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A FEEDBACK SYSTEM TO MINIMIZE THE ELECTRON BUNCH ARRIVAL-TIME JITTER BETWEEN FEMTOSECOND LASER PULSES AND ELECTRON BUNCHES FOR LASER- DRIVEN PLASMA WAKEFIELD ACCELERATORS*

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Abstract

In a laser driven plasma based particle accelerator a stable synchronization of the electron bunch and of the plasma wake field in the range of less than 2 fs is necessary in order to optimize the acceleration. For this purpose we are developing a new shot to shot feedback system with a time resolution of less than 1 fs. We plane to generate stable THz pulses by optical rectification of a fraction of the plasma generating high energy laser pulses in a nonlinear lithium niobate crystal. With these pulses we will energy modulate the electron bunches shot to shot before the plasma to achieve the time resolution. In this contribution we will focus on realization aspects of the shot to shot feedback system and the lithium niobate crystal itself. Here we compare different approximations for the modeling of the generation dynamics (second order or first order calculation) and of the dielectric function (influence of the dispersion relation, of the free carries generated by the pump adsorption and their saturation, depletion of the pump) in order to investigate the importance of a detailed description of the optical properties for the THz generation.

INTRODUCTION

Particle accelerators are important tools for fundamental research as well as for the industry and human life. Nevertheless, the technology of standard accelerators is coming to its limit given by the physical-chemical properties of the material used for the construction as well as by the huge size of new accelerators and by the financial costs. Plasma-based particle accelerators driven by laser beam overcome these problems because of their extremely large accelerating electric fields [1]. Currently, the acceleration gradients of conventional linear accelerators are limited to 10 MVm^{-1} [2]. However, the acceleration gradients of laser-driven particle accelerators can be in the order of 1 TVm^{-1}. In this method, known as plasma wakefield acceleration (PWA), the period of these fields is in the range of 10 fs, so that for an optimization of the acceleration a stable synchronization of the electron bunch and of the plasma wakefield in the range of few femtoseconds is necessary. Therefore, we are planning a new shot to shot feedback system for SINBAD, which should be able to synchronize the electron bunch with the plasma exciting laser pulse with a time resolution of less than 1 fs. In a first step, stable Terahertz (THz) pulses should be performed by optical rectification (OR) of high energy laser pulses in a periodically poled lithium niobate crystal ($LiNbO_3$) (PPLN). These pulses allow an energy modulation in the modulator placed in a chicane of the electron bunch in order to achieve the required resolution [3]. This paper focuses on the first step of the feedback system in order to understand the dependence on the conversion efficiency of the THz generation, defined as [3, 4]

$$\eta = \frac{\pi \epsilon_0 c \int_0^\infty \mathrm{d}\omega_\mathrm{T}\, n(\omega_\mathrm{T}) |E_\mathrm{T}(\omega_\mathrm{T}, z)|^2}{F_\mathrm{L}}, \tag{1}$$

on the laser intensity and on the optical properties of the nonlinear crystal. Herby E_T is THz frequency component of the electric field and F_L and ε_0 indicate the pump fluence and the vacuum dielectric constant respectively.
The paper is organized as follows. First, we derive the general equations for the description of the THz generation and then we introduce two different methods in order to include the effects of the laser pump on the crystal and we compare the corresponding results for the efficiency. The conclusions finalize this work.

MODELING THE THZ GENERATION

Following [4–7], an one dimensional system of coupled differential equation for the laser pulse $E_\mathrm{L}(\omega_\mathrm{L}, z) = A_\mathrm{L}(\omega_\mathrm{L})\mathrm{e}^{-\imath k(\omega_\mathrm{L})z}$ and for the THz wave $E_\mathrm{T}(\omega_\mathrm{T}, z) = A_\mathrm{T}(\omega_\mathrm{T})\mathrm{e}^{-\imath k(\omega_\mathrm{T})z}$ can be derived from the Maxwell equations as

$$\left(\frac{\partial^2}{\partial z^2} + \frac{\omega_\mathrm{T}^2}{c^2}\varepsilon(\omega_\mathrm{T})\right) E_\mathrm{T}(\omega_\mathrm{T}, z) = G_\mathrm{T}(\omega_\mathrm{T}, \omega_\mathrm{L}, z) \tag{2}$$

$$\left(\frac{\partial^2}{\partial z^2} + \frac{\omega_\mathrm{L}^2}{c^2}\varepsilon(\omega_\mathrm{L})\right) E_\mathrm{L}(\omega_\mathrm{L}, z) = G_\mathrm{L}(\omega_\mathrm{L}, \omega_\mathrm{T}, z), \tag{3}$$

where $\varepsilon(\omega)$ is the generalized (complex) dielectric function and the inhomogeneous term G_L and G_T are related to the nonlinear polarizations in the optical and THz frequency range respectively.

