New Approach to Generation and Amplification of the THz Radiation in Plasma Created by Intense Two-Color Laser Fields

A. M. Popov\textsuperscript{1,2,3}, A. V. Bogatskaya\textsuperscript{1,3}

\textsuperscript{1}D. V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia, alexander.m.popov@gmail.com
\textsuperscript{2}Department of Physics, Moscow State University, 119991, Moscow, Russia
\textsuperscript{3}P. N. Lebedev Physical Institute, RAS, Moscow Russia

Construction of new types of THz radiation sources is nowadays of sufficient fundamental and practical interest. This interest is motivated by the prospects of using THz radiation for THz imaging in a lot of applications in science and technology [1]. However, till now THz frequency band is still insufficiently studied in comparison with infrared and microwave ones. Among others, THz generators based on the gas ionization by high-intensity femtosecond lasers are widely studied now. Such a way of THz generation allows to obtain radiation with a continuous spectrum throughout the terahertz bandwidth that is of importance for different spectroscopy applications. Typically, optical-to-THz conversion results from the four wave mixing process (FWM) in high-intensity femtosecond two color laser field \((\omega + 2\omega)\). Unfortunately, the efficiency of such conversion remains rather small - about 0.001- 0.01%. In this respect, problems of amplification of THz pulses as well as the development of new more efficient methods of optical to terahertz energy conversion are of significant importance. In this paper we propose an alternative way to enhance significantly the process of optical-to-THz conversion by using the resonance in four-wave mixing process. Such resonant enhancement is possible in the aluminum vapor irradiated by Ti-Sa laser pulse and its second harmonic via the aluminum atom excited state \(4s^2(3\Sigma_{1/2}^+)\) with the energy \(E_{4s} \approx 3.14\) eV close to the frequency of the Ti-Sa second harmonic \(h(2\omega) = 3.1\) eV. Schematically this process is shown at fig.1. We demonstrate that the THz output can be increased up to two orders of magnitude in comparison with the non-resonant process.

\[ E(t) = f(t) \times (E_\omega \cos(\omega t) + E_{2\omega} \cos(2\omega t)) \]

where \(\omega\) the frequency of the Ti-Sa laser and \(f(t)\) is the envelope being the same for both pulses. It was chosen in the sine-squared form with the half-duration \(\tau = 880\) atomic units (~20 fs), that corresponds to 8 optical cycles of the Ti-Sa laser or 16 optical cycles for its second harmonic.

The study of atomic emission was performed in the range of intensities for both fundamental and second harmonic \(\sim 10^{-5} - 2 \times 10^{-3}\) at. un. and the intensity of second harmonic is assumed to be several time less than the intensity of the fundamental one. On the one hand, the increment of the intensity gives rise to more efficient FWM process, on the other hand the ionization and the depletion of the ground state will reduce the probability of the resonance FWM.

Typical spontaneous emission spectra obtained in our simulations for aluminum atom are presented at figure 2. Curves 1, 2 and 3 represent the spectra obtained for Ti-Sa laser irradiation, its second harmonic as well as combined two-color action respectively. First of all, the peaks of Rayleigh scattering at \(\hbar\omega_{kl} = 1.55\) eV for fundamental frequency and \(\hbar\omega_{kl} = 3.1\) eV for the second harmonic are observed. The last peak has the triple structure (triplet Mollow) due to the near-resonant transition to 4s state. There are also some additional peaks appearing for the Ti-Sa laser resulting from different processes. Most important to highlight that for two-color laser pulse one more low-frequency peak with a maximum at \(\hbar\Omega_{kl} \approx 0.2\) eV is well pronounced. This peak manifests the FWM process when the second harmonic
quantum absorption and two quanta of Ti-Sa laser stimulated emission is accomplished by spontaneous emission of THz - far IR quantum (see figure 1).

Possible realization of such a concept is performed at figure 3. Terahertz spontaneous signal emerges in the region of intense two-color laser action and then propagates through the amplifying zone which is formed by KrF laser pulse. In the frames of our concept the presence of two different lasers is mandatory because we require high-intensities for the two-color pulse to reach high level of nonlinearity for FWM process but at the same time we do not need high level of ionization in the amplifying plasma channel as domination of electron-electron collisions will cause the fast relaxation of the nonequilibrium electron energy distribution function (EEDF) and destroy the population inversion.

To conclude, in this paper we demonstrate that the resonance between quanta of the laser radiation and energy transition from the ground to one of the excited states of the atomic system can result in the dramatic enhancement of the four-wave mixing process in two-colour laser field \((\omega + 2\omega)\) providing more efficient optical to THz conversion scheme. Possibility of further amplification of the THz background is discussed. Also, the new concept allowing to enhance the THz output from the two-color scheme in a nonequilibrium plasma channel formed by UV laser was proposed.

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