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Fractional quasi phase matched broadband second harmonic generation in a tapered zinc telluride slab using total internal reflection considering the effect of nonlinear law of reflection

Sumita Deb*, Ardhendu Saha

Department of Electrical Engineering, National Institute of Technology, Barjala, Jirania, Tripura (west), Agartala 799055 Tripura, India

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ABSTRACT

We analytically describe broadband second-harmonic generation in a tapered zinc telluride (ZnTe) slab using total internal reflection fractional quasi-phase matching. The simulated results, considering absorption and reflection losses, indicate 3 dB bandwidth of 477 nm, centred at 6.01 μm, with conversion efficiency of 14.98% in a 4.5 mm ZnTe slab. Finally the destructive interference effect rooting from the basic law of nonlinear reflection has been incorporated in the analysis. As a consequence, the peak conversion efficiency has reduced to 3.73% whereas the bandwidth rises to 490 nm.

1. Introduction

Rapid development in the field of semiconductor technology has lead to extensive use of isotropic semiconductors for optical frequency conversion techniques. These isotropic semiconductors offer a number of advantages like (i) high optical second-order nonlinear susceptibility, (ii) excellent transparency range, (iii) good mechanical properties, (iv) possible future integration with the pumping source etc. [1]. Among these semiconductors, ZnTe has indeed come forward as an important nonlinear optical crystal, finding wide applications in generation of pulsed terahertz radiation in time-domain terahertz spectroscopy, terahertz imaging, holographic interferometry, optical rectification, reconfigurable optical interconnections, and in laser optical phase conjugation devices [2,3]. However, ZnTe being isotropic, no natural birefringence phase matching is possible. Therefore, quasi-phase matching (QPM) may be considered an attractive technique for frequency generation in ZnTe crystal.

In 1962, Armstrong et al. [4] first suggested that QPM can be obtained by total internal reflection (TIR) in a plane parallel slab. This technique has been demonstrated in isotropic semiconductor (GaAs, ZnSe, ZnS) slab for resonant as well as non resonant scenarios by a number of researchers [5–7]. Then it was in 2006, when Haidar proposed the concept of fractional QPM in SHG, which was theoretically shown to provide very high conversion yield, close to that of perfectly phase matched scenarios [8]. Here the interaction length between consecutive bounces is less than even one coherence length (for example half-order QPM) and appears to be always more efficient than any other QPM scenario, whatever be the QPM order and can resemble a perfectly phase matched conversion process. This enhancement can help to compensate the drop in efficiency due to reflectivity losses at each TIR bounce point.

In this paper we have analytically demonstrated broadband SHG in a tapered ZnTe slab using fractional TIR-QPM technique. As compared to our earlier paper [9], a more accurate Sellemier's equation [10] has been used in the present analysis. The coherence length of ZnTe is nearly 2 times the coherence length of GaAs or ZnSe for the incident broadband laser radiation under consideration. For a fundamental wavelength of 6.01 μm, l_c has a value of 74 μm for GaAs, while for ZnTe the value is 138 μm. This scheme seems to be technologically much easier as compared to other techniques (e.g., chirping) used for broadband generation. Extremely wide 3 dB BW has been obtained analytically with the help of computer-aided simulation. Fractional QPM ensures the possibility of highly efficient conversion efficiency. The influence of limiting factors, viz Goos-Hänchen (GH) shift, surface roughness and absorption, has also been taken care of in this analysis.

* Corresponding author. Tel.: +91 9862029099; fax: +91 0381 2326630.
E-mail address: sumita_nita@rediffmail.com (S. Deb).

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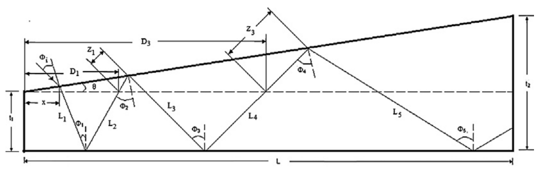

Fig. 1. Geometry of tapered semiconductor slab showing the scheme of second harmonic frequency conversion.

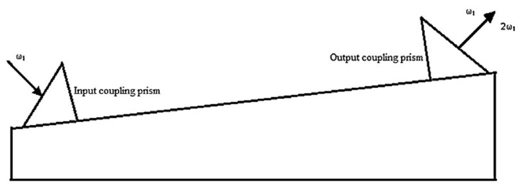

Fig. 2. Mechanism of input injection and output collection from the tapered semiconductor slab using input and output coupling prisms.

