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Efficient Ultrashort THz Pulse Generation in $LiNbO_3$, ZnTe, GaSe and DAST Crystals

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Abstract: The value of the generated terahertz power limits the major specifications of the THz coherent techniques in imaging and tomography. We report on the effective generation pulse of THz radiation in a nonlinear crystals partially filling the cross section of the rectangular waveguide. The generation of terahertz (THz) radiation in the band 0.1-3 THz via optical rectification of femtosecond laser pulses in $LiNbO_3$, ZnTe, DAST, GaSe nonlinear optical crystals are presented, as well as the results of the numerical calculations for phase-matching.

Keywords: THz radiation, nonlinear crystal, optical rectification, phase-matching.

1. Introduction

Due to the achievements of nonlinear optics, in particular nonlinear frequency conversion of femtosecond optical laser pulses in the terahertz (THz) range and the development of THz sources and detectors, interest in effective waveguide [1] has grown considerably.

In the frequency range $0.1-10THz$, a free electron lasers (FEL_S) have the highest average power, $\sim 10^{-1}-10W$ (or $100\mu J$ of energy), but their disadvantage is that they cost much and are very large in size, i.e. are inaccessible for the scientists of many countries. Optically pumped molecular lasers (THz power up to $30mW$), klystrons, backward-wave oscillator (BWOs with $P \sim 10^{-3}W$), optical rectification $(P \sim 10^{-3}W)$, difference frequency generators, Schottky and Gunn diodes, photomixers ($100mW$ (pulsed)), photoconducting antennas $\left(P_{THz} \sim 80\mu W\right)$ generate less power than FEL do. However, modern advances in the development of THz detectors make it possible to use highly sensitive and high-speed receivers to compensate for the low power of THz source.

The value of the generated terahertz power limits the major specifications of the THz coherent techniques in THz-TDS systems, imaging and tomography. Photoconductive antenna and frequency conversion in nonlinear crystals (optical rectification) are two of the most common sources of broadband THz pulses for use in research, THz-TDS and other applications. Nowadays, optical rectification of femtosecond laser pulses is one of the most promising methods for generation of high-energy THz pulses [2-4]. The advantages of the optical rectification method are the possibility for phase matching to increase the THz radiation power, a wide spectral band of THz pulse, absence of generation threshold, linear polarization of the THz field strength, simplicity, and diversity of possible applications.

Efficient generation of ultra-short THz pulses, by optical rectification, in a nonlinear crystal, partially filling a rectangular waveguide, using pico- or femtosecond optical laser pulses was proposed and performed in [5-6]. The efficiency of the nonlinear conversion of optical laser radiation to the THz range depends on the condition of phase matching (PM) in the nonlinear crystal, i.e of the equality of the group velocity of the optical pulse and of the phase velocity of the THz pulse at the difference frequency. Phase matching was obtained by the proper choice of the thickness of the nonlinear crystal, namely the degree of partial filling of the waveguide.

This paper presents the experimental spectra of THz pulse, having been generated in DAST, $ZnTe, LiNbO_3$ crystals located in a free space (the case of phase-mismatch) as well as the results of the crystals thickness numerical calculations made to ensure phase-matching when the crystal partially fills the cross section of the waveguide. DAST, $GaSe, LiNbO_3$ and $ZnTe$ crystals were studied due to their high figures of merit (FOMs [7]) as FOM provides high efficiency of conversion of optical radiation into the THz range at PM. Two figures of merit of the nonlinear crystal used for optical rectification [7] are defined as

$$FOM_W = \frac{d_{eff}^2 L^2}{n_{opt}^2 n_{THz}}, \tag{1}$$

$$FOM_S = \frac{4d_{eff}^2}{n_{opt}^2 n_{THz} \alpha_{THz}}. \tag{2}$$

FOMW (if $\alpha_{THz} < 5cm^{-1}$) and FOMS (if $\alpha_{THz} > 5cm^{-1}$) are the measure of the energy conversion efficiencies at optical rectification in a weakly and a strongly absorbing crystals, respectively.

2. The effective generation of terahertz radiation in the band 0.1-2.5THz

$LiNbO_3$, DAST and $ZnTe$ nonlinear optical crystals mounted in a free space have been used in our experiments. The optical excitation of a broadband THz pulse was performed using $200\,fs$ pulses from a Ti-Sapphire laser $(\lambda = 800nm)$, [6]. The experimental setup for generation and detection of THz pulses is shown in Fig.1. The generation of the THz pulse is based on the mixing of the spectral components of a femtosecond optical laser pulse in a nonlinear crystal (optical rectification method), [2-7].