In almost all investigations a slope varying approximation (SVA) is used [4, 8–10], in which neglecting the second spatial derivatives of the amplitudes A_m with m $\in$ L, T leads to coupled system of linear differential of the first order,

$$\left(\frac{\partial}{\partial z} + \frac{\alpha_\mathrm{m}(\omega_\mathrm{m})}{2}\right) A_\mathrm{m}(\omega_\mathrm{m}, z) = G_\mathrm{m}^\mathrm{SVA}(\omega_\mathrm{T}, \omega_\mathrm{L}, z) \tag{4}$$

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where α_{m} indicates the adsorption coefficient in the optical (m = L) and in the THz range (m = T) respectively and the inhomogeneous terms are given by

$$G_{\mathrm{T}}^{\mathrm{SVA}} = \imath G_{\mathrm{m}} \frac{\mathrm{e}^{\imath k(\omega_{\mathrm{T}})z}}{2k(\omega_{\mathrm{m}})}. \qquad (5)$$

By setting $G_{\mathrm{L}} = 0$ the system is decoupled and only Eq. (2) or Eq. (4) with (m = T) has to be solved. From the physical point of view, in this approximation, which is used in several works [3, 7–10], the direct depletion of the laser pump is missed. For Eq. 2 it holds $G_{\mathrm{T}} = -\mu_0 \omega_{\mathrm{T}}^2 P_{\mathrm{NL}}(\omega_{\mathrm{T}}, z)$, where the nonlinear polarization reads

$$P_{\mathrm{NL}}(\omega_{\mathrm{T}}, z) = \varepsilon_0 \chi^{(2)}(z) \int_0^\infty \mathrm{d}\omega E_{\mathrm{L}}(\omega_{\mathrm{T}} + \omega, z) E_{\mathrm{L}}^*(\omega, z), \quad (6)$$

where $\chi^{(2)}(z)$ is the second order nonlinear susceptibility.

The complex dielectric function $\varepsilon(\omega)$ of the material is related to the wave vector, the refractive index and the adsorption coefficient by,

$$n(\omega) = \frac{k(\omega)c}{\omega} = \Re\sqrt{\varepsilon(\omega)} \quad \alpha(\omega) = \frac{2\omega}{c}\Im\sqrt{\varepsilon(\omega)}. \qquad (7)$$

In the frequency region around ω_0 only the real part of the dielectric function is needed and for the expression $k(\omega_{\mathrm{T}} + \omega) - k(\omega)$ a linear approximation,

$$k(\omega_{\mathrm{T}} + \omega_{\mathrm{L}}) - k(\omega_{\mathrm{L}}) \approx \frac{n_{\mathrm{opt}}^{\mathrm{gr}}}{c}\omega_{\mathrm{T}} \qquad (8)$$

can be used. In order to evaluate the effects of the whole dispersion relation we additionally use the frequency dependence of the wave vector derived from the refractive index squared given by the Sellmeier equation in Ref. [11].

For the THz frequency region we use a physical motivated description for $\varepsilon(\omega_{\mathrm{T}})$ based on the oscillator model given in [12].

INFLUENCE OF THE FREE CARRIERS

The free carries (FC) generated by the pump adsorption in the material [5, 9, 10, 13] lead to a decreasing of the pump intensity in the crystal. In order to systematically consider the influence of this effect we follow two strategies.

(a) Modification of the Dielectric Function

In this first approach (a) we set $G_L = 0$ and we systematically modify the dielectric function, in order to describe the effects of FC to the optical properties as following [5, 13]

$$\varepsilon_{\mathrm{tot}}(\omega_{\mathrm{T}}) = \varepsilon_{\mathrm{osc}}(\omega_{\mathrm{T}}) - \frac{\omega_{\mathrm{pl}}^2}{\omega_{\mathrm{T}}^2 + i\omega_{\mathrm{T}}/\tau_{\mathrm{sc}}}, \qquad (9)$$

