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CONCEPT FOR THE MINIMIZATION OF THE ELECTRON BUNCH ARRIVAL-TIME JITTER BETWEEN FEMTOSECOND LASER PULSES AND ELECTRON BUNCHES FOR LASER-DRIVEN PLASMA WAKEFIELD ACCELERATORS*

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Abstract

Using laser driven plasma wakefield accelerators, the synchronization between electron bunch and the ultrashort laser is crucial to obtain an stable acceleration. In order to minimize the electron bunch arrival-time jitter, the development of a new shot to shot feedback system with a time resolution of less than 1 fs is planned. As a first step, stable Terahertz (THz) pulses should be performed by optical rectification of high energy femtosecond laser pulses in a nonlinear crystal. It is planed that the generated THz pulses will energy modulate the electron bunches shot to shot before the plasma to achieve the time resolution of 1fs. The selection of the nonlinear material is a critical aspect for the development of laser driven THz sources. In this contribution we investigate systematically the influence of the optical properties, and in particular adsorption coeffient, of lithium niobate crystal on the conversion efficiency of the generation of THz pulses.

INTRODUCTION

The investigation of new concepts for accelerator technology is a challenging task for science as well as society. Particle accelerators allow to achieve crucial new discoveries, e.g. the Higgs boson or the strong interacting Quark Gluon Plasma. On the other side, they have several applications in material science, biology, medicine and industry. The size of conventional accelerators is extremely large and costly. Therefore, new concepts as well as the realization of compact and less expensive accelerators are needed. Plasma-based particle accelerators driven by either lasers or particle beams allow to overcome these problems because of the extremely large accelerating electric fields. This method is known as plasma wakefield acceleration (PWA). The period of these fields is in the range of 10 fs to 100 fs. In the case of laser driven plasma wakefield accelerators a stable synchronization of the electron bunch and of the plasma wakefield in the range of few femtoseconds is needed in order to optimize the acceleration.

Consequently, the central aim is the minimizing the electron bunch arrival-time jitter. In order to achieve this goal we are developing a new shot to shot feedback system with a time resolution of less than 1 fs. As a first step, stable Terahertz (THz) pulses should be performed by optical rectification of high energy laser pulses in a nonlinear crystal. With the generated THz-pulses an energy modulation of the electron bunch can be performed, in order to achieve the required resolution. In this contribution we focus on the first step of the feedback system, i.e. the generation of THz pulses.

Intense ultrashort terahertz pulses are an important tool, not only for our planed feedback system, but also for many new applications, in state solid physics, spectroscopy, chemistry and biology, for security purposes and point-to point communications [1]. Therefore, the development of robust and efficient strong THz pulses is strongly needed. Consequently, the main focus is to maximize the conversion efficiency of the THz generation defined by [2],

$$\eta = \frac{F_\mathrm{T}}{F_\mathrm{p}}, \tag{1}$$

where F_p and F_T indicate the pump and the THz fluence respectively. From this point of view the optical rectification (OR) is one of the best method for this purpose and the selection of the nonlinear material is a critical aspect. Because of its high nonlinear optic coefficient, is lithium niobate ($LiNbO_3$, LN) a suitable material for THz generation, by using tilted-pulse-fronts (TPF) as well as a periodically poled crystal (PPLN) [4]. In general, three main factors lead to increase the efficiency of the THz generation: *(i)* longer pump pulses, *(ii)* large pump size and energy, and *(iii)* cooling of the crystal [3].