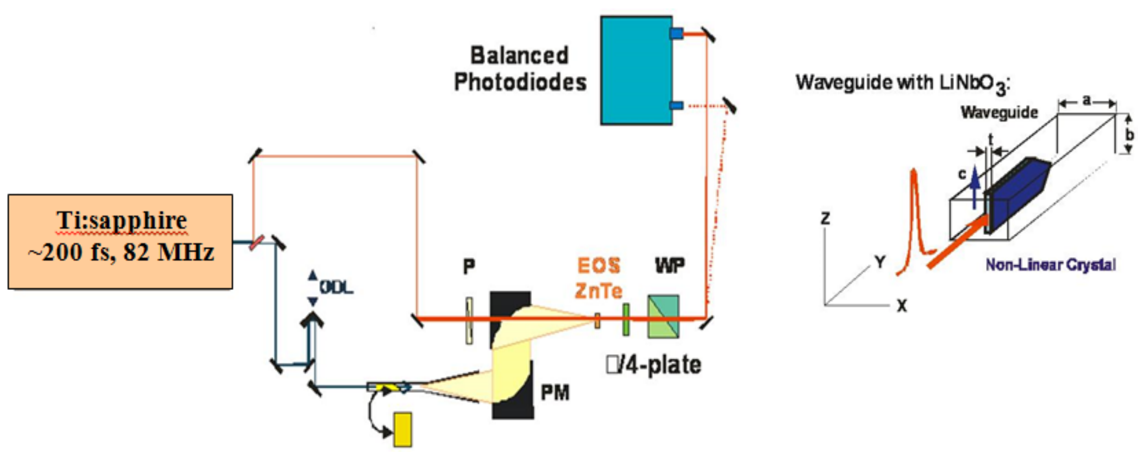

Fig.1. A simplified scheme showing the experimental instrumentation used to generate and detect THz pulses. The inset on the right shows a non-linear LiNbO3 crystal in the waveguide and the excitation geometry.

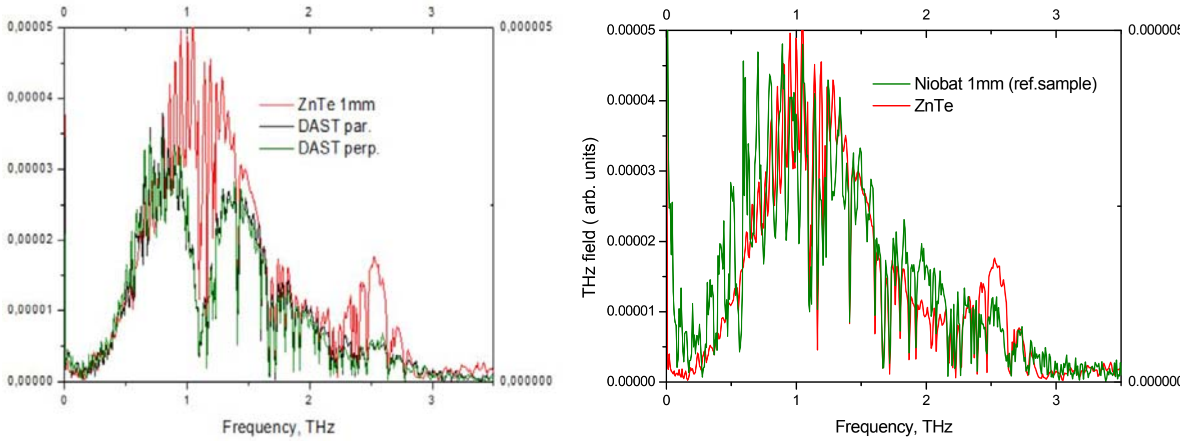

Fig.2. Spectra of THz pulses generated in $LiNbO_3$, ZnTe, DAST crystals.

