Terahertz Radiation Generation in Waveguide Partially Filled with Nonlinear Crystal

A.S. Nikoghosyan[a], N.N. Zinov'ev[b], J.M. Chamberlain[b], R.A. Dudley[c], R.M. Martirosyan[a]
[a]Department of Microwave Engineering, Yerevan State University, 1 A. Manoogian Str., Armenia
[b]Department of Physics, Rochester Building, Science Laboratories, University of Durham, DH1 3LE
[c]National Physical Laboratory, Queens Road, Teddington, Middlesex TW11 0LW, UK

***Abstract*—** We report on the effective generation pulse of THz radiation via optical rectification of femtosecond laser pulses in a nonlinear crystal. By placing the same nonlinear crystal in the free space and then inside the waveguide the phase-matching and consequently time and spectral features of the emitted THz field are changed. The rise of conversion efficiency in the order of magnitude has been obtained in waveguide structures partially filled with $LiNbO_3$ crystal.

I. Introduction And Background

To effectively transform laser emission into THz range, it is necessary to provide the phase-matching condition. Because of crystal dispersion it is difficult to provide the phase matching for all interactive frequencies in the spectrum of the optical pulse and difference frequency radiation (DFR). Phase matching at the generation of THz radiation is provided by different methods [1-3]. An approach using a hollow metal waveguide partially filled with a nonlinear crystal was first proposed and realized in [4,5]. In this case the crystal acts as a nonlinear frequency transformer, but the waveguide-crystal stands as a setup increasing the phase velocity of DFR to group velocity of laser pulse. By crystal thickness choice in the rectangular waveguide cross-section the phase matching can be controlled. The crystal thickness necessary for carrying out synchronism is defined from dispersion transcendental equation solution. It is shown that phase matching can be achieved both for the main and highest types of the waveguide mode [5].

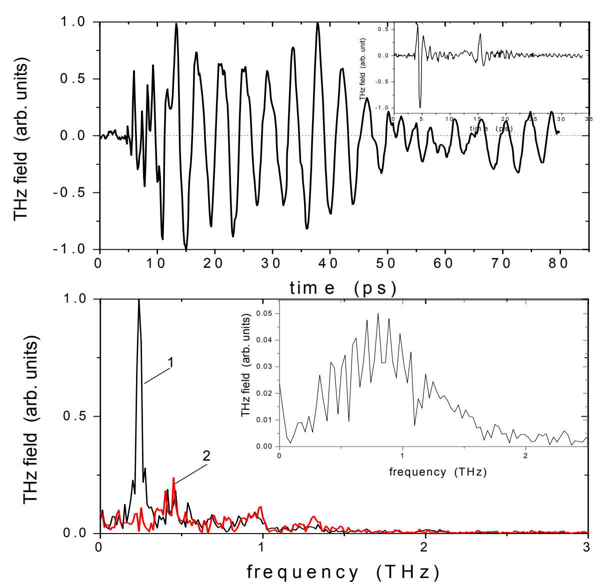
II. Results

We present the results of effective THz radiation generation in nonlinear crystal placed in the waveguide and free space. THz radiation generation was studied in waveguides with cross section from 7.2x3.6 mm to 1.8x0.9 mm. In central-symmetrical placing of the crystal in regard to the wide waveguide wall the THz radiation is spread as the sum of the main H_{10} and higher order modes of H_{no} waves when n takes odd values. Shifting the crystal towards the narrow wall of the waveguide, the mode of waves H_{no} can be controlled, thus providing band-pass tuning of the wave range. The calculations carried out show that in central-symmetrical placing of the crystal in the waveguide with cross section 5.2x2.6 mm when the crystal has parameters 3.3x2.6 mm, 62 waves of DFR in the form of the mode H_{no} in the range from 30 GHz to 1100 GHz can be spread with the same velocity, but in waveguides 2.4x1.2 mm and 1.8x0.9 mm when crystal thickness is 300 µm and 270 µm , waves can be spread from 60 GHz to 2500 GHz and from 75 GHz to 4 THz, respectively.

In paper [6] it is theoretically and experimentally shown that focused in rectangular waveguide (250µmx125µm) the linearly polarized THz pulse, generated out of the waveguide by GaAs antenna, is propagated in it as the main mode – TF_{10} (H_{10}), containing up to 35 waveguide modes in the range within 0.65 to 3.5 THz.

