DEVELOPMENT OF A THZ SEED SOURCE FOR FEL MICROBUNCHING EXPERIMENT AT THE NEPTUNE LABORATORY

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Abstract

Seeded FEL/IFEL techniques can be used for modulation of a relativistic electron beam longitudinally on the radiation wavelength. However, in the 1-10 THz range, which is of particular importance for the matched injection of prebunched electrons into a laser-driven plasma accelerating structure, a suitable radiation source is not available. At the UCLA Neptune Laboratory we have built and fully characterized a radiation source tunable in the range of 1-3 THz. The THz pulse is produced by mixing two CO_2 laser lines in a noncollinear phase-matched GaAs crystal at room temperature. The crystal is pumped by 200 ns pulses of a dual beam TEA CO_2 laser running at 1 Hz. A grating placed in each lasing section allowed to cover the spectral range for the difference frequency from 0.5-4.5 THz with a step of 30-40 GHz. The achieved narrow bandwidth ($\Delta\nu/\nu$ ~10^{-5}) and the output power of 2kW are sufficient for seeding a single-pass waveguide FEL amplifier-prebuncher. These pulses were used to measure the coupling efficiency and the attenuation for the different types of THz waveguides and the results will be reported.

INTRODUCTION

Plasma-based accelerators, such as laser- or electron-beam-driven plasma waves based structures [1], are known to have a much higher accelerating gradient than conventional RF powered systems.This has stimulated an increasing interest in advanced plasma accelerators during recent years [2]. However, there are issues that need to be solved in order for plasma accelerators to be considered a technology for next generation accelerators. One of the main issues is production of a high-quality electron beam. For example, plasma accelerators with an external injection, such as a plasma beatwave accelerator, suffer from a continuous energy spread because the electron beam covers several periods of the plasma wave [3]. In order to inject electrons into a narrow phase interval of the plasma wave, a beam needs to be prebunched into a series of ~50-15 μm long microbunches that are separated by the plasma wavelength.

At the Neptune Laboratory at UCLA we have launched an experimental program with the goal of developing a high-gain, single-pass FEL amplifier-prebuncher seeded in the 0.5-3 THz range [4]. The main objectives of the study are production of milti-megawatt radiation pulses and simultaneous microbunching of nominally 10 MeV electron beams on the THz scale. It was proposed to use a difference frequency of two CO_2 laser lines mixed in a nonlinear crystal as a seed THz source,. Here, we describe a THz source based on Difference Frequency Generation (DFG) in GaAs producing up to ~2kW power in the spectral range of 100-500 μm at 1 Hz.

THZ DFG IN NONLINEAR CRYSTALS

Tunable DFG in the THz range was demonstrated both in birefringent, e.g., $ZnGeP_2$, GaSe and isotropic , e.g., GaAs, InSb nonlinear materials. There are a number of considerations for selecting an optimal crystal to be employed in generation of the THz radiation by difference frequency mixing of 10-µm lasers: high transparency at the two input laser frequencies as well as at the THz frequency; large nonlinearity and high damage threshold. Several reasons make GaAs the best candidate for generation of the high-power, tunable THz radiation using a noncollinear DFG scheme. It has a relatively high value for the electro-optic nonlinear coefficient d^{eo}=43 pm/V. A semi-insulating GaAs with high resistivity > 10^8 Ωcm is transparent in the THz beyond 100 µm at room temperature as well as in the 10 µm region of the CO_2 laser. High-quality single crystals with a cross-section 10 x10 cm and length up to 10 cm are commercially available. Thus we chose GaAs and studied experimentally nonlinear elements with different types of phase-matching.

The GaAs crystals, being isotropic, lack birefringence. One approach to obtain phase-matched THz DFG in isotropic nonlinear materials is a noncollinear mixing of two laser beams. This is possible in any crystal that possesses an anomalous dispersion between the incident CO_2 laser radiation and the THz difference frequency radiation. Zernike [5] and Aggarwal and Lax [6] have demonstrated a noncollinear mixing of two CO_2 laser beams in semiconductor materials. A large-aperture THz frequency dowconverter from GaAs was manufactured and tested.

Another approach is using a Quasi-phase matched (QPM) structure. Even in isotropic crystals waves propagate in-phase over the coherence length, the distance over which the relative phase between the waves changes by π. For THz difference frequency mixing the coherence length is quite long, for example it is 712 µm in the case of GaAs. Clearly, the power generated in such a slab is low. Quasi-phase matching is a method for phase matching nonlinear optical interactions in which the relative phase is corrected at regular intervals using a stack of plates or periodically grown structure. We developed a novel technique for bonding GaAs wafers using an interboundary Teflon AF film and fabricated a five wafer, large-aperture THz generator.

