GENERATION OF THz RADIATION IN NONLINEAR CRYSTAL PARTIALLY FILLING A HOLLOW WAVEGUIDE

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The results of the THz pulse generation via optical rectification of pico- and femtosecond laser pulses in nonlinear crystal are presented. Detection of THz pulses is performed at room temperature by both Schottky diode and ZnTe crystal. The quantum efficiency of energy conversion up to 28% of maximum value is obtained with Schottky diode.

Keywords: Optical rectification; efficient THz pulse generation; rectangular waveguide; femtosecond laser, Schottky diode.

1. Introduction

In recent years considerable achievements were reached in development of sources and detectors in terahertz (THz) band (0.1–100 THz). They found various potential applications in terahertz time-domain spectroscopy (THz-TDS), medical diagnostics, remote sensing and security screening, space science, high-speed communications and high resolution of THz waveguide spectroscopy.

For transmitting the THz radiation from the source to the object and then to the detector it is necessary to utilize different guided structures, such as hollow metallic waveguides^{1–3}, solid wires⁴, copper coated flexible hollow polycarbonate waveguide⁵, metallic slit waveguide⁶, one-dimensional (1D) Bragg waveguide⁷, parallel-plate waveguides⁸, dielectric waveguide⁹, surface plasmon polariton waveguides^{10–11} and ribbon-based dielectric waveguides¹².

The value of the generated terahertz (THz) power limits the major specifications of the THz coherent technique applications in imaging and tomography, such as penetration depth, signal-to-noise ratio, and so on. Therefore the increase of generated THz power at room temperature will improve the overall performance of THz imaging systems.

During propagation of optical laser pulse in the medium with the second order nonlinear susceptibility a conversion of energy into radiation of sum and difference frequency owing to coherent mixing of spectral components of the optical pulse occurs. To effectively generate radiation sum or difference frequency, it is necessary to provide

the phase-matching condition for all spectral components of the optical pulse participating in a nonlinear process. Phase matching between group velocity of the optical pulse and phase velocity of difference frequency wave is performed by different methods: birefringence, dispersion in the pump frequency range, wave front tilting, artificial periodic structure. The possibility of increasing light conversion efficiency into THz range by nonlinear crystal partially filling the metallic rectangular waveguide was suggested, theoretically grounded and experimentally realized in Ref. 2, 3, 13. The metallic rectangular hollow waveguide is used to achieve phase matching, large coupling coefficients, and low propagation loss for both the optical and THz waves. This method broadens the choice of nonlinear materials. Another advantage of this method is that by choosing the crystal thickness and its disposition concerning the narrow wall of the waveguide it is possible not only to control mode type, but also to make the absorption loss of the waveguide with the crystal much less than the intrinsic loss of the crystal.

2. The Generation of THz Radiation in Nonlinear Crystal LiNbO₃ Partially Filling the Metallic Rectangular Waveguide

The optical excitation of the LiNbO₃ crystal having tapered end is performed by 50 or 200 fs pulses of a Ti:sapphire laser¹³ ($\lambda=800$ nm) with frequency repetition of 82 MHz or 1 ps pulses of a mode-locked Nd: glass laser^{2,3} ($\lambda=1.06$ μm) with pulse repetition period 7 ns. Time dependence of the THz field when LiNbO₃ is placed in a free space (FS) and then in a hollow metallic rectangular waveguide (WG) 1.8×0.9 mm² is shown in Fig.1(a) and its corresponding spectra after Fast Fourier Transform (FFT) in Fig.1(b). Coherent detection¹⁴ of linear polarized femtosecond THz pulse in the band 0.1–2.7 THz as the superposition of H_{no} modes is performed with a dynamic electro-optical sampling cell (EOSC) consisting of the crystal ZnTe orientation (110) with 1 mm thickness.

Fig.1. Time dependence (a) of the THz field and its spectrum (b) after fast Fourier transform when the crystal is placed in free space (FS) and centrally-symmetrically in the waveguide (WG) with dimensions 1.8x0.9 mm².