The second term of $\varepsilon_{\mathrm{tot}}(\omega_{\mathrm{T}})$ is modeled along the line of a Drude model [10], where the plasma frequency ω_{pl}^2 is proportional to the density of free charge carries ρ_{FC}. In our previous works [5, 13] we proposed the following phenomenological description for ρ_{FC} in a PPLN,

$$\rho_{\mathrm{FC}}(F_{\mathrm{L}}) = \begin{cases} \rho_{3\mathrm{PA}}(F_{\mathrm{L}}) & F_{\mathrm{L}} \leq F_0 \\ \rho_{\mathrm{s}} - A\,\mathrm{e}^{-a(F_{\mathrm{L}} - F_0)} & F_{\mathrm{L}} > F_0, \end{cases} \qquad (10)$$

In this way, for fluences smaller then a transition fluence F_0, the FC density is given by the three-photon-adsorption process (3PA) of the pump beam in the medium [10] and for $F_{\mathrm{L}} > F_0$ a saturation of the FC density has been modeled in order to describe the experimental observation of an increasing of η at large fluences in lithium niobate crystals [10].

In this manuscript we investigate a periodic polarized congruent lithium niobate crystal with $\chi^{(2)}(z) = \chi_{\mathrm{eff}}^{(2)}\,\mathrm{e}^{-\imath 2\pi z/\Lambda}$, where the parameter $\chi_{\mathrm{eff}}^{(2)} = 336\,\mathrm{pm\,V^{-1}}$ is the effective second order nonlinear susceptibility and $\Lambda = 237.74\,\mu\mathrm{m}$ is the quasi-phase-matching orientation-reversal period. We consider a Gaussian laser beam pulse with central wave length $\lambda_0 = 1030\,\mathrm{nm}$ and a pulse duration at full width of half-maximum $\tau_{\mathrm{FWHM}} = 25\,\mathrm{fs}$ [3–5, 8, 10, 13].

As first we consider our results for η achieved by solving directly the equation of motion as differential equation of the second order, i.e. Eq. (2). We focus on the deviation from the SVA results in this approach and we compare in Fig. 1 the results for the conversion efficiency η for a fixed pump fluence $F_{\mathrm{L}} = 5\ \mathrm{mJ\ cm^{-2}}$ as function of the crystal length L between the second order calculation (solid lines) and the SVA (dashed lines). If the linear approximation is used, see.

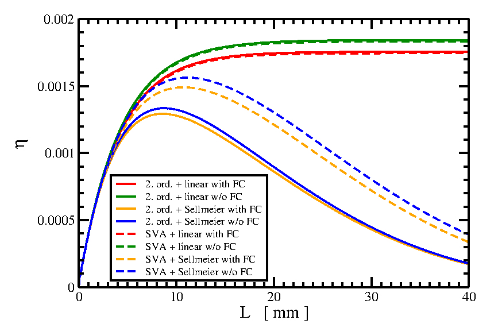

Figure 1: The conversion efficiency η for a fixed pump fluence $F_{\mathrm{p}} = 5\,\mathrm{mJ\,cm^{-2}}$ as function of the crystal length L for the second order calculation (solid lines) and the SVA (dashed lines) labeled by different colors as indicated.

Eq. (8), a typical saturation of η for large crystal lengths occurs and the deviations remain small. However, using the Sellmeier equation, the already known [5, 13] functional dependence with a maximum around $L \approx 10$ mm and is a decreasing behavior for larger crystal lengths is recovered and we note non negligible effects of the FC contributions. Nevertheless the deviations coming between the second order calculation and SVA are larger.

We can argue that at small fluences the second order dynamics effects seem to be stronger than the contribution of the free charge carries. However, that is no true at large laser pump intensities. In Fig. 2 we compare η for a crystal

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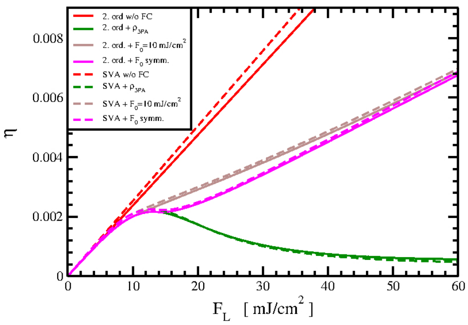

Figure 2: The conversion efficiency η for a crystal length of $L = 5$ mm as function of F_L for the second order calculation (solid lines) and the SVA (dashed lines) using the Sellmeier equation and different parameterizations of the FC density as well as for vanishing FC density as indicated.

length of $L = 5$ mm as function of F_L using the Sellmeier equation for the polarization integral and different parameterizations of the FC density as well as for vanishing FC density as indicated. The second order calculations recover not only qualitatively, but also quantitatively the SVA results found in [5, 13] with the linear behavior for vanishing FC, the asymptotic decreasing at large intensities for unsaturated free carries density as well as the three regime behavior or the slope change for the different values of F_0.