Evidently, the first two factors are fixed by the laser properties. Therefore, although it has been shown that longer (1.3 ps) pulses lead to a sizeable enhancement about 2.5% of the efficiency, these factors cannot be modified in our setup [3]. Indeed, for our feedback system only the third point can play a significant role. In fact the cooling of the crystal reduce the value of the intensity adsorption coefficient of the THz radiation $\alpha_\mathrm{T}(\Omega)$, which leads to the suppression of η. The optical properties of the material and in particular of $\alpha_\mathrm{T}(\Omega)$ are important not only for the optimization of the efficiency, but also for its stability. Therefore, in this contribution we give a first estimation of the influence of refractive index $n(\Omega)$ and adsorption coefficient, on the efficiency. Firstly, we present the models for the description of the THz generation as well as for the calculation of the optical properties of the material. Therefore we investigate in this framework the influence of the optical properties of lithium niobate crystal on the conversion efficiency of the generation of THz pulses. The Conclusions finalize this work.

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MODELING THE THz GENERATION

Starting from the Maxwell equations coupled wave equations for the optical and THz waves can be derived. Using the slowly-varying envelope approximation the equations system for the envelope at angular frequency ω of the electric field of the optical pump pulse $A_{\rm p}(\omega, z)$ and the envelope at angular frequency Ω of the THz field $A_{\rm T}\Omega, z)$ reads [4]

$$\frac{\partial}{\partial z}A_{\rm p}(\omega, z) = -\frac{\alpha_{\rm p}(\omega)}{2}A_{\rm p}(\omega, z) - I_{\rm p}, \qquad (2)$$

$$\frac{\partial}{\partial z}A_{\rm T}(\Omega, z) = -\frac{\alpha_{\rm T}(\Omega)}{2}A_{\rm T}(\Omega, z) + I_{\rm T}, \qquad (3)$$

where we define

$$I_{\rm T} = -i\frac{\Omega^2\chi^{(2)}_{\rm eff}(z)}{2k(\Omega)c^2)}\int_0^\infty {\rm d}\omega A_{\rm p}(\omega+\Omega, z)A^*_{\rm p}(\omega, z){\rm e}^{-i\Delta k(\omega)}. \qquad (4)$$

Hereby k and Δk are the wave number and the wave-vector mismatch respectively, $\alpha_{\rm p}$ indicates the adsorption coefficient of the optical wave, c is the velocity of the light in vacuum and $I_{\rm p}$ denotes an integral term analogous to the integral contribution for the THz component [4]. The parameter $\chi^{(2)}_{\rm eff}(z)$ is the effective second order nonlinear susceptibility which can be a function of the spatial coordinate z.

Because we consider in the following the undepleted approximation only, i.e. we neglect the equation of the optical wave, we omit to give a specific expression for this term[1]. The efficiency defined in Eq. (1) is a function of the amplitude of the THz wave and can be written as

$$\eta = \frac{\pi\epsilon_0 c\int_0^\infty {\rm d}\Omega\; n(\Omega)|A(\Omega, z)|^2}{F_{\rm p}}, \qquad (5)$$

where ε_0 indicates the dielectric constant of the vacuum.

By a linear approximation of the mismatch vector Δk, i.e. by neglecting of the material dispersion (GVD-MD), which has to be relaxed in future works, the absolute value of the field squared reads

$$|A(\Omega, z)|^2 = \frac{\Omega^2 P^2_{\rm NL}(\Omega, z)}{4c^2 n^2(\Omega)\varepsilon_0^2}\frac{1}{(\Delta k)^2 + a^2_{\rm T}(\Omega)/4} \times \left(\left(1-{\rm e}^{-\frac{\alpha_{\rm T}(\Omega)z}{2}}\right)^2 + 4\,{\rm e}^{-\frac{\alpha_{\rm T}(\Omega)z}{2}}\sin^2\left(\frac{\Delta k z}{2}\right)\right), \qquad (6)$$

where the nonlinear polarization $P_{\rm NL}$ is given by

$$P_{\rm NL}(\Omega, z) = \varepsilon_0\chi^{(2)}_{\rm eff}(z)\int_0^\infty {\rm d}\omega\; A_{\rm p}(\omega+\Omega, z)A^*_{\rm p}(\omega, z). \qquad (7)$$