2. Proposed scheme

We have considered a tapered semiconductor slab with the base surface parallel to the horizontal plane while the upper surface tapered at an angle θ determined by the vertical heights of the two ends t_1 and t_2, $t_1 < t_2$, as shown in Fig. 1. The broadband fundamental laser radiation is coupled to the semiconductor slab through an input coupling right angled prism placed on the upper surface of the slab. The first angle of incidence Φ_1 on the horizontal plane inside the semiconductor slab will be determined by the refractive indices of the prism material and the semiconductor slab material as calculated using the wavelength dependent dispersion equation of the materials [10]. If Φ_1 is greater than the critical angle for the range of input frequencies, then the fundamental optical radiations will undergo total internal reflections inside the tapered slab. The angle of incidence and the length between successive bounces will go on increasing with the propagation of the input broadband radiations throughout the length of the tapered semiconductor slab. The generated output is collected with the help of another right angled prism coupler as shown in Fig. 2. This scheme corresponds to fractional QPM since the interaction lengths between successive bounces are less than the coherence length for the frequencies available in the input band of fundamental laser radiations. In our earlier paper [11], it has been analytically demonstrated that the use of a tapered semiconductor (GaAs and ZnSe) slab results in flatter spectra of the generated second harmonic BW in comparison to a parallel slab with $t_2 = t_1$, although the conversion efficiency will be lower in case of the tapered slab. The same explanation holds good in the present case also. Moreover the use of ZnTe as the slab material results in fractional QPM thereby highly enhancing the SH conversion efficiency even in the presence of surface roughness and absorption losses. In his work on fractional QPM [12], Haidar has demonstrated fractional QPM (half order) scenario in a 50 μm thick parallel GaAs slab, wherein the plate behaves as a highly multimodal waveguide for both the fundamental and the generated second-harmonic waves. The author has used a fundamental optical beam of waist around 30 μm [13] which has been injected in the narrow plate through an input coupling prism and the output has been collected with the help of an output coupling prism. It has been analytically established that 5.8 mm of a half-order QPM crystal is as efficient as 7.6 mm of a first-order QPM crystal, both providing an energy conversion efficiency of nearly 1%. Similar arrangement has been proposed in this present work where we have used a tapered slab of $t_1 = 90$ μm and $t_2 = 95$ μm in which a fundamental beam has been injected through a coupling prism as shown in Fig. 2.

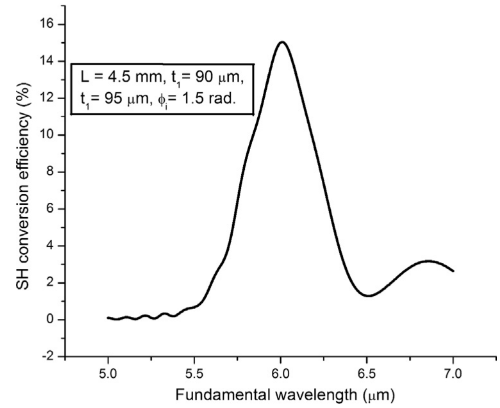

Fig. 3. Variation of SH conversion efficiency with respect to fundamental wavelength for the tapered slab configuration considering losses due to surface roughness, linear absorption and GH shift.

In the present analysis we have considered *ppp* polarization configuration. The value of d_{14} is considered to be 90 pm/V for ZnTe compound [14]. In the proposed scheme, since the angle of incidence changes at each reflection bounce, the effective d-coefficient (d_{ppp}) also undergoes change in its value at each reflection bounce.

The SHG conversion efficiency is limited by three important factors namely the surface roughness, GH shift and absorption loss of the material. For surface roughness a $p - v$ value of 30 nm has been considered in the computer-aided simulation [15].

In our case, we will encounter two expressions for GH shift, one for the parallel base while the other for the tapered upper surface. Both the cases are considered in the analysis.

ZnTe shows a linear absorption coefficient (α_ω) of 0.008 cm^{-1} corresponding to a wavelength of 10.6 μm [16]. Since α_ω is a function of wavelength (λ_ω), we have used an approximate relation [$\alpha_\omega = (4\pi k/\lambda_\omega)$] between the two to calculate the absorption losses for each wavelength of the fundamental BW as well its corresponding SH. However, the extinction coefficient (k) has been assumed to remain constant over the wavelength range under consideration.

2.1. Calculation of SH conversion efficiency

The SH conversion efficiency has been calculated using the expression

$$\eta_{\text{con}} = \frac{S_2}{S_1} \times 100\% \qquad (1)$$

where S_1 is the fundamental beam intensity and S_2 is the resultant SH intensity [11].

In our analysis the interaction length between the last bounce and the exit point from the slab has not been considered.

3. Results and discussions

In the computer-aided simulation, undepleted pump wave approximation has been assumed with input fundamental beam intensity of 10 MW/cm^2. The analysis uses an input fundamental broadband source of (5.5–6.5) μm for the ZnTe slab.

Under ideal conditions, the peak efficiency is 19.6% while the 3 dB BW is 475 nm. When the effects of surface roughness, GH shift and absorption losses are considered, the conversion efficiency reduces to 14.98% while the BW obtained is 477 nm. Thus the effects of these losses are more catastrophic on the conversion efficiency than on the BW which remains almost unaffected. Fig. 3 shows the variation of SH conversion efficiency w.r.t. the fundamental wavelength under lossy conditions.