Design of a continuous-wave tunable terahertz source using waveguide-phase-matched GaAs

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Abstract: A novel source of continuous-wave terahertz radiation based on difference frequency generation (DFG) in GaAs crystal is proposed. Phase matching is provided using integration of appropriate optical and terahertz waveguides based on dispersive properties of GaAs. The output frequency can be tuned between 0-3.5 THz by tuning the incident wavelengths in the range of 1.5-1.6 μm.

OCIS codes: (190.4410) Nonlinear optics, parametric processes; (190.2620) Frequency conversion.

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1. Introduction

Unique applications of terahertz radiation in various fields such as biology and medical sciences, remote sensing, and chemical detection have motivated researchers to develop compact and coherent sources for this least touched region of electromagnetic spectrum [1]. Of the many techniques for generating terahertz signals [1], difference frequency generation (DFG) in various crystals such as $LiNbO_3$ [2], GaSe, $ZnGeP_2$, and GaP [3] is one of the most explored methods. Various phase matching methodologies, including phase matching in bulk crystals based on birefringence [3], and quasi-phase matching [2] have been proposed for this purpose.

Although GaAs has a high second-order nonlinear coefficient, it is one of the least employed crystals for DFG due to phase-matching difficulties. First, it does not provide birefringence in the bulk crystal for birefringence phase matching [4]. Second, GaAs quasi-phase matching has been shown only in few works such as [5] because patterning the nonlinear susceptibilities in semiconductors is not achieved easily.

However, GaAs has been used in several electro-optic devices based on other related types of nonlinear interactions in which phase-matching is provided using wave-guiding techniques [6]-[9]. In the case of GaAs based optical modulators or up-converters, integration of a slab waveguide and slow-wave coplanar electrodes is used to phase match the optical and RF signals [7]. Operation with RF frequencies up to 40 GHz has been demonstrated. Another example is a combination of a double-metal waveguide with a quantum cascade laser to modulate the optical beam with a terahertz signal [8]. Dependency of the supported terahertz frequency on dimensions of the ridge waveguide results in narrowband terahertz operation. A co-planar waveguide on top of a ridge slab optical waveguide has also been used as an optical rectifier to generate ultra-short pulses in GaAs [9].

A rod-type waveguide phase matching has also been accomplished using a GaP rod for Raman difference-frequency mixing to generate terahertz radiation [10]. In addition to the low output power, the dependency of the supported frequency on the width of the waveguide results in a single frequency source. Another waveguide structure is proposed recently for terahertz generation in a nonlinear polymer as the cladding of a silicon core [11]. Using different waveguide dimensions, output terahertz radiation is predicted to cover frequencies between 0.5 and 14 THz while incident wavelengths are tuned in the range of 1.3-1.6 μm.

In this paper, integration of a GaAs optical waveguide and a terahertz waveguide is proposed as a wide-band phase-matching technique for DFG to generate high-power coherent terahertz radiation. Using pump wavelengths between 1.5 and 1.6 μm, where low cost and high optical powers are available, we predict phase matching for terahertz generation in the range of 0-3.5 THz. We exploit the differences between the GaAs dielectric constant in optical and terahertz range, a high second-order nonlinear coefficient, and a low terahertz absorption [5]. Simulated results show the appropriate behavior of the device for both optical and terahertz waves.

2. Approach

For efficient DFG, two conditions must be satisfied: energy conservation

$$\Omega_{THz} = \omega_1 - \omega_2, \tag{1}$$

and momentum conservation

$$k_{THz} = k_1 - k_2; \tag{2}$$

where ω_1 and ω_2 are the optical angular frequencies, Ω_{THz} is the terahertz angular frequency, and k_1, k_2, k_{THz} are corresponding wave numbers in the waveguide direction. Dividing Eq. (1)

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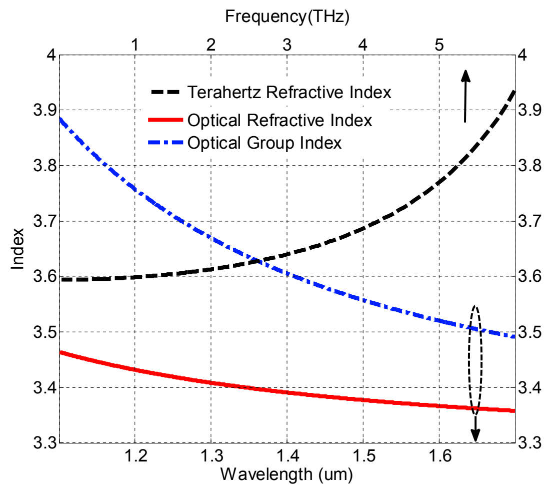

Fig. 1. The optical refractive index (solid line) and group index (dash-dot line) and the terahertz refractive index (dash line) of GaAs.

