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WAVEGUIDE STRUCTURES FOR GENERATION OF TERAHERTZ RADIATION BY ELECTRO-OPTICAL PROCESS IN GaAs AND $ZnGeP_2$ USING 1.55 μm FIBER LASER PULSES

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Abstract—By discussing the basic schemes of the terahertz generation methods based on the 1550-nm ultrafast lasers briefly, GaAs and $ZnGeP_2$ are likely to be promising nonlinear optical crystals for terahertz waves generation by using optical rectification process. However, the mismatches of velocities between the terahertz waves and optical pulses are so large that the phase-matching coherent lengths are quite short, for example, the coherent length of 0.7 mm for GaAs and 0.5 mm for $ZnGeP_2$ at 2 THz around, respectively. That limited extremely the applications of these bulk excellent nonlinear optical crystals in terahertz regime. In this paper, we demonstrated theoretically that the dielectric planar waveguide could be used to enhance the coherent length of optical rectification process in THz regime. And for the first time, a dielectric planar THz waveguide that has potential applicable value in THz generation by optical rectification method was proposed. We predicted that the effective coherent length could be extended to 4 mm at 2 THz in a GaAs/$ZnGeP_2$ dielectric planar waveguide during optical rectification process pumped by ultrafast optical pulses at wavelength of 1550 nm.

1. INTRODUCTION

Recent advances in the ultrafast-pulse-laser technique have spurred the rapid development of the generation and detection of the terahertz (THz) electromagnetic pulse, which has led to various applications, such as material characterization, time-domain spectroscopy, and imaging. The THz emitter, based on ultrafast laser, is a potential candidate that has a wide THz bandwidth. But the Ti: Sapphire solid state laser that is currently being used as a pump source, is too expensive and bulky. Hence, developing a compact, low cost THz field source and detection technique, based on 1550-nm fiber laser, is a necessity. The present research trend suggests a shift of the pump wavelength from 810 to 1550 nm of ultrafast fiber laser to use cheaper components for optical communication wavelength [1]. And fiber laser also has the advantages of compact, low cost, free of water-cooling, etc.

There exist two schemes for THz pulse generation by tabletop devices. These are photoconductive switches illuminated by ultrashort laser pulses, and optical rectification of ultrashort laser pulses in nonlinear crystals. To realize photoconductive switches operable with 1550-nm light, the band gap of the material should be reduced so as to enable efficient photoexcitation. Though low-temperature-grown (LTG) $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ ($0.4 < x < 0.53$) has been shown to work at 1560-nm excitation [2], there is no well established photoconductive material suitable for 1550-nm excitation yet. A nonresonant electro-optical (EO) process is the simplest method for both THz generation with optical rectification and detection using EO sampling methods because the optimization of nonlinear crystal is well established even in the long wavelength region. Optical rectification of femtosecond laser pulses in nonlinear crystals is a proven way to generate THz radiation. The earliest optical rectification experiments were performed by Yang et al. in a LiNbO_3 nonlinear optical crystal. Later, other groups applied the optical rectification technique to different nonlinear crystals such as LiTaO_3, GaAs, GaSe and others, and used femtosecond laser pulses to increase the generated THz bandwidth [3]. Recently, 10 μJ ultrashort THz pulses have been generated by optical rectification in a lithium niobate crystal based on a 10 Hz Ti: sapphire laser [4]. However, there is rare successful examples of THz pulses generation by optical rectification in a nonlinear crystal based on an ultrafast fiber laser at a wavelength of 1550-nm. The main reason is that matching between the optical group velocity and THz phase velocity is crucial for efficient optical rectification. For a large set of well known nonlinear crystals with low absorption in THz band, such as GaAs, GaSe, GaP, ZnTe and ZnGeP_2, their phase matching conditions are not satisfied at 1550 nm, resulting in quite small coherent length. So the enhancement of coherence length of the nonlinear process is crucial way to improve the THz radiation efficiency. In this paper, we are intent on designing a planar waveguide configuration to reduce the degree of mismatching between the optical group velocity and THz phase velocity.

There several groups have demonstrated the planar waveguide structures in THz generation. They all aimed on confining the THz radiation in a metallic planar waveguide effectively in which the THz field is forced to be a fundamental guide mode of transverse electromagnetic (TEM) mode [5–7]. The phase velocity of TEM mode in a metallic planar waveguide is the same as electromagnetic waves in free space. That means that the metallic waveguide structure would not be effective to narrow the velocity gap between the optical pulses and THz radiation. Normally, the phase velocity of THz wave is smaller than the group velocity of the near infrared ultrashort pulse in nonlinear optical crystals. In this paper, we try to establish a dielectric planar waveguide for THz waves in which the fundamental mode is transverse magnetic (TM) mode of which effective propagation velocity is larger than TEM mode in a metallic planar waveguide. This is the first time, to our knowledge, to establish a dielectric planar waveguide for THz waves to enhance the coherent length of optical rectification of ultrashort optical pulse at a wavelength of 1550-nm for THz wave generation.

