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Design and analysis of a metallic waveguide with a DAST cap for continuously phase-matched terahertz difference frequency generation

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ABSTRACT

We present a novel source for continuous terahertz (THz) wave generation using an organic ionic salt, 4-dimethylamino-*N*-methyl-4-stilbazolium-tosylate (DAST). THz waves are generated based on difference frequency generation (DFG) in the device. Phase matching condition and THz generation between 1.3 THz and 2.7 THz, for optical pump around 1.6 μm, are investigated. Our calculations predict that the device produces a relatively high THz output power of 11.07 μW from a 4 cm long waveguide at 2 THz.

1. Introduction

Recent growing demands on terahertz (THz) waves for applications in various fields of technology [1] lead to a considerable number of research work focusing on the development of compact and coherent sources for THz generation and detection. There are several methods for THz generations [2] such as optical rectification (OR), using antennas, multilayer quantum wells or quantum cascade lasers, and difference frequency generation (DFG). In DFG method, two optical pumps are interacted in nonlinear optical crystal to generate difference frequency wave in THz range. In this process phase matching condition must be satisfied, it means $\beta_1 - \beta_2 = \beta_{THz}$, where β is the propagation constant.

Using waveguides enables us to access compact and coherent THz sources that are able to achieve phase matching in a desired THz wave. The geometry of the waveguide strongly affects on light confinement and optical parameters of the guided modes. Hence, a well-chosen geometry of the waveguide is required to have an efficient device. The optical field in a waveguide is confined when the waveguide scale is limited to the order of wavelength. The problem for designing THz waveguides is that the THz wavelength is longer than optical pump wavelength. To overcome this problem some techniques are suggested [3], using metallic waveguides to provide THz confinement in nano-scale geometry is one of the most interesting.

GaAs is a widely used nonlinear medium in THz conversion waveguide devices whereas continuous THz wave is generated based on DFG process [4]. GaAs is also used in suspended waveguides for generation of continuous THz wave at 1.3 THz [5]. A metallic slot waveguide with a dielectric strip embedded within is another device to produce continuous THz waves [6].

Bulk DAST is a major nonlinear crystal for THz generation. The combination of low dielectric constant and high nonlinearity makes DAST crystal a promising candidate for high speed modulation and frequency mixing applications [7]. It is demonstrated that DAST has very large nonlinear optical susceptibility and large electro optic coefficient. The good alignment of optical wave in DAST results the large diagonal nonlinear coefficient d, with the highest $d_{111} = 1040 \pm 110$ pm/V at 1318 nm [8,9]. To compensate the phase mismatch that accompanies THz generation in bulk DAST crystal a DAST/SiO_2 multilayer structure has been proposed [10]. In this structure, near-single-cycle THz transients with average frequency around 6 THz via collinear optical rectification of 800 nm femtosecond laser pulse are generated.

We propose the use of a metallic slot waveguide with a DAST cap for efficient generation of THz waves. Material selection is important since they must have low loss in both the optical and THz wavelength. This fact that quartz has THz refractive index higher than optical refractive index ($n_{THz} = 2.13$ and $n_{optical} = 1.45$) makes it an interesting choice for being the dielectric medium in waveguide. To calculate the THz output power we use a finite difference time domain (FDTD) method [11] to calculate wave number β, effective index n_{eff}, group index n_g, and the modal profile of all the relevant modes. For the optical wave we use a computational window size

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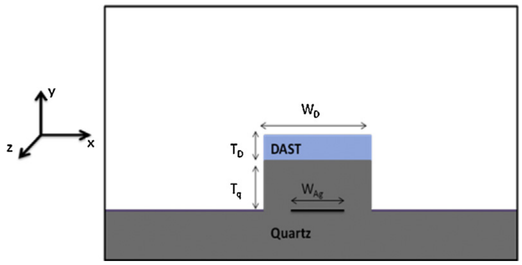

Fig. 1. Structure of DAST cap waveguide $W_D = 1.1\ \mu m$, $T_D = 250\ nm$, $T_q = 300\ nm$, $W_{Ag} = 450\ nm$.

of 3 μm by 2.2 μm with a minimal grid of 10 nm. For the THz wave we use a computational window size of 2 μm by 1.7 μm with a minimal grid of 10 nm.

2. Modelling and simulation

The phase matching condition for DFG process in collinear configuration is expressed by:

$$\nu_{THz} = (\nu_1 - \nu_2)$$
$$\beta_{THz} = \beta_1 - \beta_2 \quad (1)$$

Where ν_1, ν_2, and ν_{THz} are optical frequencies and THz frequency, β_1, β_2 and β_{THz} are propagation constant of optical guided modes and THz mode, respectively. In order to satisfy phase matching condition from Eq. (1), the waveguide must have the phase velocity of THz wave equal to the group velocity of optical wave; this means the effective index of THz wave equal the group index of optical wave.

