COMPARISON OF THE DETECTION PERFORMANCE OF THREE NONLINEAR CRYSTALS FOR THE ELECTRO-OPTIC SAMPLING OF A FEL-THZ SOURCE

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Abstract

The detector of a FEL-THz source at HUST is now in the physical design stage. The electro-optic (EO) sampling method will be employed for the coherent detection. The performances of three widely used EO crystals will be evaluated and compared numerically in the time domain detection: zinc telluride (ZnTe), gallium arsenide (GaAs) and gallium phosphide (GaP). The phase matching properties are analyzed to find the appropriate probe wavelength. The EO detection response is calculated to select the suitable crystal thickness and to discuss the detection ability of each crystal.

INTRODUCTION

The EO sampling method is widely applied for the coherent detection of THz pulse due to its short response time, high sensitivity and wide bandwidth. This method will be used for the detection of the FEL-THz pulse source at HUST which will operate initially at 3-6 THz [1]. The EO crystals should be carefully optimized to operate in the 3-6 THz frequency range. The scheme of the THz detection system is shown in Fig. 1.

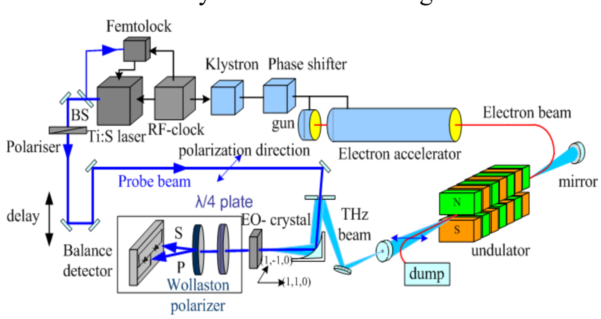

Figure 1: Scheme of the EO sampling for FEL-THz source at HUST.

A femtosecond laser is used as the probe laser which should be phase locked to the radio frequency clock of the FEL (2856 MHz). The probe laser is elliptically polarized by the THz pulse in the EO crystal (110) plane. A 1/4 wave plate imparts a $\pi/4$ optical phase difference and a wollaston polarizer separates the two orthogonal polarized beams. A balance detector is used to measure the intensity difference which is proportional to the THz electric field strength.

In this paper, the performances of three EO materials (ZnTe, GaAs, GaP) as detection crystals are analyzed and compared to find the best one.

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PHASE-MATCHING PROPERTIES OF EO CRYSTALS

In the THz range, a good approximate expression for the complex dielectric function of EO crystal is [2]:

$$\varepsilon(f) = \varepsilon_\infty + \frac{S_0 f^2}{f_0^2 - f^2 - i\Gamma_0 f} . \quad (1)$$

where ε_∞ is the optical dielectric constant in high frequency, S_0 , f_0 and Γ_0 is oscillator strength, eigenfrequency and damping constant of the lowest transverse optical (TO) lattice oscillation, respectively.

The complex index is the square root of the permittivity:

$$\sqrt{\varepsilon} = n_{THz} + i\kappa_{THz} . \quad (2)$$

The electro-optical coefficient γ_{41} is taken from Ref. [3], where the frequency dependence in THz range is neglected. These coefficients are list in table 1 [2-4].

Table 1: Crystal Coefficients for ZnTe, GaAs and GaP

Crystal	ε_∞	S_0	f_0 (THz)	Γ_0	γ_{41} (THz)
ZnTe	7.4	2.7	5.3	0.09	4.04
GaAs	11.1	1.8	8.025	0.066	1.43
GaP	8.7	1.8	10.98	0.02	0.97

For the EO sampling, the phase-matching condition requires the group velocity of probe pulse equals to the phase velocity of THz pulse. We can define the phase mismatch as [5]:

$$\Delta k = \frac{f_{THz}}{c}(n_{THz}(f_{Thz}) - n_g(f_{probe})) . \quad (3)$$

where n_{THz} is the refractive index in THz range, n_g is the group refractive index of the probe laser which can be calculated from the refractive index in the visible and infrared range [6]. The phase mismatch is expected to approach zero for the EO detection of a THz pulse.

The refractive indexes of ZnTe, GaAs, GaP in THz range are shown in Fig. 2, 3, 4. The group refractive indexes at commonly used probe wavelength of 800 nm, 1060 nm and 1550 nm are presented as a reference.

Figure 2 indicates that the phase match is almost perfect for frequency below 3 THz at 800 nm probe wavelength in ZnTe. While at 1060 and 1550 nm, the phase mismatch is too large.