into Eq. (2) results in

$$\frac{\Omega_{THz}}{k_{THz}} = \frac{\omega_1 - \omega_2}{k_1 - k_2}. \tag{3}$$

Assuming that the difference between optical frequencies is very small, (i.e. in our case it is terahertz vs. optical), and also the similar situation for the wave numbers, Eq. (3) can be rewritten as:

$$\frac{\Omega_{THz}}{k_{THz}} = \frac{d\omega_{optical}}{dk_{optical}}. \tag{4}$$

So, phase matching for DFG requires that the phase velocity of the terahertz wave equal the group velocity of the optical wave. Alternatively, the effective index of the terahertz wave (n_{THz}) must be equal to the group index (n_{gr}) of the optical signal. This means that the velocity of the optical envelope should be equal to the velocity of the generated terahertz wave for efficient DFG.

Our approach to waveguide phase matching is made feasible by the dispersive properties of GaAs around its Reststrahlen's band [8]. Figure 1 shows the refractive index and group index of GaAs over a range of optical wavelengths in comparison with the terahertz refractive index [12]. At any frequency in the range of 0-6 THz, n_{THz} can be matched to n_{gr} of an optical wavelength between 1.1-1.4 μm. This means, for example, if we want to generate 2 THz, we have $n_{THz} = 3.61$, which should be equal to n_{gr}. That can be obtained at a central wavelength of 1.39 μm. By keeping the frequency difference of two incident optical wavelengths equal to 2 THz, they can be tuned to the appropriate phase matching condition.

Although the dispersive property of GaAs is promising for covering the entire mentioned terahertz range, we also require precisely tunable laser sources and wideband high power optical amplifiers. Unfortunately, these cannot be found easily in 1.1-1.4 μm optical wavelength range. We prefer to operate near 1.55 μm where such components are widely available and inexpensive. However, in that range there is no corresponding terahertz frequency for phase matching. To overcome this problem, an integration of a three layer ridge slab waveguide, for the optical signal, with a metallic slit waveguide [13], for the terahertz wave is proposed.

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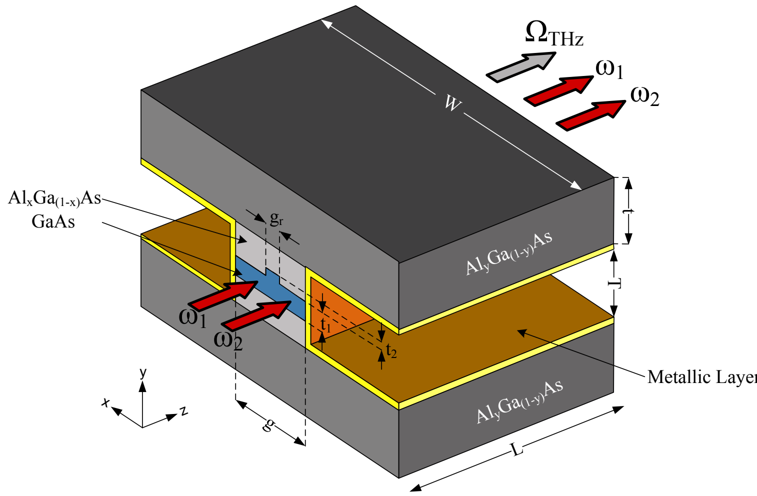

Fig. 2. The proposed device which is an integration of a dielectric slab and a metallic slit waveguide (The drawing is not to scale; dimensions are specified in table 1).

3. Device design

In addition to overcoming the phase mismatch near 1.55 μm, we seek a waveguide structure that has low loss, can be fabricated easily, and maximizes high overlap between optical and terahertz modes. The latter suggests maximizing the mode area of the optical mode while minimizing that of the terahertz mode. The proposed waveguide structure is depicted in Fig. 2. The optical waveguide supports only a single x-polarized mode for wavelengths longer than 1.45 μm and has a mode distribution as depicted in Fig. 3-a. For the terahertz wave, the metallic slit waveguide [13] is used because it supports a non-dispersive TEM-like mode and the field is tightly confined in the slit area, as depicted in Fig. 3-b. The outer area of the slit waveguide is filled with $Al_yGa_{(1-y)}As$, $y = 0.4$ to obtain appropriate terahertz effective index. Table 1 shows the values of the device parameters.