MODELING THE MATERIAL PROPERTIES

Eq. (6) shows the importance of the purpose of this work, i.e. investigation of the influence of the optical properties on the conversion efficiency. In particular the adsorption coefficient should play a key role because of the exponential suppression factor. In order to determine the optical properties, we have to calculate the complex dielectric function $\varepsilon(\Omega)$ of the material. The relation between $\varepsilon(\Omega)$ and the refractive index and the adsorption coefficient is given in general by

$$n(\Omega) = \Re\sqrt{\varepsilon(\Omega)} \quad \text{and} \quad \alpha(\Omega) = \frac{2\Omega}{c}\Im\sqrt{\varepsilon(\Omega)}. \qquad (8)$$

A physical motivated description for the dielectric function is based on an oscillator model, i.e.

$$\varepsilon(\Omega) = \varepsilon_\infty + \sum_j \frac{S_j\Omega_j^2}{\Omega_j^2 - \Omega^2 - i\Omega\Gamma_j}, \qquad (9)$$

where the summation over the lattice oscillators with the strength S_j, angular resonance frequency Ω_j and resonance width Γ_j is performed and the bound electron contribution to the dielectric function is denoted as ε_∞ [5]. These parameters are to be evaluated by the comparison with the experimental data in the relevant frequency range. Another possibility is to fit the experimental data with polynomial function. For LN, a polynomial to the fourth or fifth degree is used for the refractive index [6, 7]. For α an explicit functional dependence has not been given, but only the experimental data are listed [6].

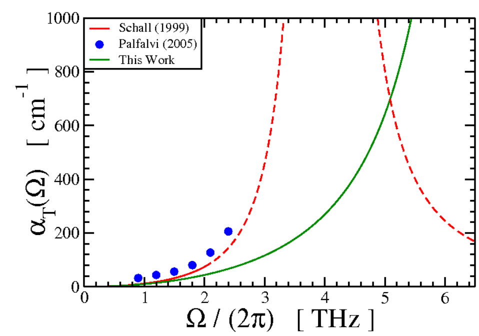

Figure 1: The adsorption coefficient as function of the frequency using the single oscillator model from Schall [5] (red line), the experimental data from Pálfalvi [6] (blue circles) and repararameterization of the fit by Kuznetsov [7] using a single oscillator model (green line).

The comparison of these models and results shows different values for their validity range as well as in general a large scattering of the results, in particular for the adsorption coefficient, even in the case of the same typology of crystal. As example we compare in Fig. 1 the adsorption coefficient for a congruent undoped LN at room temperature as function of the frequency using the single oscillator model from Schall [5] (red line), the experimental data from Pálfalvi [6] (blue circles) and repararameterization of the fit by Kuznetsov [7] using a single oscillator model (green line). We use as parameters of the one single oscillator model are $\varepsilon_\infty = 0.1$, $S_0 = 25.03$, $\Omega_0 = 45.46$ THz and $\Gamma_0 = 3.04$ THz. In order to show the validity range, we plot

[1] Additionally we note, that in the integral term $I_{\rm p}$ different effects can be considered [4].

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the red line as solid and dashed line for the value of the frequency within and outside of the validity range respectively. The differences between the models are sizeable and lead to no negligible modifications in the evaluation of η.

Another source of modifications by the determination of the conversion efficiency is given by the evaluation of the contribution to the optical properties by the free carries generated by the pump adsorption [8]. In order to describe this contribution a Drude model can be used, so that the whole dielectric function, in one single oscillator model, is given by

$$\varepsilon_{\rm tot}(\Omega) = \varepsilon_{\rm osc}(\Omega) + \varepsilon_{\rm FC}(\Omega), \quad (10)$$

where $\varepsilon_{\rm FC}$ can be written as

$$\varepsilon_{\rm FC}(\Omega) = \varepsilon_\infty^{\rm FC}\left(1 - \frac{\omega_{\rm pl}^2}{\Omega^2 + i\Omega/\tau_{\rm sc}}\right). \quad (11)$$