Nanostructured GaAs Schottky barrier diodes have been widely used not only as low noise mixers in high resolution heterodyne spectrometers in the spectral range 300 GHz to 5 THz (1–20 meV) and a spectral resolution of $\nu/\Delta\nu > 10^6$, as well as frequency multipliers and detectors. Schottky diodes (rectifying metal-semiconductor junctions) are used as a detector because of their higher switching speeds and their inherent suitability for low-voltage. The high-frequency performance of GaAs Schottky barrier diodes is limited by the parasitic circuit elements within the diode, particularly the series impedance and junction capacitance. The cutoff frequency of GaAs diode¹⁵, specifically model 1T15 is 25 THz (Table 1).

Table 1. Schottky diode parameters.

Diode	Anode Diamet. d(μm)	Epilayer Thickn. t (Å)	Series Resist. R (Ω)	Zero-Bias Capacit. C (fF)	ΔV at 10-100μA (mV)	Ideality Factor, η 10-100 μA (mV)	Cut-off Frequency $\nu=1/2\pi RC$, (THz)
1T14	0.45	400	8-10	0.9-1.1	85-90	1.4-15	18
1T15	0.25	300	25	0.3	90	1.5	25
1T6	0.45	1000	40	0.4	81-83	1.35-1.4	10
117	0.80	800	10-13	0.8-1.4	77	1.3	12.6

The optimum current dependence on frequency for four diodes¹⁶ is shown in Fig.2. The local oscillator frequencies are used in the range of from 11 GHz to 2550 GHz.

Fig.2. The optimum current dependence on frequency for diodes, showing the linear relationship for each of the diodes.

In our experiment the Schottky diode was used as a direct detector in broad frequency range with the cutoff frequency $f_c(\text{GaAs}) \sim 7 \text{ THz}$ and with extremely fast response time $< 1 \text{ ps}$. Therefore the THz pulse train envelope reproduces the envelope of laser pulse train in the required frequency range at room temperature. The lengths of the utilized LiNbO_3 crystal were changed from 0.4 mm to 23 mm. The effective generation of THz pulse (in partially filled with nonlinear crystal waveguide) with high intensity makes it possible to detect THz radiation by Schottky diode located at the end of sufficiently long waveguide, that is 60 cm long.

Oscillograms of picosecond laser pulses (a) and GHz-THz (b) pulse train at timebase 10 ns/mm is shown in Fig.3 when the crystal is centrally-symmetrically located in the waveguide with cross-section $7.2 \times 3.6 \text{ mm}^2$

Fig.3. Oscillograms of the trains of laser (a) and GHz-THz (b) pulses when the crystal is located centrally-symmetrically in the waveguide with cross-section $7.2 \times 3.6 \text{ mm}^2$.

The duration of trains is 500 ns. The maximum peak power is 2.6 W. Whisker-contacted Schottky diode is the preferred nonlinear element, but it works on linear part of its volt-ampere characteristic, because amplitude envelopes of the picosecond laser and THz pulse trains are similar (Fig. 3a, 3b).

THz picosecond pulse train with repetition pulses of ~ 7 ns, at timebase 5 ns/mm, and peak power 142 mW detected by Schottky diode in waveguide 2.4×1.2 mm² is shown in Fig.4(b).

Fig.4. Oscillograms of the trains of laser (a) and THz (b) pulses when the crystal is located centrally-symmetrically in the waveguide with cross-section 2.4×1.2 mm².

3. Conclusion

Increasing conversion efficiency in the order of magnitude has been obtained in waveguide partially filled with LiNbO₃ compared to the crystal placed in a free space¹⁷. At phase matching in waveguide efficiency energy of nonlinear conversion compared to mismatching is increased ~ 50 times. The quantum efficiency of energy conversion up to 28 % of maximum value is obtained with Schottky diode.

For high efficiency THz radiation generation it is suggested¹⁸ to coherently combine THz radiation from nonlinear crystal-waveguide arrays. These dielectric antenna arrays can be used for implement efficient, robust, and compact THz sources suitable for applications such as security screening, medical imaging, quality control, chemical composition detection and package and container inspection.

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