These results are important for they allow to realise the propagation of the THz pulse in the waveguide as the main mode with unambiguous value of the wave vector. It makes easier the collection and detection of the THz field. The pulsed bandwidth THz radiators are of great importance as coherent effective sources for spectral THz imaging systems, high-speed communications, high-resolution THz waveguide spectroscopy.

Optical excitation of the crystals $LiNbO_3$ was performed with 200 femtosecond pulses of a Ti:sapphire laser (λ=800 nm), the average power being 750 mW [7]. In the chosen geometry of crystal the nonlinear polarization is determined by the largest component of the dielectric susceptibility tensor χ_{33}=34 pV/m. The optical beam was focused to a spot the size of which could be varied from 100 µm to 1.5 mm. Crystals had length from 0.5 to 8 mm. The end face of the gilded waveguide having 25 mm length was connected to the pyramidal horn amplifying 24 db. Horn parameters were chosen so that the full matching with the receiving aperture of parabolic mirrors collecting radiation from the waveguide was obtained.



(a)

(b)

978-1-4244-2120-6/08/$25.00©IEEE.

Coherent detection was performed by using dynamic electrooptic sampling cell (EOSC) with crystal ZnTe of the (110) facet orientation and 1 mm thickness. Fig.1 represents (a) time dependence of the THz field and (b) its spectrum after fast Fourier transform when the crystal is placed centrally–symmetrically (1) and then it was shifted to the narrow wall (2) in the waveguide with dimensions 2.4x1.2mm. The time waveform of the THz pulse consists of a large number of cycles with a spectrum of phase-matched frequencies, the central frequencies being at 239 GHz. The time and spectrum form changing of the THz pulse is observed by changing the location of the crystal. In shifting the crystal to the narrow wall of the waveguide the central frequency is offset to the high frequency region - 449 GHz. The inserts show the THz pulse and its spectrum when the crystal is placed in the free space. Two pulses in the waveform result in appearing oscillations in the spectrum. Two single-cyclic pulses irradiated from the front and end faces of $LiNbO_3$ crystal having thickness 1.08 mm is explained by "transition radiation", i.e. reaction of nonlinear medium on crossing its boundaries by ultra-short light pulse [8]. Fig.1 (c) represents time dependence of the THz field and the envelope of the power spectrum (d), after statistical processing of the crystal having parameters 3.3x2x6 mm in the waveguide with cross-section 5.6x2.6 mm. The frequencies of the most intensive radiation line are well agreed with the frequency calculation values for which phase matching is performed with the given thickness of the crystal and its central-symmetric location in the waveguide. If the absorption of THz waves is ignored by water vapours in the air, as well as by dependence of absorption coefficient in the structure "waveguide-crystal" near critical frequency of the partially filled waveguide, then 62 waves can propagate with similar velocity within the range from 30 to 1100 GHz. If [1-3] matching is performed for the given THz frequency, the THz field has a sinusoidal form with a large number of cycles.

The method of the phase matching by the partially loaded waveguide broadens the choice of nonlinear materials, as it is applied to the crystals in which the birefringence is absent or is insignificant, though nonlinear susceptibility is high and absorption is weak, e.g. GaSe, $ZnGeP_2$. The calculations performed for the crystal GaSe show that in central-symmetrical placing GaSa in waveguides with dimensions 2.4 mmx1.2 mm, 1.8 mmx0.9 mm, 0.25 mmx0.125 mm with design thickness of crystal providing phase matching the THz pulses can be generated in frequency bandwidth from 44 to 1000 GHz, 60 - 1300 GHz, 0.42 -9.6 THz, respectively. If the crystal length is increased to optimal one the high efficiency of energy conversion can be achieved in generation and in detecting with the high sensibility for precise specification of the THz pulse amplitude and phase.

