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# Analysis of Tunable Terahertz Generation in Gallium Phosphide Using Difference Frequency Mixing

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**Abstract**
In this paper numerical analysis has been carried out to study the tunable terahertz (THz) generation in gallium phosphide using difference frequency generation. By varying the input wavelengths in the range 930- 1030 nm we obtained 0.1-3 THz tunable THz frequency. Theoretical dependence of THz wave power on GaP crystal length and effect of simultaneous tuning of both the input wavelengths has been studied. The simulated values of THz peak power were 0.6 W, 0.7 W and 0.48 W which were obtained at 1.3, 2 and 2.7THz respectively.

**Keywords**- Difference Frequency Generation, Terahertz Frequency and Gallium Phosphide.

## 1. Introduction
The development of monochromatic tunable and coherent THz-wave source is of great importance in advanced application including biomedical analysis and stand-off detection of hazardous materials. Though there are several techniques to generate THz (Hebling et al., 2008; Mueller, 2006), the Nonlinear Optical (NLO) techniques which includes short pulse rectification commonly known as Optical Rectification (OR), Terahertz Parametric Oscillation (TPO) and Difference Frequency Generation (DFG), have become quite popular. All of these techniques involve the mixing of the two closely spaced wavelengths such that their difference lies in the THz regime. In fact OR of a femtosecond pulse is difference frequency generation between the particular spectral components within the ultra-short laser pulse. Thus for OR to take place an ultra-short pulse, or a femtosecond laser is must, while TPO and DFG can be achieved from a nanosecond or even with a Continuous Wave (CW) laser. The TPO has an advantage that it requires only one pump laser with a fixed wavelength, however, it has large threshold. On the other hand DFG has no threshold and it has likely wider tunability than TPO by selecting suitable input wavelengths and appropriate NLO crystal.

Though, nonlinear materials have, in general high absorption in THz-wave region, GaP has much less THz power absorption coefficient as compared to other NLO materials like GaAs,

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ZGP, GaSe, ZnTe, $LiNbO_3$ and $LiTiO_3$ (Tonouchi, 2007). GaP is a semiconductor crystal having wide transparency in near-IR wavelength range (Wang, 2001). Since the transverse optical phonon frequency in GaP crystal is nearly 11 THz hence the transparency in THz range extends upto 5 THz (L'huillier et al., 2007). Besides, GaP has nearly equal refractive indices at IR and THz wavelengths therefore the participating wavelengths do not suffer from spatial walk-off, making GaP suitable for noncritical and collinear phase matching (Taniuchi and Nakanishi, 2004; Vodopyanov, 2008).

In this paper, a collinear difference frequency mixing between two wavelengths (say $\lambda_1$ and $\lambda_2$) has been treated theoretically. An appropriate range of wavelength has been estimated which would be suitable for the generation of THz tunable from 0.1 – 3 THz. The refractive index of GaP has been calculated by making use of Sellmeier equation in IR as well as THz region. With the help of these values of indices, the coherence length (which is a measure of momentum mismatch) corresponding to the input infrared wavelengths has been estimated. The absorption coefficient of GaP (Vodopyanov, 2008) has also been calculated. We have also studied the dependence of THz power on the thickness of the GaP crystal. We have incorporated the effect of momentum mismatch and the absorption within the GaP while studying the tuning characteristics of the THz power. We have also demonstrated the dependence of THz power on the crystal length and spot size of input beams for 1.5 THz, 2 THz and 3 THz.

## 2. Theory

For the efficient THz generation through nonlinear parametric process, it is important to have an adequate phase matching between the participating wavelengths. The phase matching condition for collinear DFG is given by energy conservation and momentum conservation which can be expressed as below

$$\left|\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right|=\frac{1}{\lambda_3} \quad \text{and} \quad \left|\frac{n_1}{\lambda_1}-\frac{n_2}{\lambda_2}\right|=\frac{n_3}{\lambda_3}$$

where $n_1$, $n_2$ and $n_3$ are the refractive indices corresponding to the wavelengths $\lambda_1$, $\lambda_2$ and $\lambda_3$ respectively. The phase matching condition gives an estimation of the wavelength range and the power of generated output THz waves.