Table 1. Design parameters.

g	T	t	W	L	g_r	t_1	t_2	x	y
$4.5\mu m$	$5\mu m$	$10\mu m$	$30\mu m$	$4cm$	$1.1\mu m$	$0.8\mu m$	$1.2\mu m$	0.2	0.4

An incident beam consisting two x-polarized optical frequencies ω_1 and ω_2 is guided by the optical waveguide. When the $< 111 >$ direction of the crystal is parallel to the x axis, field magnitudes in all crystal axes will be equal. The isotropic nonlinear susceptibility of the GaAs crystal then results in a difference-frequency signal generated with equal magnitudes in all crystal axes, resulting in a $x-$polarized generated signal [4] to be guided by the metallic slit waveguide. This means that the nonlinear tensor of GaAs, which has nonzero elements of d_{xyz} and its permutations, allows electric fields for all three frequencies to be linearly polarized along $< 111 >$ direction. Accurate waveguide phase matching would let us extend the length of the device up to a couple of centimeters to increase terahertz output powers.

Due to the substantially sub-wavelength dimensions in terahertz regime, higher-order TE and TM modes confined in the slit area are not supported. Other higher-order modes such as hybrid modes, which are not confined in the slit area, are not going to be excited significantly due to

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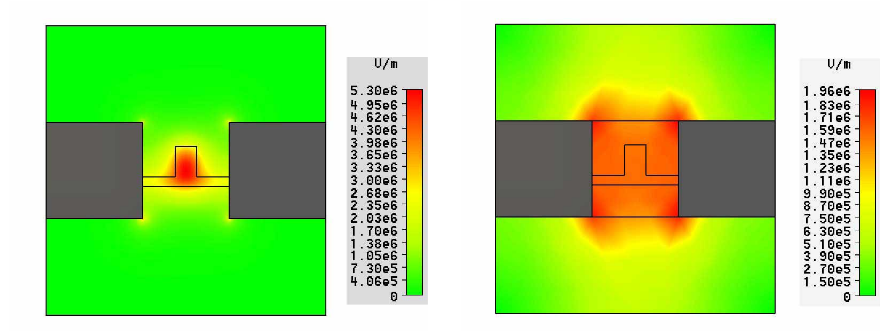

Fig. 3. Electric field distribution of (a) the optical mode, and (b) the terahertz mode.

the overlap mismatch.

4. Results and discussions

To analyze the device, CST microwave studio is used to simulate the terahertz behavior, and effective index method is employed for the optical behavior. The terahertz effective index and optical group index of the proposed device are depicted in Fig. 4, showing phase matching in the range of 0-3.5 THz by adjusting the optical wavelengths between 1.5-1.6 μm.

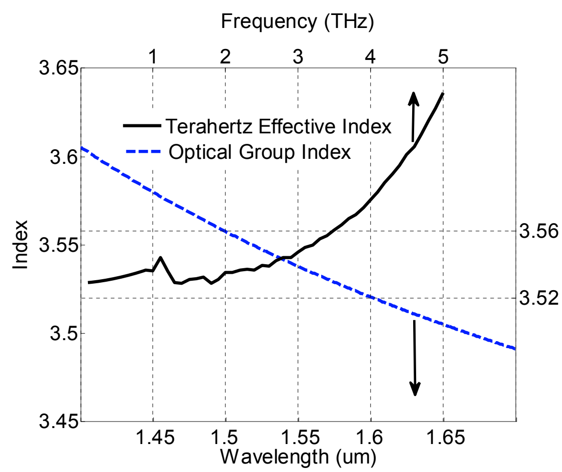

Fig. 4. The effective group index of the optical waveguide and the effective index of the terahertz waveguide. Horizontal dash lines show the range of optical group index for the wavelengths in between 1.5 and 1.6 μm which can be matched to a terahertz effective index up to 3.5 THz.

Figure 4 shows that for optical wavelengths between 1.5 and 1.6 μm the optical group index varies in between 3.52 and 3.56. This range of optical group index could be phase matched to the terahertz effective index for the frequencies from 0 to 3.5 THz. For example to generate 2 THz, the terahertz effective index is 3.54 which is equal to the optical group index at 1.55 μm. This means that when the difference-frequency between the optical wavelengths is 2 THz

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and the central wavelength is 1.55 μm, the device provides perfect phase matching for the DFG-based terahertz generation. For any other terahertz frequency in the range of 0-3.5 THz, appropriate central optical wavelengths could be found in the range of 1.5-1.6 μm.

For the perfectly phase matched process, the output power of the device can then be calculated using [4, 14]:

$$P_{THz} = 2\frac{A_{THz}^{eff}}{\left(A_{optical}^{eff}\right)^2}(d\Gamma)^2\left(\frac{\mu}{\varepsilon_0}\right)^{3/2}\frac{P_1P_2\Omega_{THz}^2}{n_1n_2n_{THz}}\left(\frac{e^{-\frac{\alpha_{THz}}{2}L}-1}{\frac{\alpha_{THz}}{2}}\right)^2, \tag{5}$$

while the the loss of the metallic waveguide for the targeted terahertz frequency [13] and the material loss for the optical regime are neglected [12].

Table 2. Parameters used in Eq. (5) for calculation of the output power at $\Omega_{THz} = 2\pi \times 2$ THz, while optical wavelengths are about $1.55\mu m$.