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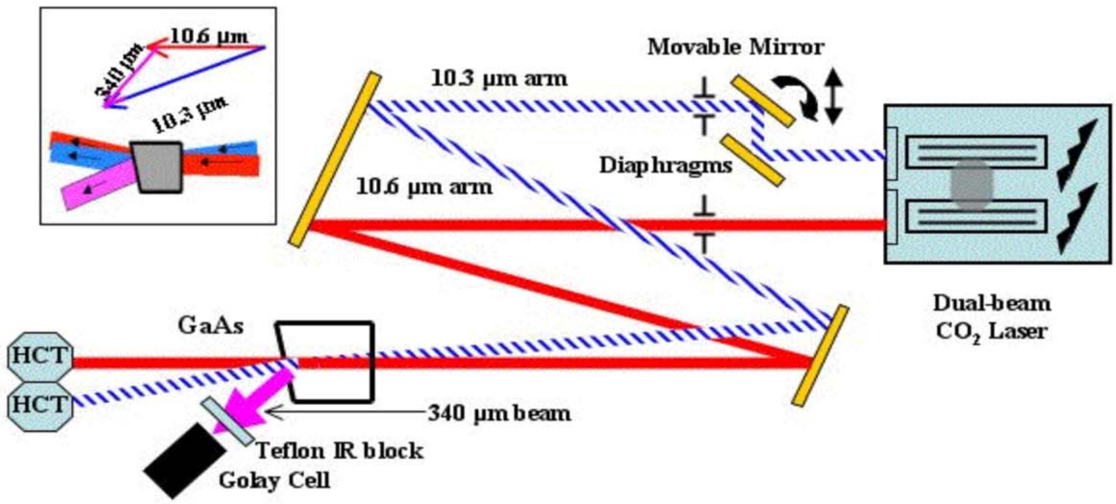

Figure 1: A simplified scheme of a THz DFG source.

Experimental set-up

The experiments on THz DFG have been performed with a dual-beam CO_2 laser built at UCLA using commercial TEA lasing sections running at 1Hz. This dual-beam laser uses one spark gap to trigger two parallel CO_2 lasing sections, thus providing jitter-free operation for two optical pulses. By choosing lines with approximately the same gain coefficient we extracted more than 1J per line simultaneously. A grating placed in each section allowed covering the spectral range for the difference frequency from 0.5-4.5 THz with a step of 30-40 GHz.

The optical scheme for DFG in GaAs, when the 10.3 µm (ω_1) line was mixed with the 10.6 µm (ω_2) line resulting in the 340 µm (ω_3) difference-frequency radiation, is shown in Fig.1. For noncollinear phase-matched mixing of two laser lines of frequencies ω_1 and ω_2 to generate the difference-frequency radiation at ω_3, the conditions of photon energy and momentum conservation require that $\omega_3=\omega_1-\omega_2$ and that matching of the respective wave vectors occurs as shown in the insert.

The 10.6 µm radiation beam was directed at the normal incidence to the crystal surface. The beam path of the 10.3 µm arm was adjustable by a movable mirror in order to scan the phase matching angle. For a ~2.9-m-long base of both arms, we obtained an angle resolution of 0.01° while scanning the phase matching angle. The 21° angle of propagation of the THz beam inside the crystal is greater than the critical angle of total internal reflection. Therefore, the output face of the GaAs crystal (in the form of a 2x4x2.5 cm^3 rectangular parallelepiped) was cut at an angle of ~10° to decouple both the 10- and 340-µm beams. The THz radiation was collected by an off-axis parabolic mirror and sent onto a Golay cell for detection. The detector with a known spectral response was calibrated in an energy scale using the 10 µm pulse.

The experimental set-up shown in Fig.1 was modified for collinear phase matching simply by placing a 135 gr/mm grating in the plane where the two CO_2 laser beams intersect. The grating worked as a beam combiner and after the grating two collinearly propagating beams were slightly focused by a curved mirror and a beam sent on a QPM GaAs structure.

Noncollinear Phase Matched GaAs crystal

As seen in Fig. 2 (a), for the 344 µm line the signal peaked at the external phase matching equal to 2.33° and the full-width of the phase-matching curve was 0.07°. The measured width of the phase-matching curve indicated that the interaction length for 15-20 mm beams was clearly limited by the crystal length. It is also shown in Fig.2 that by selecting another line for the 10.3 µm arm separated by ~ 40 GHz a step-tunable operation is achievable. After the correction of Sellmeier coefficients for GaAs using the experimental data, tunability in the broad range of 0.6-2.8 THz or 500-110 µm was achieved with a very good agreement between the calculated and measured angles.