Consider, $E_1$, $E_2$ and $E_3$ to be the three participating wavelengths propagating collinearly in the $y$- axis direction such that their electric fields are given as

$$E_m = E_{mo}\exp\{i(k_m y-\omega_m t)\} \qquad m = 1, 2 \text{ and } 3$$

where $E_{mo}$, $k_m$ and $\omega_m$ are the field amplitudes, propagation constants and the angular frequencies respectively corresponding to these fields.

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The nonlinear coupled wave equation for collinear DFG, taking into account the absorption coefficient of the material, can be derived from the Maxwell's equation and is given as

$$\frac{\partial E_{10}(y)}{\partial y} = \frac{-i\omega_1 d_{ij} E_{20} E_{30}}{n_1 c} e^{i\Delta ky} - \frac{\alpha_1}{2} E_{10}(y) \tag{1.1}$$

$$\frac{\partial E_{20}(y)}{\partial y} = \frac{-i\omega_2 d_{ij} E_{10}^{*} E_{30}}{n_2 c} e^{-i\Delta ky} - \frac{\alpha_2}{2} E_{20}(y) \tag{1.2}$$

$$\frac{\partial E_{30}(y)}{\partial y} = \frac{-i\omega_3 d_{ij} E_{10}^{*} E_{20}}{n_3 c} e^{-i\Delta ky} - \frac{\alpha_3}{2} E_{30}(y) \tag{1.3}$$

The growth of THz power after propagating the thickness '$L$' is obtained by solving equation (1.3) and it is given as (Borghesi and Guizzetti, 1985).

$$P_3 = \frac{2\omega_3^2 d^2 L^2}{\varepsilon_0 n_1 n_2 n_3 c^3} \left( \frac{P_1 P_2}{\pi r^2} \right) \times S \tag{2.1}$$

Where

$$S = \frac{\left\{ 1 + e^{-\alpha_3 L} - 2\cos(\Delta k L) e^{-\frac{\alpha_3 L}{2}} \right\}}{(\Delta k L)^2 + \left( \frac{\alpha_3 L}{2} \right)^2}, \text{ and } \Delta k = |k_1 - k_2 - k_3|$$

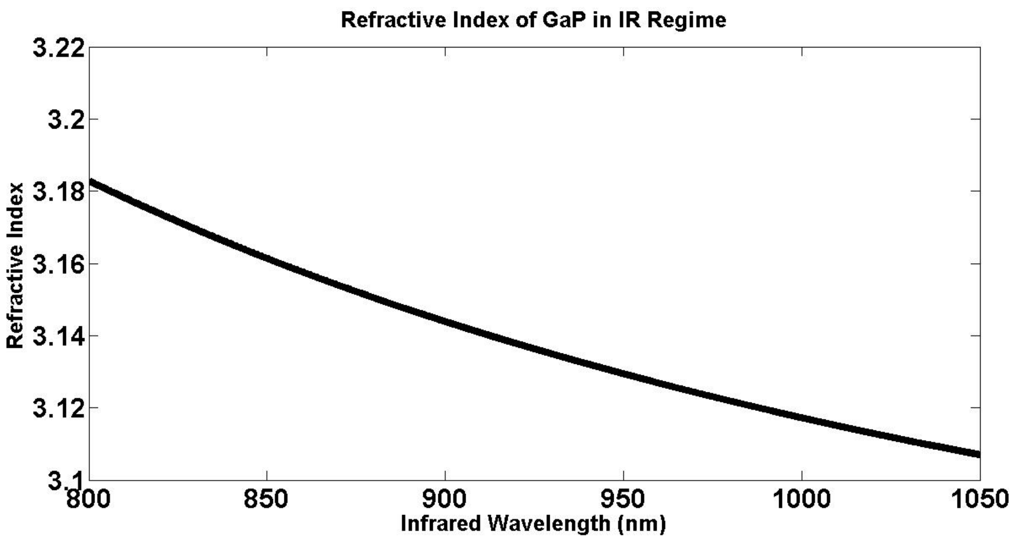


**Figure 1. Refractive index of Gallium Phosphide in IR region**

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where $d$ is the nonlinear coefficient and $L$ is the thickness of the GaP crystal. $P_1$, $P_2$ are the power of two input beams at $\lambda_1$ and $\lambda_2$ respectively; $T_1$, $T_2$ and $T_3$ are the Fresnel transmission coefficients; $r$ is the focal spot radius and has been assumed equal for both the input beams and $\Delta k$ is the momentum mismatch between optical beams and THz wavelength. $n_1$, $n_2$ and $n_3$ are the refractive indices whereas $\alpha_1$, $\alpha_2$ and $\alpha_3$ are the absorption coefficients at wavelengths $\lambda_1$, $\lambda_2$ and $\lambda_3$ respectively. $\omega_3$ is the angular frequency corresponding to $\lambda_3$.

