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Broadband second-harmonic generation in a double-tapered gallium arsenide slab using total internal reflection quasiphase matching

Ardhendu Saha, Sumita Deb*

Electrical Engineering Department, National Institute of Technology, Agartala, Tripura, India

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ABSTRACT

This article analytically describes broadband second-harmonic generation in a double-tapered gallium arsenide (GaAs) slab using total internal reflection quasi-phase matching technique. This double-tapered configuration ensures a combination of increasing and then decreasing bounce lengths which provides an extremely wide 3 dB bandwidth of 573.6 nm with a conversion efficiency of 1.929%, after considering reflection and absorption losses. Effect of varying the slab dimensions, viz., length and tapering angles, as well as the operating temperature on the performance parameters has also been incorporated in the analysis.

1. Introduction

Rapid development in the field of semiconductor technology has led to extensive use of isotropic semiconductors for optical frequency conversion techniques in different wavelength ranges. 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]. However, most of these semiconductors being isotropic, no natural birefringence phase matching is possible. Therefore, quasiphase matching (QPM) may be considered an attractive technique for frequency generation in these isotropic crystals and is practically implemented through molecular bonding of the semiconductor plates [2] or localized growth [3]. However, the difficulty of this technique lies in the stringent conditions of QPM which leads to technological difficulties [4]. The advent of total internal reflection (TIR) QPM [5] in a plane parallel isotropic slab has indeed exaggerated the use of isotropic semiconductors like gallium arsenide (GaAs), zinc selenide (ZnSe), zinc sulphide (ZnS), etc. for newer optical frequency generation through resonant as well as nonresonant scenarios [6–8]. In the case of a parallel slab [6,7], the width, *t*, of the slab is optimized to have maximum conversion yield for second-harmonic generation (SHG) of a given input laser wavelength. But since a broadband SHG frequency converter converts a band of frequencies, rather than a single frequency, it is difficult to optimize the interaction length between successive bounces for each frequency available in the input broadband source using a parallel slab configuration. Recently, random quasi-phase matching, as experimentally demonstrated by Raybaut *et al.* [9], has come forward as a wonderful technique for broadband frequency generation using polycrystalline isotropic sample consisting of a number of randomly oriented single-crystal domains of random shapes and sizes. This technique has been demonstrated in transparent (ZnSe) [9] as well as opaque [gallium phosphide (GaP)] [10] semiconductors and can indeed make the nonlinear optical technology accessible to a much wider range of potential users. Broadband SHG has also been theoretically reported in single-crystal tapered isotropic configuration (GaAs, ZnSe) using TIR-QPM technique [11]. Since a tapered slab has been considered, the length between successive bounces goes on increasing as the input collimated fundamental laser radiation propagates through the tapered slab, thereby ensuring the possibility of both non-resonant and resonant QPM. In this case, it may so happen that one interaction length between two successive bounces may coincide with an odd multiple of the coherence length for a particular frequency of the input broadband source, whereas another interaction length may coincide with an odd multiple of the coherence length of another frequency of the input broadband source and so on, thereby resulting in a flatter SH broadband output. The simulated results indicated 3 dB bandwidth (BW) of 187 and 196 nm with conversion efficiency of 1.052 and 1.043% in a 30 mm long tapered slab of GaAs and ZnSe, respectively.

* Corresponding author. Tel.: +91 9862029099; fax: +91 381 2326630.
E-mail address: sumita_nita@rediffmail.com (S. Deb).

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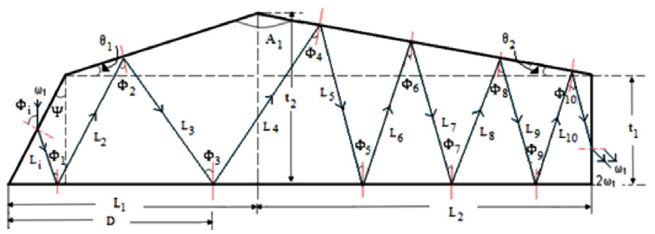

Fig. 1. Geometry of double-tapered semiconductor slab showing the scheme of second harmonic frequency conversion.

In this article, we have extended the concept of SHG through TIR-QPM to a double-tapered configuration using GaAs as the slab material and the simulated analysis shows quite impressive results in terms of 3 dB BW as well as SH conversion efficiency. For a 30 mm long double-tapered GaAs slab, exceptionally high BW of 573.6 nm and a conversion efficiency as high as 1.929% have been obtained. The influence of limiting factors, viz., Goos-Hänchen (GH) shift, surface roughness and absorption, has also been taken care of in this analysis. The dependence of SH conversion efficiency and its BW on temperature, length and tapering angles of the semiconductor slab has also been studied.

2. Proposed scheme

We have considered a double-tapered semiconductor slab with the base surface parallel to the horizontal plane. The upper surface is made of two tapered sections connected end to end as shown in Fig. 1. We will call the first tapered section as forward tapered and the second tapered section as reverse tapered. Both the forward and reverse tapering angles, i.e., θ_1 and θ_2, respectively, are determined by the vertical heights t_1 and t_2, $t_1 < t_2$, and the section lengths L_1 and L_2 as shown in Fig. 1. The reverse section length L_2 is expressed in terms of the forward section length L_1 as $L_2 = \gamma \times L_1$, where γ can be either a positive integer or a positive fraction. The face on which the fundamental laser radiations will be incident upon is cut at an angle ψ with respect to a plane perpendicular to the horizontal plane.