In [9] it is shown that at present "highly efficient THz source based on optical pulse rectification is a hollow metal waveguide partially filled with nonlinear material wherein phase matching between a THz wave and optical pulse, or both phase and group velocity matching between a THz wave

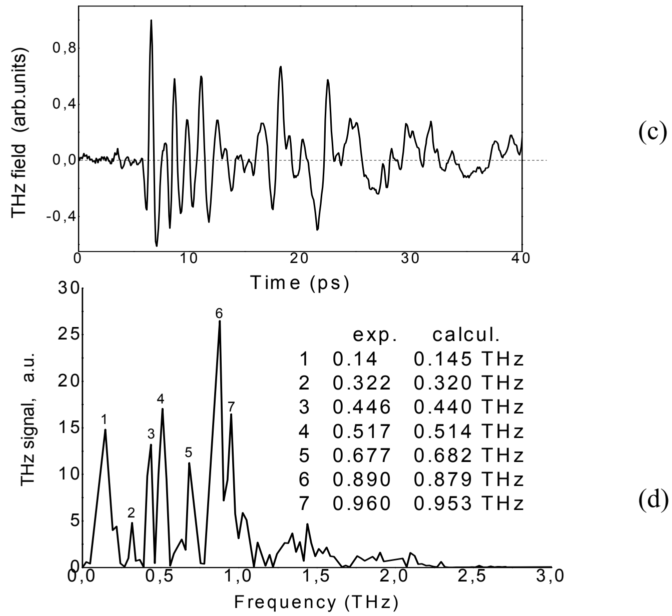


Fig.1 Time waveform (a, c) and spectrum (b) of THz pulse

and optical pulse" is performed owing "to waveguide dispersion and overcoming the Manley-Rowe limits of optical schemes".

Conclusion. The results of the numerical calculations and experimental data show that changing the crystal thickness and its location in regard to the narrow wall of the waveguide the H_{no} mode of the waves and conversion effectiveness and therefore spectrum composition of the THz pulse and its time behavior can be reproductively controlled.

REFERENCES

[1] W. Shi, Y. J. Ding, N. Ferneliusand, K. Vodopyanov, ''Efficient, Tunable and Coherent 0.18–5.27 THz Source Based on GaSe Crystal". Opt. Lett., 2002, vol. 27, no.16, pp. 454-1456.

[2] A. Nahata, A. S. Weling, and T. F Heinz. "A Wideband Coherent THz Spectroscopy System Using Optical Rectification and Electro-Optic Sampling". Appl. Phys. Lett., 1996, vol. 69, no. 16, pp.2321-2323.

[3] Y. S. Lee, T. Meade, T. B. Norris and A. Galavanauskas. "Tunable Narrow-Band Terahertz Generation from Periodicaly Poled Litium Niobate". Appl. Phys. Lett., 2001, vol. 78, pp. 3583-3585.

[4] A. S. Nikoghosyan. "USP Generation in the Millimeter and Centimeter Bands in a waveguide Partially Filled with a Nonlinear Crystal". Kvantovaya Elektronika, Moscow, 1988. vol. 15, no.5, pp 969-971.

[5] E. M. Laziev, A.S. Nikoghosyan. "Phaze Synchronizm and Ultrashort SHF Pulses Generation in Waveguides". SPIE, Mode-Locked Lasers and Ultrafast Phenomena, 1991, vol. 1842, pp.113-118.

[6] G. Gallot, S. P. Jamison, R. W. McGowan, D. Grischkowsky. "THz Waveguides. J. Opt. Soc. Am. B, 2000, vol. 17, no.5, pp. 851-863.

[7] A.S. Nikoghosyan, R.M. Martirosyan, A.A. Hakhoumian, J.M. Chamber lain, R.A.Dudley, N.N.Zinov'ev. "Generation of THz Radiation in Waveguide Partially Loaded with Nonlinear Crystal". Electromagnetic waves and Electronic Systems, 2006, vol. 11, N4, pp. 47- 55.

[8] N.N. Zinov`ev, A.S. Nikoghosyan, J.M. Chamberlain. "Terahertz Radiation from a Nonlinear Slab Traversed by an Optical Pulse". Physical Review Letters, 2007,vol. 98, pp. 044801-1 044801-4.

[9] R. R. Hayes S. Ionov, "Highly efficient waveguide pulsed THz electromagnetic radiation source and group-matched waveguide THz electromagnetic radiation source". USA Patent Issued on 18.09.2008 No. 11355245

978-1-4244-2120-6/08/$25.00©IEEE.