The refractive indices of GaP crystal at optical frequencies are calculated by using Sellmeier equations (Tanabe et al., 2003). Figure 1 shows the refractive indices of GaP as function infrared wavelengths.

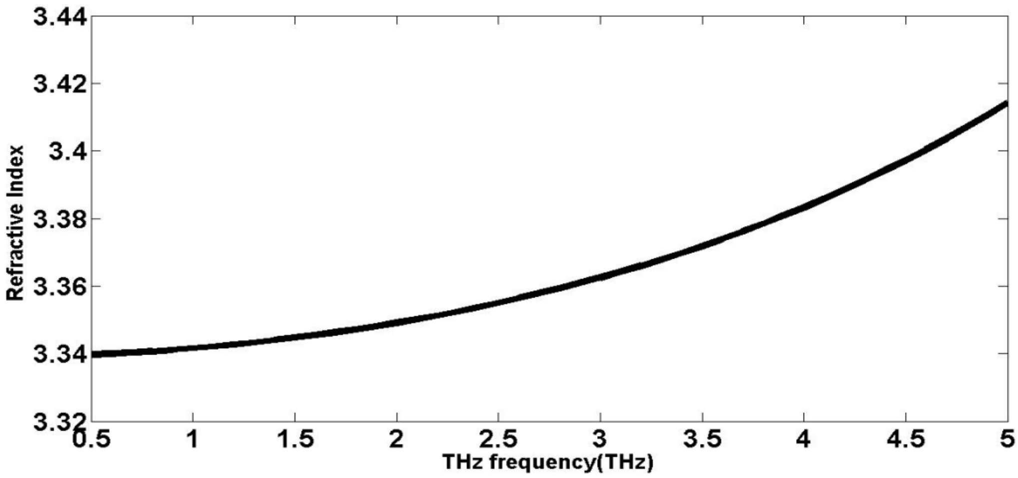


**Figure 2. Refractive index of Gallium Phosphide in THz region**

Figure 2 and Figure 3 shows the variation of refractive index and absorption coefficient of GaP as a function of THz frequencies. The refractive index of GaP in THz region $n_3$ is determined from the dispersion relationship of phonon-polaritons in GaP which is given as follows (Tanabe et al., 2003).

$$\left(\frac{cq}{2\pi\nu}\right)^2 = n_3^2(\nu) = \frac{\varepsilon_s \nu_0^2 - \varepsilon_\infty \nu^2}{\nu_0^2 - \nu^2} \tag{3}$$

where, $q$ is the wave-vector of the phonon-polariton mode, $\varepsilon_s$ and $\varepsilon_\infty$ are the static and optical frequency dielectric constants respectively ($\varepsilon_s$ = 11.5, $\varepsilon_\infty$ =9.20), and $\nu_0$ = 11.01THz, is the pure Transverse Optical (TO) phonon frequency and therefore this equation holds providing the generated THz frequency is not very near to $\nu_0$. The absorption coefficient for lattice resonance is given by (Tanabe et al., 2003).

$$\alpha(\nu) = \left(\frac{\Gamma}{n_3 c}\right) \times \frac{(\varepsilon_s - \varepsilon_\infty)\nu_0^2 \nu^2}{(\nu_0^2 - \nu^2)^2} \tag{4}$$

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where, Γ is the damping constant of the TO phonons.