Hereby $\tau_{\rm sc}$ denotes the electron scattering time and the plasma frequency $\omega_{\rm pl}^2$ is related to the density of free charge carries $\rho_{\rm FC}$ by

$$\rho_{\rm FC}=\frac{\varepsilon_0\varepsilon_\infty^{\rm FC} m_{\rm eff}}{e^2}\omega_{\rm pl}^2, \quad (12)$$

where $\varepsilon_\infty^{\rm FC}$ denotes the bound electron contribution to the dielectric function and e and $m_{\rm eff}$ are the electron charge and effective masse respectively [8]. In this work we use $\varepsilon_\infty^{\rm FC} = 5.3$, $\tau_{\rm sc} = 200$ fs [8] and $m_{\rm eff} = 0.25 m_{\rm e}$, where $m_{\rm e}$ indicates the electron mass. Although in a consistent derivation the whole adsorption coefficient has to be extracted from the imaginary part of the total dielectric function given in Eq. (10), several calculations use a simple sum $\alpha_{\rm T}(\Omega) = \alpha_\varepsilon(\Omega) + \alpha_{\rm FC}(\Omega)$, where the two terms are calculated separately starting from a dielectric function without free carries and the dielectric function of the Drude model $\varepsilon_{\rm FC}$ respectively [8]. The Fig. 2 shows that this simplification leads to sizeable differences using the single oscillator model from Schall and the Drude model for a density $\rho_{\rm FC} = 4 \times 10^{20}\,{\rm m}^{-3}$, which can lead to a strong suppression of the conversion efficiency.

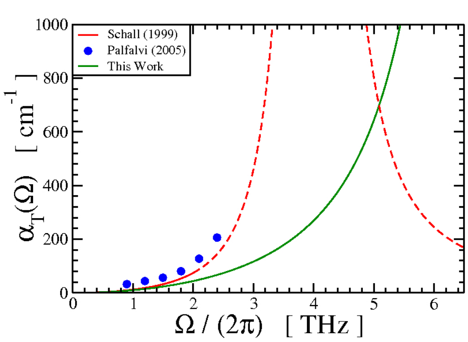

Figure 2: Comparison of the exact calculation (red line) and the approximated estimation (green line) of the whole adsorption coefficient as function of the frequency using the single oscillator model from Schall [5] and the Drude model for the free carries for a density $\rho_{\rm FC} = 4 \times 10^{20}\,{\rm m}^{-3}$.

FIRST RESULTS

In order to investigate the influence of the optical properties we consider a PPL congruent LN crystal with $\chi^{(2)}_{\rm eff} = 336\,{\rm pm\,V}^{-1}$ at room temperature with a Gaussian laser beam pulse centered at $\omega_0 = 800$ nm and a pulse duration at full width of half-maximum $\tau_{\rm FWHM} = 25$ fs [2,4,8]. In this case the amplitude and the fluence of the pump read

$$A_{\rm p}(\omega) = \frac{E_0\tau}{2\sqrt{\pi}}\exp\left(-\frac{\tau^2(\omega-\omega_0)^2}{4}\right), \quad (13)$$

$$F_{\rm p} = \sqrt{\frac{\pi}{2}}\frac{c\varepsilon_0 n_0}{2}E_0^2\tau, \quad (14)$$

where E_0 is the peak value of the electric field, τ is given by $\tau = (2\sqrt{2})^{-1/2}\tau_{\rm FWHM}$ and $n_0 = n(\omega_0) = 2.16$. With this optical beam the nonlinear polarization can be calculated analytically and one obtains

$$P_{\rm NL}(\Omega, z) = \varepsilon_0\chi^{(2)}_{\rm eff}\frac{E_0^2\tau}{2\sqrt{2\pi}}\exp\left(-\frac{-\tau^2\Omega^2}{8}\right). \quad (15)$$