The spectra of the THz pulses having been generated in $LiNbO_3, ZnTe$, DAST crystals, acquired after fast Fourier transform of the time-domain THz waveform, are illustrated in Figure 2. The maximum spectral density of the THz radiation in the frequency range from 0.1 to $3THz$ is observed at $997GHz$, $1.04THz$, $802GHz$ for $LiNbO_3, ZnTe$ and DAST crystals, respectively. The registration of the spectrum to up to $3THz$ is due to the fact that a $1mm$-thick $ZnTe$ crystal was used for coherent detection, which is the optimal crystal for the pump wavelength of $800nm$, i.e., within the tuning range of the widely used Ti: sapphire femtosecond lasers. By the selection of the optical pump wavelength (λ_{opt}) between 700 and $1600nm$ in organic DAST crystal [8] were obtained several maxima in the spectral range between 0.4 and $6.7THz$, with an optimum at $2THz$ generated with $1500nm$ laser pulses. For example, at $\lambda_{opt} = 710nm$, two spectral density maxima have been observed at about of $600GHz$ and $1.4THz$. Two spectral density maxima are observed at $802GHz$ and $1.4THz$ in our case as well, at a pump wavelength of $800nm$. In the case of a DAST crystal, the spectral density minima within the THz field at $1.3THz$ and $3THz$ (Fig. 2) are due to the maximum absorption coefficient for these frequencies. [8].

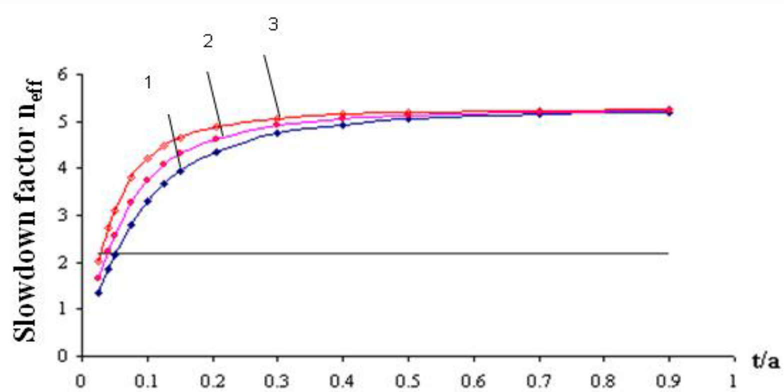

Fig.3. Slow-down factor n_{eff} of difference frequency radiation depending on t/a for $LiNbO_3$, when ε^e_{DFR} =28, $n^e(f_{DFR}) = 5.291$, $n^e(0.8\ \mu m) = 2.1745$. Curve 1 - $k_2 = a/\lambda = 0.5$; curve 2 - $k_2 = 0.65$; curve 3 - $k_2 = 0.9$.

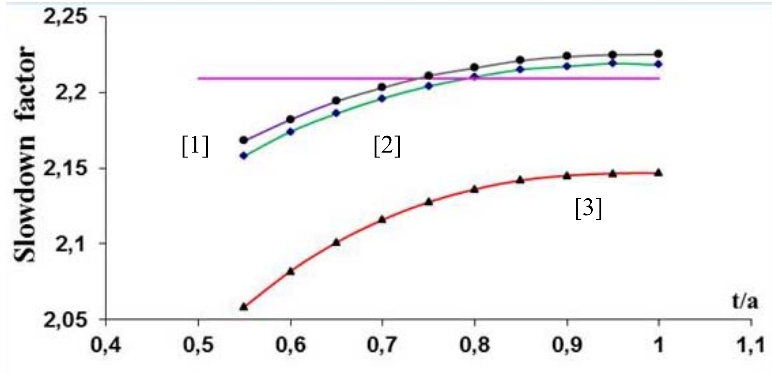

Fig.4. DFR slowdown factor n_{eff} versus t/a for DAST, ε (λ_{DFR}) = 5.2, a/λ = 1; 0.95; 0.65;

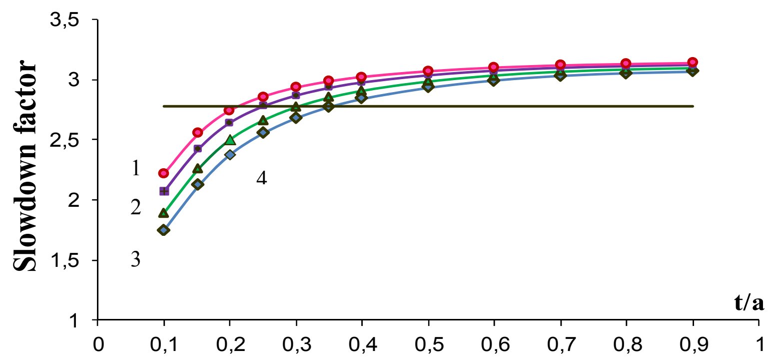

Fig.5. Calculated dependences of DFR slowing-down factors n_{eff} for ZnTe, ε(λ_{DFR}) = 10.1, in given a/λ.
1 - a/λ=1; 2 - a/λ= 0.85; 3 - a/λ= 0.7; 4 - a/λ=0.6.