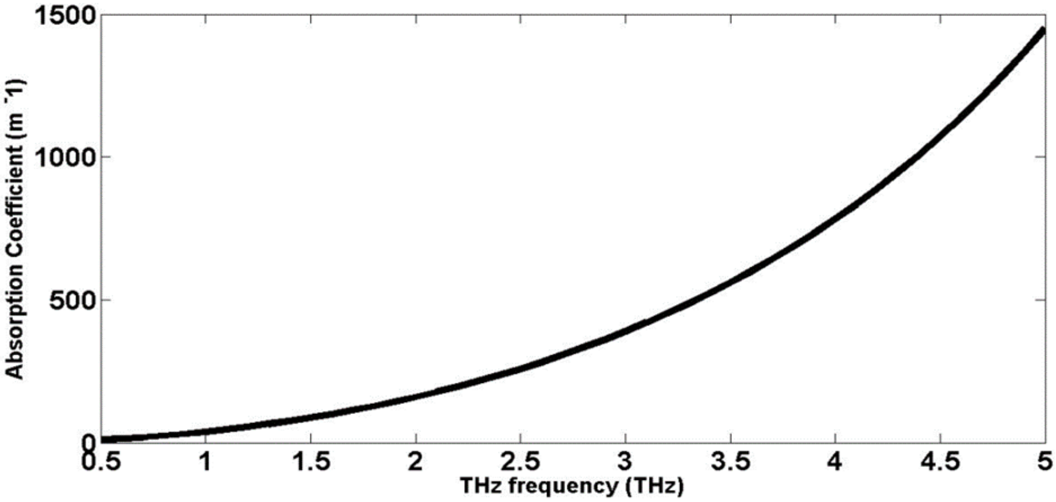


**Figure 3. Absorption of Gallium Phosphide in THz region**

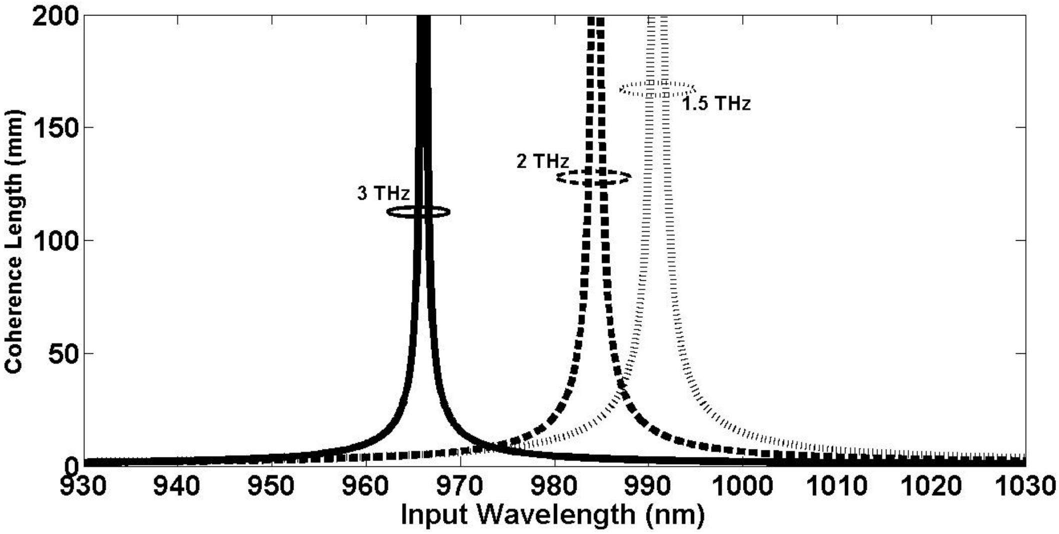


**Figure 4. Coherence length as a function of input wavelengths**

## 3. Results and Discussions

To determine the input wavelengths for the generation of 0.1 - 3 THz, we calculated coherence length for 1.5 THz, 2 THz and 3 THz by varying one of the input wavelengths (say $\lambda_1$) from 930 nm to 1030 nm. Figure 4 depicts the variation of the coherence length as a function of input wavelength. We found that for 100 μm (3 THz), 150 μm (2 THz) and 200 μm (1.5 THz) coherence length was maximum (or momentum mismatch was minimum) at input wavelengths of 961 nm, 984 nm and 991 nm respectively which corresponds to $\lambda_2$ equal to 975.5 nm, 990.9nm and 1004 nm.

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To choose the appropriate crystal length for optimized THz generation we investigated the THz power dependence on crystal length for 1.5 THz, 2 THz and 3 THz (Figure 5).