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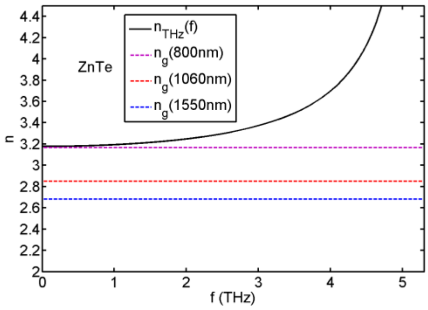

Figure 2: THz refractive index of ZnTe and group refractive index at 800 nm, 1060 nm, 1550 nm.

For GaAs, there are two perfect phase match points at 7.6 THz for 800 nm probe wavelength and 6.4 THz for 1060 nm probe wavelength as shown in Fig. 3. But the mismatch grows rapidly when the frequency diverges from the perfect point. For 1550 nm probe wavelength, almost perfect match can be obtained if frequency is below 4 THz.

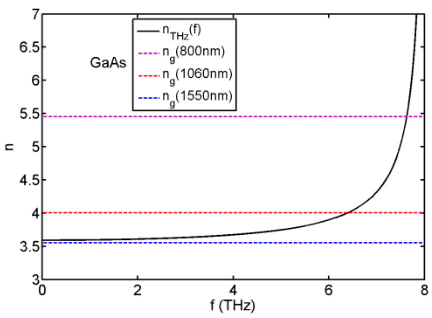

Figure 3: THz refractive index of GaAs and group refractive index at 800 nm, 1060 nm, 1550 nm.

For GaP, the perfect match points are 8.43 THz for 800 nm and 5.04 THz for 1060 nm probe wavelength as shown in Fig. 4. The mismatch is relatively small for 1060 nm probe wavelength up to 6 THz.

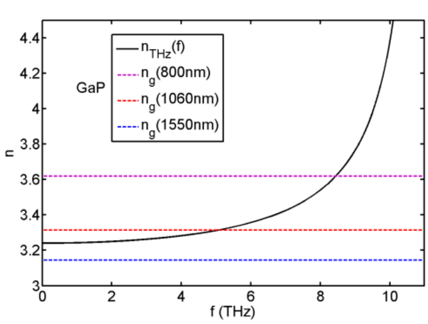

Figure 4: THz refractive index of GaP and group refractive index at 800 nm, 1060 nm, 1550 nm.

As a result, for the 3-6 THz FEL source, ZnTe crystal with the 800 nm probe laser, GaAs crystal with the 1550 nm probe laser, and GaP crystal with the 1060 nm probe laser are better solutions, depending on the probe wavelength.

DETECTION RESPONSE OF THE EO CRYSTALS

A detailed description of the detected EO signal from the balance detector in Fig. 1 is [3,5]:

$$S_{EO}(f) = n_p^3 \gamma_{41} \frac{f_p}{f_p(800\,\text{nm})} G(f) T(f) . \quad (4)$$

where n_p is the refractive index of the probe laser, f_p is the frequency of probe laser which is normalized to its value at 800 nm. $G(f)$ is the geometric response function of crystal. This term describes the effect of phase mismatch and absorption on detection, and it can be optimized by reducing the thickness of crystal.

$$G(f) = \int_0^d \exp[i\Delta kz - \frac{2\pi f}{C}\kappa_{THz} z]dz . \quad (5)$$

Additionally the amplitude transmission coefficient in THz range must be taken into account:

$$T(f) = \frac{2}{1 + n_{THz}(f) + i\kappa_{THz}(f)} . \quad (6)$$

The detection response of ZnTe, GaAs and GaP at matched probe wavelength is calculated, and the results are shown respectively in Fig. 5, 6, 7. Different crystal thicknesses are considered to optimize the detection response. It should be mentioned that there is strong absorptions around the TO phonon lattice oscillation frequency in the crystal lattice. This effect limits the detection bandwidth of the crystal. The amplitude of detection response is proportional to the thickness of crystal, but a thicker crystal amplifies the effects of phase mismatch which result in the reduction of bandwidth. The compromise should be made between the detection response and bandwidth.