For the 200 ns pulses with a peak power $P_{10.3}\approx P_{10.6}\approx 6$ MW in an unfocused laser beam, we detected THz pulses with energy of 400 µJ corresponding to a peak power of 2 kW. The measurement was done by mixing the 10R(22) and 10P(26) CO_2 laser lines resulting in the 260 µm (1.15 THz) output. This peak power corresponds to a ~$2x10^{-4}$ external conversion efficiency. As seen in Fig 2b, the DFG power at a room temperature GaAs decreases below 1 kW level at 100 µm due to the strong absorption in the phonon band. However, cooling the crystal to ~ 80 K should decrease the absorption [6] and power above 1kW

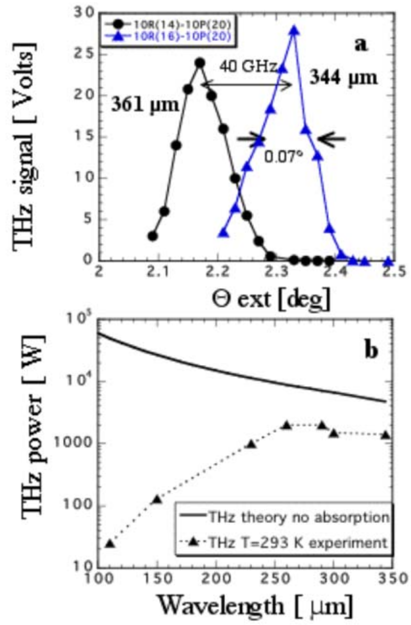

Fig.2 DFG power at 344 μm (triangles) and at 361 μm (circles) versus external phase matching angle Θ_{ext} in GaAs (a) and calculated (solid line) and measured (triangles) DFG peak power in the THz range (b).

is projected for the whole range of 1-3 THz (see solid line in Fig. 2b).

Teflon Bonded QPM GaAs Structure

Creation of a free-standing stacked wafer QPM structure requires a bonding mechanism in order to eliminate the Fresnel losses. The developed Teflon bonding technology is summarized in Table 1. To create a bonded structure, a very thin film of Teflon AF was deposited homogeneously on GaAs wafers (2” diameter, semi-insulating, specific resistivity >1.2E8). The wafers were baked in a furnace for complete removal of the solvent. After this step, the wafers were removed from the furnace and assembled into a stack in the clamp, which was then returned to the furnace at 320°C. Pressures sufficient for bow compensation were applied after the assembly of stacks. The pressures were maintained until the temperature was well below the glass transition temperature of the Teflon. Stacks of up to ten 1” by 1” diced wafers were fabricated via this procedure. The average Teflon layer thickness was measured with a micrometer to be around 5 μm.

Table 1: GaAs wafer bonding procedure

Procedure	**Temperature, Pressure**	**Time**
Spin on Teflon solution, 6000 rpm	RT, 0 MPa	30-45 s
Boil off FC-75 solvent	160 C, 0 MPa	15 min
Melting Teflon film	320 C, 0 MPa	15 min
Bonding wafers	320 C, 1-3 MPa	60 min
Cooling step1	100 C, 1 MPa	30 min
Cooling step 2	To RT, 0 MPa	15-20 min

Structures with such boundaries between materials with different refractive indicies were modelled as a sequence of etalons and good agreement was achieved between the calculated and measured incident angles for which transmission of a 10 μm beam was maximum. Using a stack of five (110) commercial GaAs wafers (725±25 μm), we detected about 0.7 μJ of energy at 343 μm. This was smaller by a factor of ~2 than a theoretical value calculated without taking into account losses. In the experiment the nonparallelism of GaAs wafers available caused a drop in transmission of a pump and, therefore a lower THz DFG efficiency. Such a QPM GaAs structure can be improved in the future by the use of prefabricated parallel GaAs slabs. The power achieved by now is below the requirement for the THz seed source for the FEL buncher, however, some other experiments can benefit from a simple, drop-off THz generator with a very low sensitivity to angle misalignment.

GUIDING OF THE THZ RADIATION

For a 2-m long THz FEL undulator [4], guiding of the THz pulse is a tool to minimize diffraction losses. We carried out a series of measurements on guiding of the THz DFG pulse using waveguides made of different materials and different profiles. The best results were obtained with a circular waveguide made of copper. Up to 90 % transmission was measured in a 50-cm long circular compared to 50% transmission in a rectangular one made of aluminium. The combination of smaller coupling losses for a more similar, round, focused THz beam and smaller surface roughness can explain the observed results for the circular copper waveguides. Note that the skin depth for the THz radiation is of the order of 100 nm.

ACNOWELEDGEMENTS

This work was supported by US. Department of Energy contract DE-FG03-92ER40727.

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1-4244-0917-9/07/$25.00