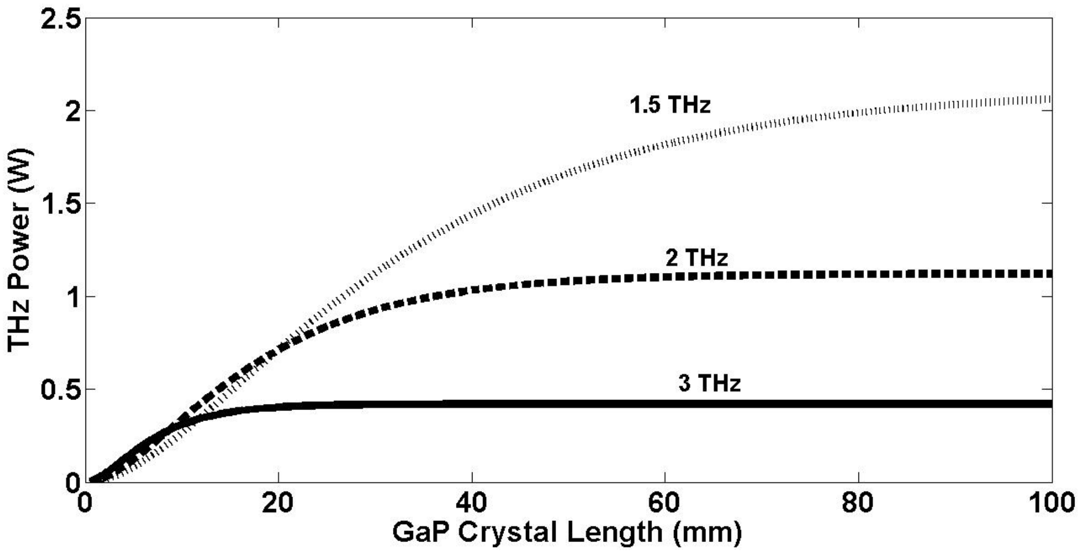


**Figure 5. THz power as a function of the crystal length**

From equation 2, it is clear that THz power increases as the square of the crystal thickness. However, even for the completely phase-matched condition it does not grow indefinitely. Rather, the power saturates beyond a certain value (≈ 20 mm for 3 THz) of thickness due to the absorption of THz waves in GaP. It is important to note in Figure 5 that in the lower frequencies (1.5 THz and 2 THz), the THz wave power continued to increase even at 20mm length. It was due to the reason that absorption losses were not significant for 20 mm crystal length at 1.5 and 2 THz. The THz power was saturated at 65.3 mm and 95.7 mm for 2 THz and 1.5 THz respectively.

To obtain continuous tunability we fixed $\lambda_1$ equal to 980 nm and tuned $\lambda_1$ from 930-1030 nm. We have used the following data for the theoretical calculations; $L$= 20 mm, $d_{11}$= 20 pm/V, $P_1$=$P_2$= 30 kW, $r$ = 0.5mm $\alpha_1$= $\alpha_2$= 0.1 cm$^{-1}$ while $\alpha_3$ was calculated with the help of equation 4. Figure 6 shows the continuous tunability of THz frequency over the range 1- 3 THz. A maximum of 0.38 W THz output power was obtained at 1.02 THz frequency.

It can be seen that though, we get continuous tunability yet it is only over a narrow range. The full width was only 0.87 THz at half maximum of the THz output power. To obtain THz output with wider tunability we varied both $\lambda_1$ and $\lambda_2$ simultaneously. $\lambda_1$ was varied from 980-1000 nm while $\lambda_2$ was tuned from 930- 1030 nm (Figure 7). The theoretical values of THz peak power were 0.6 W, 0.7 W and 0.48 W which were obtained at 1.3, 2 and 2.7THz respectively.