For perfectly phase match condition, the output power of the device can be calculated from [12]:

$$P_{THz} = 2\frac{A_{THz}^{eff}}{(A_{THz}^{eff})^2}(d\Gamma)\left(\frac{\mu}{\varepsilon}\right)^{3/2}\frac{P_1P_2\Omega_{THz}^2}{n_1n_2n_{THz}}\left(\frac{e^{-\frac{\alpha_{THz}}{2}}-1}{(\alpha_{THz}/2)}\right)^2 \quad (2)$$

Where A_{THz}^{eff} is the effective area of the mode and calculated using:

$$A_i^{eff} = \frac{\iint \left|\vec{E}_i(x,y)\right|^2 dxdy}{\max(\iint \left|\vec{E}_i(x,y)\right|)^2} \quad (3)$$

$\vec{E}_i(x,y)$ is the electric field distribution of each mode. Γ is the overlap factor, d is the second-order nonlinear effective coefficient. P_1 and P_2 are the input optical powers, n_1, n_2 are the optical effective index and n_{THz} is the THz effective index. $\Omega_{THz} = 2\pi\gamma_{THz}.\alpha_{THz}$ is the THz absorption from [13].Our calculation shows modal area for the optical pump wave is $A_{optical}^{eff} = 425700(\mu m)^2$ and for THz modal area is $A_{THz}^{eff} = 839300(\mu m)^2$.

The overlap factor is defined as fraction of power from fundamental mode that can propagate in mode1.

$$\Gamma = Re\left[\frac{(\int \vec{E}_1 \times \vec{H}_2^*.d\vec{s})(\int \vec{E}_2 \times \vec{H}_1^*.d\vec{s})}{\int \vec{E}_1 \times H_1^*.d\vec{s}}\right]\frac{1}{Re(\int \vec{E}_2 \times H_2^*.d\vec{s})} \quad (4)$$

Γ is the overlap factor. It is obvious from (2) that utilizing a nonlinear medium with a large nonlinear coefficient can increase the output power.

In order to achieve phase matching, we have proposed a compact waveguide structure that is depicted in Fig. 1. The proposed waveguide consists of a thin silver layer in quartz substrate with a DAST cap.

The proposed waveguide is designed to support both optical and THz wave. We assume the optical pump beams having electric fields along the x direction and the electric field of THz beam along y direction. The orientation of DAST crystal is chosen such that a and c axes of DAST coincide with the x and y axes, respectively. In this condition the nonlinear coefficient d_{311} of DAST crystal is used. Metallic layer in the waveguide allows strong confinement of THz wave in waveguide and increases THz efficiency.

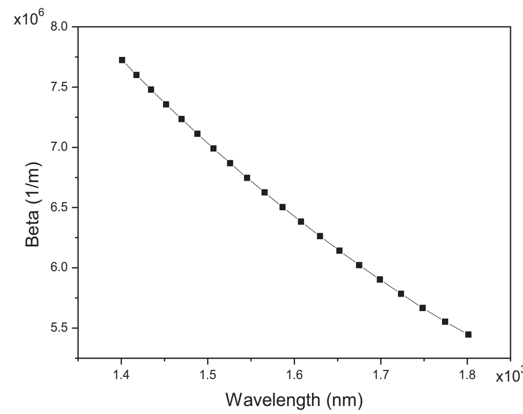

Fig. 2. Propagation constant variation of the waveguide in the optical range with the metal layer (solid line), without the metal layer (squares).

3. Results and discussion

The numerical investigations indicate that phase matching can be seen in a well chosen geometry of the waveguide. Based on the properties of optical and THz modes, we choose the geometrical dimension of the waveguide as $W_D = 1.1\ \mu m$, $T_D = 250\ nm$, $T_q = 300\ nm$, $W_{Ag} = 450\ nm$, the thickness of Ag equal to 50 nm, and the optical pump frequency range around $\lambda = 1.6\ \mu m$. In this condition the optical modes are mainly supported by DAST layer and its modal profiles decay exponentially in quartz and air. For such a geometrical dimension the distribution of the optical guided mode is not influenced by metal. However by changing the waveguide dimensions, one can design the waveguide such that the metal layer (Ag) affects on the guided modes. The propagation constant variation of the proposed waveguide with the metal layer and without metal layer is depicted in Fig. 2.

From Fig. 2 it is obtained that the metal layer doesn't affect on optical mode distribution. Our FDTD calculations indicate that when the DAST cap dimensions decrease, while other dimensions are fixed, the influence of metal on beta will increase. Considering the result of calculations we have chosen the dimensions as Fig. 1 to achieve the phase matching.

The modal profile of the fundamental guided modes for the geometry of Fig. 1 is shown in Fig. 3.

Phase matching condition for DFG process requires that the group index of the optical modes equal the THz effective index. In

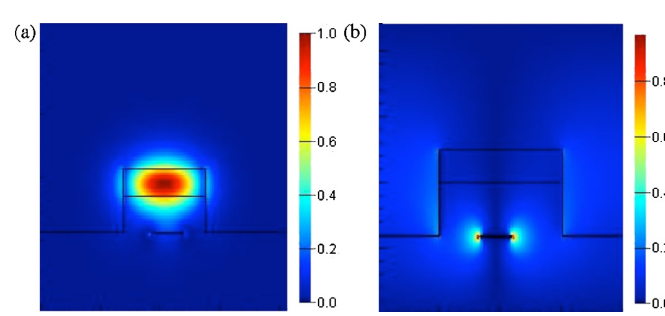

Fig. 3. The modal profile of guided modes at optical pump range (a) THz frequency range (b).