For the PPL, the mismatching is given by

$$\Delta k = \frac{\Omega}{c}(n(\Omega) - n^{\rm gr}_{\rm opt}) - \frac{2\pi}{\Lambda}, \quad (16)$$

where $n^{\rm gr}_{\rm opt} = 2.25$ is the optical group velocity refractive index and $\Lambda = 237.74\,\mu$m is the quasi-phase-matching orientation-reversal period [4]. By neglecting the adsorption and under the assumptions that the refractive index is constant, $n(\Omega) \equiv n_1$, and that the length of the crystal is very larger than the coherence length $l_c = \pi c/\Omega(n(\Omega) - n^{\rm gr}_{\rm opt})$, an analytic expression for the efficiency can be derived [2]. In this case the integral over the frequency in Eq. (5) is proportional to a delta-function $\delta(\Omega - \Omega_0)$, with $\Omega_0 = 2\pi c/\Lambda\Omega(n(\Omega) - n^{\rm gr}_{\rm opt})$. Finally one obtains

$$\eta_0 = \frac{\Omega_0^2\chi^{(2)}_{\rm eff} L F_{\rm p}}{2\varepsilon_0 c^2 n(\Omega) n_0^2(n_1 - n^{\rm gr}_{\rm opt})}\exp\left(-\frac{-\tau^2\Omega_0^2}{4}\right). \quad (17)$$

With these parameters we can investigate the efficiency as function of the crystal length L for different scenarios for a fixed pump fluence $F_{\rm p} = 5\,{\rm mJ\,cm}^{-2}$.

As first, we consider the limiting case $\alpha_{\rm T} \equiv 0$. In Fig. 3 we show η_0 (green line) using $n_1 = 4.96$, η using the same constant value for n_1 but performing the integration until to the convergence of the integral (red line) and η using different models to calculate the refractive index and stopping the integration at the upper limit of the validity of the models (see the legend of the figure). As expected, the behavior of the efficiency as function of the crystal length is linear, but the angular coefficient is model dependent. In particular, we see that the cut-off at slow frequency change the results dramatically.

In the case of no vanishing adsorption, the differences between the models become larger. The results are plotted in Fig. 4 for a fixed pump fluence $F_{\rm p} = 5\,{\rm mJ\,cm}^{-2}$. Although a similar qualitative behavior can be observed, i.e.

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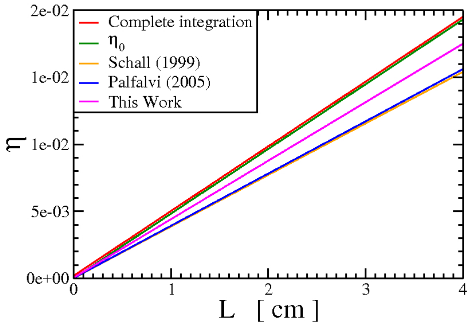

Figure 3: Conversion efficiency η for a fixed pump fluence $F_p = 5\,\mathrm{mJ\,cm^{-2}}$ as function of the crystal length L with constant refractive index $n_1 = 4.96$ with the complete integration (red line) and with different models for stopping the integration at the upper limit of the validity of the models as indicated in Fig. To comparison we show the analytic estimation η_0 (green line).

a saturation of η for large crystal lengths, the values of the plateau indicate the strong dependence of the conversion efficiency on the model and/or data. Similar sizeable modifications can be observed, if the contribution of the free carries is implemented. In Fig.5 we show $\eta(L)$ for a fixed pump fluence $F_p = 5\,\mathrm{mJ\,cm^{-2}}$ calculated using the Schall model without the free carries (orange line), using consistent approach presented in this work (red line) and using the approximation used in the literature [8] (green line) for a density $\rho_{FC} = 4 \times 10^{20}\,\mathrm{m^{-3}}$. The huge deviation from the exact calculation indicates clearly the necessity to perform consistent calculations of the optical properties.

CONCLUSION

The influence of the optical properties of the lithium niobate crystal on the conversion efficiency of the generation of THz pulses has been investigated. The comparison of different models for the estimation of the adsorption coefficient shows the necessity of a better description of the optical properties, not only in the THz range, but also at higher frequencies. The approximations that we used in this preliminary work should be relaxed in order to evaluate systematically the influence of the other factors on η.