Therefore, at high fluences η seems to be dominated by the details of the formation and saturation of FC, whereas the effects of the second order effects do no play a significant role.

(b) Decreasing of the Pump Intensity

The second strategy (b) in order to consider the effects of the free carriers is including directly the decreasing of the pump intensity [7] induced by the three photon adsorption and given in frequency domain by [13]

$$I_L(\omega_T, z) = e^{-\imath q z} \sum_{n=0}^{\infty} \tilde{I}_n \, z^n, \text{ with } \tilde{I}_n = \frac{u_n}{2\sigma_n \sqrt{\pi}} e^{-\frac{\omega_T^2}{4\sigma_n^2}} \quad (11)$$

where we introduce the quantities $u_n = \binom{-1/2}{n} I_0 \left(2\gamma_3 I_0^2\right)^n$, $\sigma_n^2 = \frac{2}{\tau^2}(2n+1)$ and $q = \omega_T n_{\text{opt}}^{\text{gr}}/c$.

Because the nonlinear polarization and the intensity are proportional, for the coupled system given by Eq. (4) the inhomogeneous terms are given within the linear approximation, see. Eq. (8), by

$$G_T(\omega_T, z) = -\imath \frac{\omega_T^2}{2k(\omega_T)c^3 n_0 \varepsilon_0} I_L(\omega_T, z) e^{\imath k(\omega_T) z} \quad (12)$$

$$G_L \omega_L, z) = \text{FT}_{t\to\omega}\left[-\frac{\gamma_3}{4} n(\omega_0 c \varepsilon_0)^2 E_L^3(t) \left(E_L^*(t)\right)^2\right], (13)$$

where $\text{FT}_{t\to\omega}$ indicate the Fourier transform from time to frequency domain and the linear adsorption in the optical regime is neglected, i.e. $\alpha_L \equiv 0$ and α_T is calculated from the oscillator model dielectric function given in [12]. For a Gaussian pulse the amplitude A_T can be written as $A_T(\omega_T, z) = \sum_{n=0}^{\infty} a_n \, z^n$, where the coefficient a_n are given in [13].

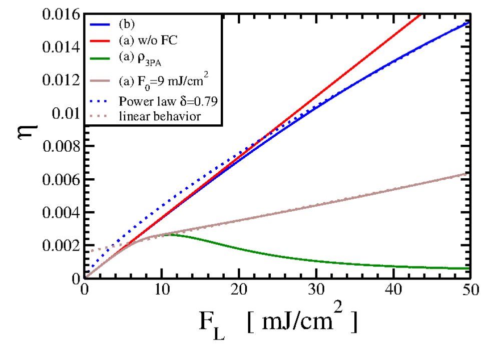

Figure 3: Comparison of η obtained within a (minimal) depleted calculation (b) for a crystal length of $L = 40$ mm as function of F_L (orange line) using as well as the efficiency η calculated in SVA (undepleted) within the linear approximation within the approach (a) for the different parameterizations of the FC density as well as for vanishing FC density as indicated.

This expression for A_T allows us to calculate the efficiency with this approach, that is a (minimal) depleted calculation In Fig. 3 η calculated obtained within a (minimal) depleted calculation (b) for a crystal length of $L = 40$ mm as function of F_L using as well as the efficiency η calculated in SVA within the linear approximation within the approach (a) for the different parameterizations of the FC density. We note a deviation from the linear dependence on F_L, which is typical by vanishing FC. Furthermore, in the depleted calculation the asymptotic behavior for large fluence follows a power law $\eta \propto F_L^\delta$ with $\delta = 0.79$, whereas the efficiency calculated including the FC contribution parameterized by $F_0 = 9$ mJ cm^{-2} show a linear asymptotic behavior.

CONCLUSION

We present systematic calculations of the optical properties of the lithium niobate crystal and of their influence on the efficiency of the generation of THz pulses. We compare different approximation for the modeling of the generation dynamic (SVA vs. second order calculation) as well as for different treatment of the influence of the free carriers. In particular a (minimal) depleted calculation has been used. In this way we can clearly show the importance of a consistent description of the optical properties as well as a detailed generation dynamics in order to develop the planned shot to shot feedback system, which have to perform the synchronization between electron bunch and the ultrashort laser with a time resolution of less than 1 fs.

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