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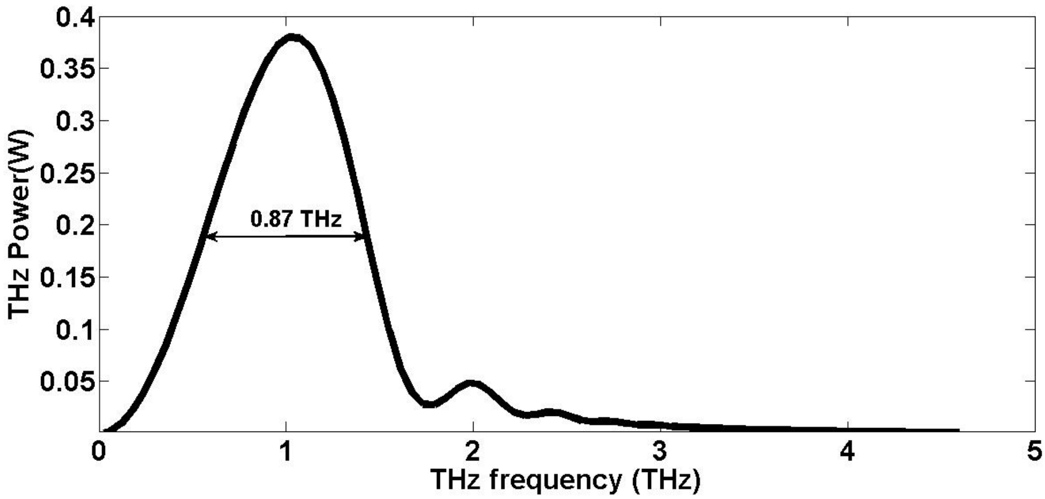


**Figure 6. THz power as a function of the THz frequency**

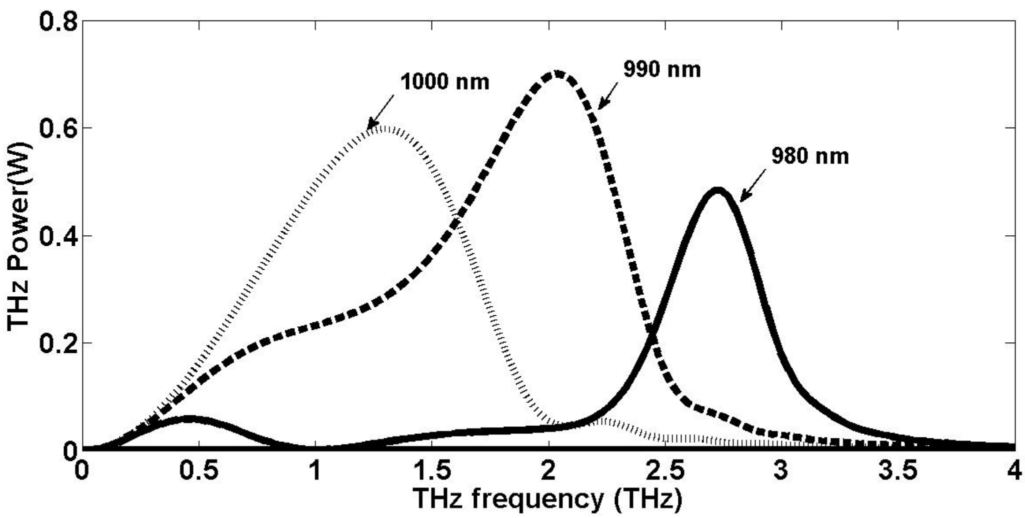


**Figure 7. Wider tunability of THz frequency along with the higher output power**

## 4. Conclusions and Future Work

It was concluded that collinear phase matching easily can be achieved in GaP by fixing wavelength (say $\lambda_1$) of 980 nm and a varying the other input wavelength (say $\lambda_2$) from 930-1030 nm. However, the tunability achieved will be over narrow range therefore, to obtain wider tunability and greater THz output power, it is necessary to vary both the input wavelengths simultaneously. We obtained a continuous tunability from 0.1 – 3THz with a peak power of 0.38 W at 1.02 THz. It was only after simultaneous tuning of both the input wavelengths, the theoretical values of THz peak power were 0.6 W, 0.7 W and 0.48 W which were obtained at 1.3, 2 and 2.7 THz respectively.

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The refractive index of GaP crystal both in IR and THz region was calculated by using Sellmeier equation. The absorption coefficient of GaP crystal in THz region was also taken into account. It was also found that for the 1.5 THz, 2 THz and 3THz frequency the output power saturated at 95.7 mm, 65.3 mm and 20 mm of thickness of the GaP crystal respectively. Future research should include the study and analysis of terahertz in periodicially poled or plates stacked gallium phosphide.

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