ZnTe has the narrowest bandwidth as show in Fig. 5. For 0.05 mm thick crystal, the detection response decreases to -3 dB at 4.0 THz, then rapidly attenuated to zero. While the thickness increases to 0.1, 0.2 and 0.3 mm the bandwidth decreases to 3.5, 3.0, 2.7 THz correspondingly. The EO efficient of ZnTe is highest (4.04 pv/m), yielding the best performance at frequency lower than 2.7 THz. The oscillations on the response curve are due to the periodical variation of geometric response function at imperfect phase match.

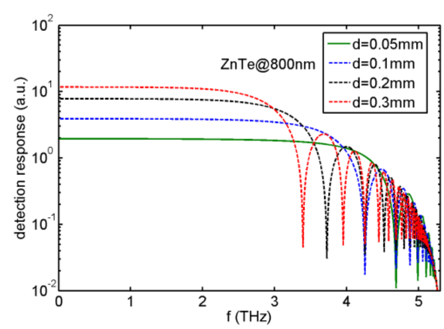

Figure 5: Detection response of the ZnTe for a thickness of 0.05 mm, 0.1 mm, 0.2 mm, 0.3 mm at 800 nm.

The material GaAs has a wider detection bandwidth than ZnTe as shown in Fig. 6. For thickness 0.05, 0.1, 0.3 and 1 mm the corresponding -3 dB bandwidth is 6.1, 5.3, 3.8 and 2.2 THz. But its performance at high frequency (>2.2 THz) is not as good as GaP which will be discussed later.

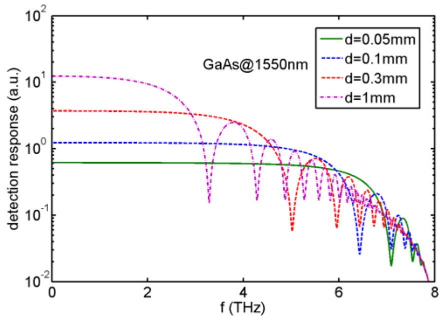

Figure 6: Detection response of the GaAs for a thickness of 0.05 mm, 0.1 mm, 0.3 mm, 1 mm at 1550 nm.

GaP has the widest bandwidth. For thickness 0.05, 0.1, 0.3 and 1 mm the corresponding -3 dB bandwidth is 8.3, 7.5, 6.4 and 5.6 THz. Although its EO efficient is lowest, a thicker crystal can make up for this defect. If the thickness increases to 1mm, obvious absorption appears in 2-4 THz range, which can be seen in Fig. 7. It means that crystal thickness higher than 1 mm is not applicable.

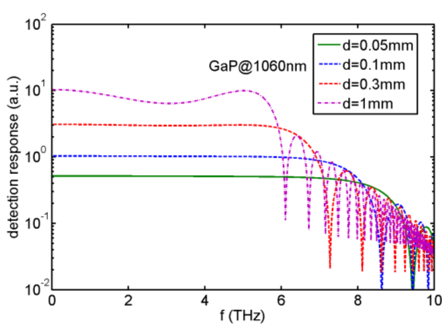

Figure 7: Detection response of the GaP for a thickness of 0.05 mm, 0.1 mm, 0.3 mm, 1 mm at 1060 nm.

For the HUST-FEL source (3-6 THz), GaP has the best detection performance. 1 mm thick GaP can detect 3-5.6 THz pulse with the highest response amplitude. For 5.6-6 THz pulse, the 0.3 mm GaP is suitable. All the feasible crystals in 3-6 THz range are list in table 2.

CONCLUSION

Direct numerical calculation of the phase mismatch and detection response of three EO crystals (ZnTe, GaAs, GaP) was obtained to evaluate their detection performances as the crystal of EO sampling for the FEL-THz source at HUST (3-6 THz). The results indicate that ZnTe crystal with the 800 nm probe wavelength, GaAs crystal with the 1550 nm probe wavelength, and GaP crystal with the 1060 nm probe wavelength has a better phase match. The 0.3-1 mm thick GaP at probe wavelength of 1060 nm has the best performance compared with the other two crystals, because its -3 dB bandwidth covers 3-6 THz and the detection response is the most highest. The results provide useful guidance for the detection experiments. Further simulation will treat the case of frequency dependent EO coefficient of crystals.

Table 2: Feasible Crystals for FEL-THz at HUST

Crystal	**Thickness (mm)**	**Bandwidth (THz)**	**Response Amplitude (a.u.)**
ZnTe	0.05	4.0	1.95
	0.1	3.5	3.91
GaAs	0.05	6.1	0.62
	0.1	5.3	1.24
	0.3	3.8	3.72
GaP	0.3	6.4	3.12
	1	5.6	10.3

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