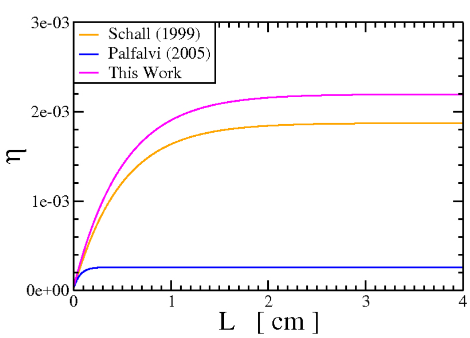

Figure 4: Conversion efficiency η for a fixed pump fluence $F_p = 5\,\mathrm{mJ\,cm^{-2}}$ as function of the crystal length L using the refractive index and the adsorption coefficient from different models as indicated in the legend.

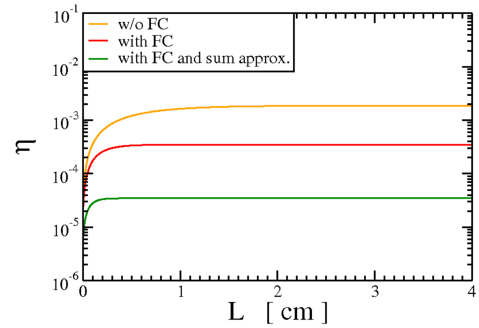

Figure 5: Conversion efficiency for a fixed pump fluence $F_p = 5\,\mathrm{mJ\,cm^{-2}}$ as function of the length using the Schall model [5] without the free carries (orange line), within the consistent calculation presented in this work and the approximation used in the literature [8] (red and green solid line respectively) for a FC density $\rho_{FC} = 4 \times 10^{20}\,\mathrm{m^{-3}}$.

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REFERENCES

[1] A. G. Stepanov, S. Henin, Y. Petit, L. Bonacina, J. Kasparian, and J.-P. Wolf, "Mobile source of high-energy single-cycle terahertz pulses", *Appl. Phys. B*, vol. 101, no. 1, pp. 11–14, 2010.

[2] K. Vodopyanov, "Optical generation of narrow-band terahertz packets in periodically-inverted electro-optic crystals: conversion efficiency and optimal laser pulse format", *Optics Express*, vol. 14, no. 6, pp. 2263–2276, 2006.

[3] J .A. Fülöp *et al.*, "Generation of sub-mJ terahertz pulses by optical rectification", *Optics Letters*, vol. 37, no. 4, pp. 557–559, 2012.

[4] K. Ravi, D. Schimpf, and F. Kärtner, "Pulse sequences for efficient multi-cycle terahertz generation in periodically poled lithium niobate", *Optics Express*, vol. 24, no. 22, pp. 25582–25607, 2016.

[5] M. Schall, H. Helm, and S. R. Keiding, "Far Infrared Properties of Electro-Optic Crystals Measured by THz Time-Domain Spectroscopy", *International Journal of Infrared and Millimeter Waves*, vol. 20, no. 4, pp. 595–604, 1999.

[6] L. Pálfalvi, J. Hebling, J. Kuhl, Á. Péter, and K. Polgár, "Temperature dependence of the absorption and refraction of Mg-doped congruent and stoichiometric LiN", *Journal of Applied Physics*, vol. 97, no. 12, p. 123505, 2005.

[7] K. A. Kuznetsov *et al.*, "Dispersion of the dielectric function real part for Mg:LiNbO3 crystals at terahertz frequencies", *Appl. Phys. B*, vol. 101, no. 3, pp. 881–815, 2010.

[8] S. Zhong *et al.*, "Optimization of terahertz generation from LiNbO3 under intense laser excitation with the effect of three-photon absorption", *Optics Express*, vol. 23, no. 24, pp. 31313–31323, 2015.