Symbol	Description	Value
A_{THz}^{eff}	effective area of the terahertz mode	$2.3 \times 10^{-11}\ m^2$
$A_{optical}^{eff}$	effective area of the optical mode	$5.6 \times 10^{-12}\ m^2$
d	second-order nonlinear coefficient	$47\ pm/V$ [15]
Γ	overlap factor	0.14
P_1, P_2	input optical powers	$500\ mW$
n_1, n_2	optical effective index	3.38
n_{THx}	terahertz effective index	3.54
α_{THz}	terahertz absorption	$0.5\ cm^{-1}$ [5]
P_{THz}	output power	$10.4\ \mu W$

Table 2 shows the description of the parameters and the values used in this equation for output power calculation. Effective areas of the modes are calculated using:

$$A_i^{eff} \equiv \frac{\int\int|\vec{E}_i(x,y)|^2dxdy}{max(|\vec{E}_i(x,y)|)^2}, \tag{6}$$

where $E_i(x,y)$ is the electric field distribution of each mode as depicted in Fig. 3. The overlap factor, Γ, is defined as the overlap between the normalized power distribution of the optical mode and the normalized electric field distribution of the terahertz mode [16].

Numerical simulation of the device shows that at 2 THz, for a 4-cm device, when the input pumps have power of 500 mW each, the output power is 10.4 μW. This high output power is obtained due to the small dimensions of the device cross section, which results in high intensity and the long interaction length provided by waveguide phase matching. The efficiency of the proposed device can be enhanced by optimizing the dimensions of the waveguides.

Although phase matching is provided for the range of 0-3.5 THz, according to Eq. (5) the output power depends quadratically on the targeted terahertz frequency. This means for frequencies close to zero the conversion efficiency is very low, which suggests a practical lower limit for the generated frequency.

Nonlinear loss associated with two-photon absorption in GaAs is expected to be negligible due to the low optical intensity ($\sim 10^{-2}\ GW/cm^2$) compared to high pulsed intensities [17]. However, even small numbers of free carriers generated by this process may affect the terahertz waveguide properties. These may be reduced by applying a DC bias. To be able to use the

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device for higher optical intensities, the same structure can be redesigned using AlGaAs with a higher portion of Al ($> 14\%$) such that two-photon absorption is eliminated.

Realization of the proposed device requires that it be fabricated with reasonable processing techniques and that the tolerances of this processing preserve accurate phase matching. This sensitivity can be estimated by exploring the impact of variations in refractive indices. The dependence of the output power on the index mismatch for different device lengths is depicted in Fig 5. The figure shows that for L=4 cm, half maximum output power would be obtained with an index mismatch of 0.005, which is more than 0.1% of the material refractive index.

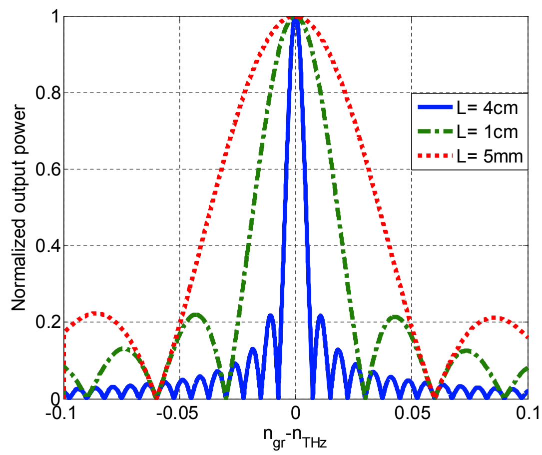

Fig. 5. Normalized output power vs. index mismatch for different device lengths.

Fabrication of the proposed device could begin with growth of all layers up to and including the optical ridge, etching of the ridge, and regrowth of the remaining layer. A mesa of width W would then be etched to depth of $2t+T$. A selective etch could then define the rib by selectively removing the relatively low x alloy. Finally, evaporation of gold into the rib completes the structure.

One of the challenges for this fabrication method is the regrowth required for the ridge used for lateral confinement of the optical mode. As an alternative, lateral confinement can be obtained by deposition of thin layers of a low refractive index dielectric (oxide) on the sides of the slab waveguide before metalization. We continue to explore the optimization of the device geometry and possible fabrication methods.

5. Conclusion

A new waveguide phase matching methodology is employed to design a tunable terahertz source in the range of 0-3.5 THz that uses available telecommunication lasers and amplifiers. A relatively high output power of 10.4 μW from a 4-cm long device is predicted at 2 THz. Since the terahertz wave is a guided single mode, it can be easily coupled to other waveguides or antennas. Moreover, the proposed waveguide phase matching can be useful for other types of devices using similar nonlinear phenomena, such as coherent detection, electro-optic modulation, and ultra-short pulse generation.

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