG output energy vs input energy

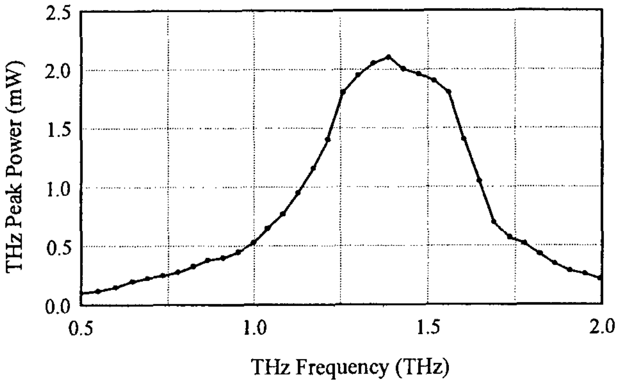

Fig.7 Frequency dependence of DFG output power

The DFG experiment was carried out with an undoped 20mm-long GaP crystal with high resistivity (> 10^6 Ωcm). The direction of input waves was along <110> direction of the GaP crystal. The generated THz-wave was collimated with a parabolic mirror and detected using a Si bolometer (4.2 K), as shown in Fig.4. The maximum DFG output was obtained when the polarization of the incident optical waves was perpendicular to the <100> direction of the GaP crystal. The polarization of the generated THz-wave, measured by rotating the wire-grid polarizer, was parallel to the <100> direction of the GaP crystal.

A continuously tunable THz-wave was successfully generated in the range of 0.5 to 2.0 THz by angle-tuning the KTP crystals as shown in Fig. 7. In this experiment, the angle of the first KTP was fixed to generate signal wave at $\lambda_1 = 980$ nm and the second KTP was tuned at $\lambda_2 = 982$ - 987 nm. The peak power of the THz-wave was about 1.4 mW at 1.4 THz, when input average power was 5 mW. The decrease in the generated THz-wave above 2 THz is due to the absorption in GaP. The bandwidth of the THz wave obtained was estimated to be about 60 GHz, corresponding to the optical spectral bandwidth of 0.2 nm. To generate a narrow THz wave, the spectral bandwidth of the KTP-OPO must be narrowed by inserting a grating element in the cavity.

Fig.8 shows the DFG output energy as a function of input energy. It is shown that DFG output energy increases proportional to square of input energy. We can find that the photorefractive damage and the two photon absorption in the GaP crystal are small in the power range of 5mW(average).

IV. CONCLUSIONS

We have investigated THz-wave DFG in GaP crystal. Continuously tunable THz-wave generation was demonstrated using a dual-wavelength KTP-OPO. The frequency of the THz wave was tuned in the 0.5 to 2.0 THz range by varying the KTP crystal angle in the OPO cavity. Maximum peak power of 1.4mW was obtained at 1.4 THz. The dual-signal wave KTP-OPO presented here is a suitable light source for generating a widely tunable THz wave.

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