2. COHERENT LENGTH

The phase matching condition for the optical rectification process (collinear difference frequency mixing) is given by

$$\Delta k = k\left(\omega_{\text{opt}} + \omega_{\text{THz}}\right) - k\left(\omega_{\text{opt}}\right) - k\left(\omega_{\text{THz}}\right) = 0 \tag{1}$$

where ω_{opt} and ω_{THz} are the optical and THz wave frequencies, respectively, and ω_{opt} and $(\omega_{\text{opt}} + \omega_{\text{THz}})$ lie within the spectrum of the optical pulse. If we neglect dispersion in the optical spectral range, we can express the coherence length $lc(= \pi/\Delta k)$ as

$$l_c = \frac{\pi c}{\omega_{\text{THz}}\left|n_{\text{opt,phase}} - n_{\text{THz}}\right|} \tag{2}$$

Here, c is the speed of light and $n_{\text{opt,phase}}$ and n_{THz} are the optical and THz wave refractive indexes of bulk crystals, respectively. For an ultrashort optical pulse, the dispersion in the optical refractive index may be used to obtain collinear, noncritical phase matching over a broad bandwidth in the THz band. For a medium with dispersion at optical frequencies, the phase matching condition of Eq. (1) may be rewritten as [8]

$$\frac{k(\omega_{\text{THz}})}{\omega_{\text{THz}}} \approx \left(\frac{\partial k}{\partial \omega}\right)_{\text{opt}} \tag{3}$$

This relation implies that phase matching is achieved when the phase of the THz wave travels at the velocity of the optical pulse envelope (i.e., the optical group velocity, v_g). The corresponding coherence length for difference frequency mixing is now

$$l_c = \frac{\pi c}{\omega_{\mathrm{THz}} \left| n_{\mathrm{opt,group}} - n_{\mathrm{THz}} \right|} \tag{4}$$

where $n_{\mathrm{opt,group}}$ is the group index at the optical pump frequency in the bulk nonlinear optical crystal and can be determined by the dispersion property of the optical crystal as following expression

$$n_{\mathrm{opt,group}} = n_{\mathrm{opt,phase}} - \lambda_{\mathrm{opt}} \left. \frac{dn_{\mathrm{opt,phase}}}{d\lambda_{\mathrm{opt}}} \right|_{\lambda_{\mathrm{opt}}} \tag{5}$$

where λ_{opt} is the center-wavelength of pumping ultrashort optical pulse.

Using published values [9–11] for the relevant optical parameters, we have calculated the $n_{\mathrm{opt,group}}$ at optical wavelength of 1550 nm and n_{THz} at 2 THz for a set of well known nonlinear crystals. The results are shown in Table 1.

Table 1. The group index at the optical pump frequency and the phase index at THz frequency of well known nonlinear crystals.

	GaAs [9]	$\mathrm{ZnGeP_2}$ [10, 11]	GaP [11]	ZnTe [9]
$n_{\mathrm{opt,phase}}$@ 1550 nm	3.3767	3.1697	3.0543	2.7330
$n_{\mathrm{opt,group}}$@ 1550 nm	3.5174	3.2745	3.1705	2.8065
n_{THz}@ 2 THz	3.61	3.420	3.3494	3.22
$\lambda_{\mathrm{opt,phase-maching}}$ @ 2 THz [nm]	1330	1191	1000	800
l_c@ 1550 nm [mm]	0.78	0.5155	0.42	0.1

From the Table 1 we can see that the coherent length is quite small for optical rectification process because of the difference between the $n_{\mathrm{opt,group}}$ and n_{THz}, and n_{THz} is normally larger than $n_{\mathrm{opt,group}}$. So we have to reduce the n_{THz}, or increase the phase velocity of THz wave by introducing appropriate waveguide structure to enhance the coherence length if the $n_{\mathrm{opt,group}}$ is kept unchangeable in that waveguide structure.

3. DIELECTRIC PLANAR WAVEGUIDE FOR THZ WAVES

We set up a dielectric planar waveguide (See Fig. 1) for THz waves other than a metallic planar waveguide because the electromagnetic waves could travel faster in dielectric planar waveguides than in a bulk counterpart dielectric medium.

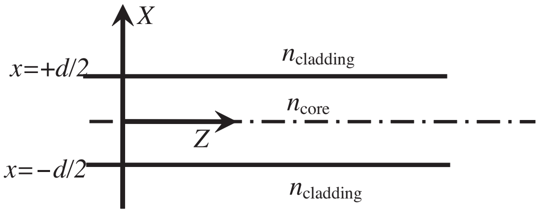

Figure 1. Dielectric planar waveguide geometry.