The fundamental broadband optical radiation having a centre frequency ω_1 is incident at an angle ϕ_i with respect to the normal on the inclined slab end face. Angle of incidence on the horizontal plane inside the semiconductor slab will be determined by the refractive index of the material as calculated using the wavelength-dependent dispersion equation of the material [12]. If ϕ_1 is greater than the critical angle for the range of input frequencies, then the collimated 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 semiconductor slab up to forward section length, L_1, after which both the angle of incidence and the bounce length will go on decreasing in the reverse section length, L_2, till the beam emerges out of the slab. Fig. 2 shows the variation of the bounce lengths with respect to the number of bounces inside the slab corresponding to the fundamental centre wavelength of 9.146 μm. As explained in our earlier work [11], the present scheme also corresponds mainly to non-resonant QPM since the interaction lengths between successive bounces cannot be optimized to be equal to an odd multiple of the coherence length for all the frequencies available in the input band of fundamental laser radiations. But a situation may arise wherein one length may coincide with an odd multiple of the coherence length of a particular frequency in the input band of fundamentals, whereas another length may coincide with an odd multiple of the coherence length of another frequency in the band and so may not give rise to resonant QPM scenario. However, the

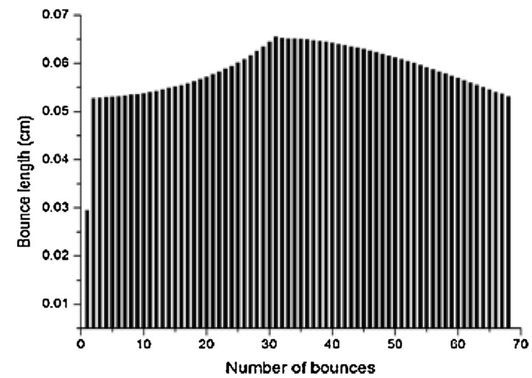

Fig. 2. Variation of bounce length with respect to number of bounces inside the double-tapered slab.

conversion efficiencies of other frequencies will be lower for that interaction length due to non-resonant QPM. This will result in a flatter second-harmonic spectrum as already demonstrated in the case of the tapered slab configuration. But the use of double-tapered configuration has further elevated the possibility of a flatter 3 dB BW also with improved conversion efficiency.

Now, for this double-tapered slab configuration (Fig. 1), the equations for length between consecutive bounces for the forward tapered section can be expressed as

$$L_i = \frac{x \cos \psi}{\sin(\phi_r + \psi)} \tag{1}$$

where L_i is the length between the entrance point and the point of first TIR point inside the slab, x is the slant distance of the entrance point from the base of the slab and $\varphi_r = \sin^{-1}[(\sin \varphi_i)/n_k]$, where n_k is the refractive index corresponding to each individual frequency of the input broadband laser radiation. The distance between successive bounces can be expressed by the following coupled equations:

$$\begin{aligned}
&l_2 = x \sin \psi + (x \cos \psi \tan \varphi) + t_1 \tan \varphi_1 - t_1 \tan \psi \\
&z'_{2n-1} = \frac{l_{2n-2} \sin \theta_1}{\cos \varphi_{2n-2}}, \quad n = 2, 3, \ldots, n_{tot} \\
&l_{2n} = l_{2n-2} + z'_{2n-1} \sin \varphi_{2n-3} + [(z'_{2n-1} \sin \varphi_{2n-3})/\tan(\tfrac{\pi}{2} - \varphi_{2n-1})] \\
&\quad +2t_1 \tan \varphi_{2n-1}, \quad n = 2, 3, \ldots, n_{tot} \\
&z'_{2n+1} = \frac{l_{2n} \sin \theta_1}{\cos \varphi_{2n}}, \quad n = 1, 2, 3, \ldots, n_{tot} \\
&L_{2n} = \frac{t_1}{\cos \varphi_{2n-1}} + \frac{l_{2n} \sin \theta_1}{\cos \varphi_{2n}}, \quad n = 1, 2, 3, \ldots, n_{tot}
\end{aligned} \tag{2}$$

$$L_{2n+1} = \frac{t_1}{\cos \varphi_{2n+1}} + \frac{z'_{2n+1} \cos \varphi_{2n-1}}{\cos \varphi_{2n+1}}, \quad n = 1, 2, 3, \ldots, n_{tot} \tag{3}$$

Here

$$\theta_1 = \tan^{-1}\left(\frac{t_2 - t_1}{L_1}\right) \tag{4}$$

$$\varphi_n = (n-1)\theta_1 + \varphi_1, \quad n = 1, 2, 3, \ldots, n_{tot} \tag{5}$$

where $\varphi_1 = \pi/2 - (\varphi_r + \psi)$ and n_{tot} is the total number of bounces inside the tapered slab.

For the reverse tapered section, the bounce lengths can be expressed with slight modifications in the expressions for the