In the case of collinear interaction of optical and THz waves in a crystal, the crystal thickness required for PM is determined by the dependence of $n_{eff}(\lambda_{THz}) = c/v(\lambda_{THz})$ on $k_1 = t/a$ and $k_2 = a/\lambda_{THz}$ for a given value of the dielectric susceptibility of the THz wave, $\varepsilon(\lambda_{THz})$, from dispersive transcendental equations [6]. The calculated values of n_{eff} as functions of k_1 (crystal thickness $t = ak_1$) and some of k_2 values in the frequency band of the fundamental mode of the H_{10} type of the waveguide, are shown in Fig.2 - 6. In the case of a thin crystal $(k_2 < 0.2), n_{eff}$ quickly grows and tends to the value of the refractive index n_{THz} of the wave of the crystal placed in a free space. The line parallel to the k_1 axis, having the value $n_{eff} = n(\lambda_{opt})$ [5], intersects the family of curves $n_{eff} = f(t/a)$ at the points defining $k_1 = t/a$ or the thickness of the crystals for which the phase matching condition is satisfied. Thus the crystal acts as a nonlinear frequency converter, and the waveguide + crystal structure acts as a device that changes the phase velocity of the THz wave to the value of the group velocity of the laser pulse.

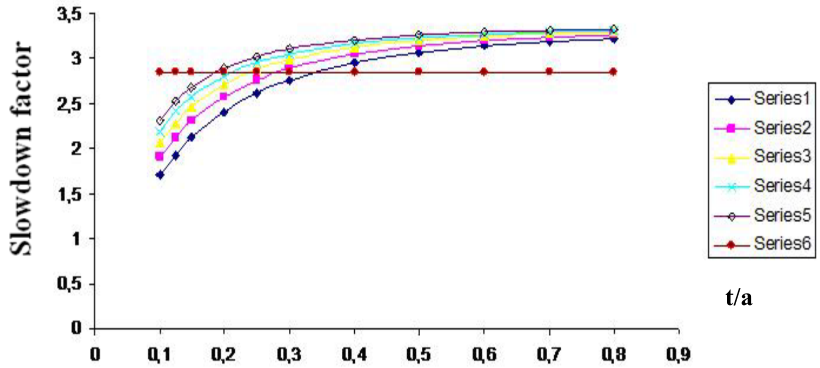

Fig.6. DFR slowdown factor versus t/a for GaSe, ε(λ_{THz}) = 11.5, a/λ = 0.5 Series 1; a/λ = 0.6 Series 2; a/λ = 0.7 Series 3; a/λ = 0.8 Series 4; a/λ = 0.9 Series 5.

3. Conlusion

Optical excitation of broadband THz pulse was performed using $200\,fs$ pulses from a Ti-Sapphire laser ($\lambda = 800nm$). DAST, $GaSe, LiNbO_3$ and $ZnTe$ crystals were studied due to the high efficiency of conversion of optical radiation to THz range by OR. The crystals were located in a free space - the case of phase-mismatch. Frequencies in the range $0.1-3THz$ are obtained.

The results of numerical calculations show that it is possible to provide phase matching of nonlinear polarization waves and THz wave by choosing the degree of filling of the cross section of the waveguide with one of these crystals. This method allows to increase the nonlinear conversion efficiency of ultra-short laser pulses in the $GHz-THz$ range. The results of experiments with a $LiNbO_3$ crystal show that the DFR intensity increases by an order of magnitude as compared with the case with no phase matching [6]. These results show a technique for the generation of high-power, broadband, high-repetition-rate THz pulses in a waveguide partially filled with a nonlinear crystal. The results can be used for creating effective THz broadband active waveguide systems or frequency scanning antenna.

Acknowledgments

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