The solution of TM modes for the electric field may be written [12]

$$E_x = E_y = 0, \quad E_z = \begin{cases} -\dfrac{\alpha_x}{i\omega n_{\mathrm{cladding}}^2} B e^{-\alpha_x x} e^{-i\beta z} & x > \dfrac{d}{2} \\ -\dfrac{k_x}{i\omega n_{\mathrm{core}}^2} A \sin k_x x e^{-i\beta z} & |x| < \dfrac{d}{2} \\ -\dfrac{\alpha_x}{i\omega n_{\mathrm{cladding}}^2} B e^{\alpha_x x} e^{-i\beta z} & x < -\dfrac{d}{2} \end{cases} \tag{6}$$

where k_x is the transverse propagation number and β is the longitudinal propagation number which is equal to the propagation number of TM mode in the core range, α_x is the transverse parameter of mode section, ω is the angular frequency of electromagnetic field, n_{core} and n_{cladding} are the refractive indices of core medium and cladding medium of the planar waveguide, respectively.

By matching the boundary conditions at $x = d/2$, we can have the determinantal equation

$$\frac{k_x}{i\omega n_{\mathrm{core}}^2} \tan \frac{k_x d}{2} = \frac{\alpha_x}{i\omega n_{\mathrm{cladding}}^2} \tag{7}$$

The longitudinal propagation number, β, and the transverse propagation number of k_x can be determined by combining the relations (8) as following derived from wave equations with Eq. (7).

$$\begin{aligned} \beta^2 - \alpha_x^2 &= \omega^2 \mu_0 n_{\mathrm{cladding}}^2 = k_{\mathrm{cladding}}^2 \\ \beta^2 + k_x^2 &= \omega^2 \mu_0 n_{\mathrm{core}}^2 = k_{\mathrm{core}}^2 \end{aligned} \tag{8}$$

where k_{core} and k_{cladding} are the propagation numbers in unbounded mediums of which indices are n_{core} and n_{cladding}, respectively.

The propagation number β is smaller than k_{core}, thus indicating that the phase velocity of mode is greater than the speed of an infinite plane wave in a medium with a uniform index n_{core}. This situation can not be happened in a metallic planar waveguide in which the fundamental mode is TEM mode which electric field can be written

$$E_x = \begin{cases} 0 & x > \frac{d}{2} \\ E_0 e^{-i\beta z} & |x| < \frac{d}{2}, \quad E_y = 0, \quad E_z = 0 \\ 0 & x < -\frac{d}{2} \end{cases} \tag{9}$$

where β is the propagation number of the TEM mode and is equal to the k_{core} if the medium with refractive index of n_{core} is sandwiched between two metallic films or plates.

We finally choose two kinds of nonlinear optical crystals which have high effective nonlinear coefficients for optical rectification process and low absorption in THz regime, GaAs and ZnGeP_2, after examining a large set of well known nonlinear crystals. We designed three different planar waveguide structures by using different crystals and calculated the propagation number β of TM_0 mode, the fundamental mode, and the effective index, $n_{\text{THz,eff.}}$, at a frequency ω of 2 THz according to the Eq. (10). The results are summarized in Table 2.

$$\beta^2_{TM_0} = \omega^2 \mu_0 n^2_{\text{THz,eff.}} \tag{10}$$

The coherence length for difference frequency mixing in waveguide configuration is becoming now

$$l_{\text{c,eff.}} = \frac{\pi c}{\omega_{\text{THz}} \left| n_{\text{opt,group}} - n_{\text{THz,eff.}} \right|} \tag{11}$$

where $n_{\text{opt,group}}$ could be still the group index at the optical pump frequency in the bulk nonlinear optical crystal because the effects of waveguide are quite weak for optical wave of which optical wavelength is much smaller than the thickness of the planar waveguide. Thus we considered that optical pulses pass the waveguide in such a way that it travel in an unlimited uniform medium.

The best result is the $\text{GaAs}/\text{ZnGeP}_2$ dielectric planar waveguide in which the effective coherent length enhances to 4 mm from 0.78 mm without waveguide structure. For $\text{GaAs}/\text{ZnGeP}_2$ waveguide, the maximum thickness of single mode planar waveguide is about 65 μm and the absorption coefficients at THz regime are 0.5 cm^{-1} and 0.1 cm^{-1} for GaAs and ZnGeP_2, respectively.

Table 2. Three different planar waveguide structures and their coherence lengths.

	Core medium: GaAs Cladding medium: $ZnGeP_2$	Core medium: $ZnGeP_2$ Cladding medium: Si	Core medium: $ZnGeP_2$ Cladding medium: GaP
Thickness of planar waveguide [μm]	60	500	100
n_{THz} in core medium @ 2THz	3.61	3.42	3.42
$n_{\mathrm{THz,eff}}$□of TM_0 mode @ 2THz	3.5335	3.4190	3.3922
l_c @1550 nm [mm]	0.78	0.5155	0.5155
$l_{c,\mathrm{eff.}}$ with waveguide @1550 nm [mm]	4.0	0.5191	0.637

4. CONCLUSIONS

In summary, we demonstrated theoretically that the dielectric planar waveguide could be used to enhance the coherent length of optical rectification process in THz regime. And for the first time, a dielectric planar THz waveguide that has potential applicable value in THz generation by optical rectification method was proposed. We predicted that the effective coherent length could be extended to 4 mm at 2 THz in a GaAs/$ZnGeP_2$ dielectric planar waveguide during optical rectification process pumped by ultrafast optical pulses at wavelength of 1550 nm.

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