Broadband quasi-phase-matched second-harmonic generation in MgO:LiNbO$_3$ waveguide*

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(Received 13 January 2011)

The quasi-phase-matched (QPM) condition of broadband second harmonic generation (SHG) in Ti-diffused MgO:LiNbO$_3$ waveguide is theoretically simulated. The results show that the center wavelength of broadband SHG dependent on the waveguide width is around 1550 nm and the bandwidth is 50 nm.

Document code: A **Article ID:** 1673-1905(2011)03-0202-3

DOI 10.1007/s11801-011-1004-0

Periodically poled LiNbO$_3$ (PPLN) is a representative quasi-phase-matched (QPM) device, which has demonstrated the impressive performance on optical frequency conversion because of its very large nonlinear coefficient. Compared with the traditional type-0 nonlinear interaction, type-I phase-matching geometry usually offers a spectral range in which the wave-vector mismatch varies more slowly with the fundamental wavelength[1]. Thus, the type-I interaction promises broadband second harmonic generation (SHG) process. Moreover, by exploring the appropriate choice of MgO-doping concentration, the broadband wavelength region of SHG can be adjusted to the communication band (around 1550 nm). The wavelength conversion in type-0 geometry based on the cascaded second-order nonlinear effect in PPLN is limited by the narrow bandwidth of pump. Recently, the flexible wavelength broadcast on MgO doped PPLN in type-I geometry has been demonstrated by tuning the wavelength of pump[2]. Broadband SHG also means the group velocity matching between the fundamental harmonic (FH) and the second harmonic (SH), and quadratic femtosecond soliton also has been widely investigated in the type-I geometry[3]. In order to be integrated with fiber-type lasers or fiber communications, the waveguide structure is further required for broadband SHG so as to achieve the spatial confinement of the light. In order to produce stable, single-mode and low-loss waveguides that exhibit the nonlinear optical properties comparable with the bulk substrate, two methods have been widely investigated. The annealed proton-exchange (APE) process is believed to be the best solution[4-6] and Ti-diffused methods also have been widely demonstrated as a success for QPM waveguide[7,8]. The SHG performance is mainly dependent on the QPM period in the waveguide. In this work, we theoretically analyze the type-I QPM geometry in a periodically poled Ti-diffused MgO:LiNbO$_3$ channel waveguide and suggest a broadband SHG. The effective refractive index of the channel waveguide is calculated by means of the variational method. The center wavelength of the broadband SHG is also investigated as a function of the waveguide width.

The actual refractive profile of the Ti-diffused waveguide is described as an error function and a Gaussian distribution function in the depth and width directions, respectively

$$n^2(y,z)=\begin{cases}1 & ,z<0\\ n_b^2+(n_s^2-n_b^2)f(z,d_a,d_e)g(y,d_w),z>0, & \end{cases}\quad(1)$$

where $f=[erf(\frac{d_e+z}{d_a})+erf(\frac{d_e-z}{d_a})]/2erf(\frac{d_e}{d_a})$ and $g(y,d_w)=\exp(-4y^2/d_w)$. d_e, d_a and d_w are the exchange depth, diffusion depth and channel width of the waveguide respectively. n_b is the refractive index of the substrate, as MgO:LiNbO$_3$ material[1], and n_s is the refractive index at the center waveguide of the surface. The two-dimensional wave equation for the extraordinary light is:

* This work has been supported by the National Natural Science Foundation of China (No.60978004), and Shanghai Municipal Education Commission (Nos.10YZ14 and 10SG38).

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$$[\frac{\partial^2}{\partial y^2}+(\frac{n_e}{n_0})^2\frac{\partial^2}{\partial z^2}]\phi(y,z)+k_0^2 n_e^2(y,z)\phi^2=\beta^2\phi \ . \qquad (2)$$

As for the ordinary light, n_e is substituted with n_o.

We take Gaussian/Hermite-Gaussian mode field distributions in the direction of width/depth as trial solution distributions in the channel waveguides[3],

$$\phi(x,y)=\phi_y(y)\phi_z(z) \ ,$$

$$\phi_y(y)=(2/w_y^2\pi)^{1/4}\exp(-z^2/w_y^2) \ ,$$

$$\phi_z(z)=\begin{cases}0 & ,z<0\\ (1/2w_z^6\pi)^{1/4}4z\exp(-z^2/w_z^2), & z>0,\end{cases} \qquad (3)$$

where w_y and w_z are mode sizes. Due to the variational properties of the propagation constant β in channel waveguide, those mode sizes (w_y and w_z), which make the propagation constant β maximized, are very close to the actual field distribution[9].

We investigate the type I nonlinear interaction (o + o: e) of the Ti-diffused $MgO:LiNbO_3$. The QPM period of type I is given as:

$$\Lambda=2\pi/\Delta\beta=2\pi/|2\beta_{FH}^0-\beta_{SH}^e| \ , \qquad (4)$$

where β_{FH}^0 is the propagation constant of the ordinary FH while β_{SH}^e is that of the extraordinary SH. The QPM period as a function of the FH wavelength is shown in Fig.1.

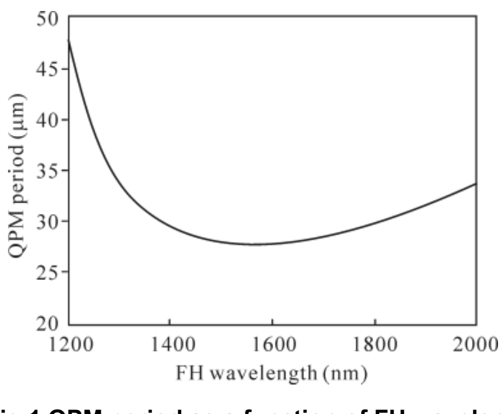

Fig.1 QPM period as a function of FH wavelength

In order to achieve a broadband SHG, the conversion region, where the QPM period has a slow variation, should be chosen. The variation of the QPM period is equivalent to that of the phase mismatch $\Delta\beta$, which can be deduced as:

$$\frac{d(\Delta\beta)}{d\lambda}=\frac{4\pi c}{\lambda^2}\delta \ , \qquad (5)$$

where δ is the group velocity mismatch (GVM) between the FH and the SH waves. When the GVM is equal to zero, the variation of the phase mismatch is also zero. Hence, the group velocity matching between FH and SH is equivalent to the broadband SHG. The zero point of the GVM also implies the center wavelength of the broadband SHG. As shown in Fig.2, both the group velocity and the GVM as a function of the FH wavelength are investigated and the zero point of the GVM is around 1550 nm. The 1550 nm conversion band is similar to that in bulk MgO: PPLN, which means that the Ti diffused process does not have great influence on the center wavelength of the SHG and the bandwidth of the SHG is about 50 nm.

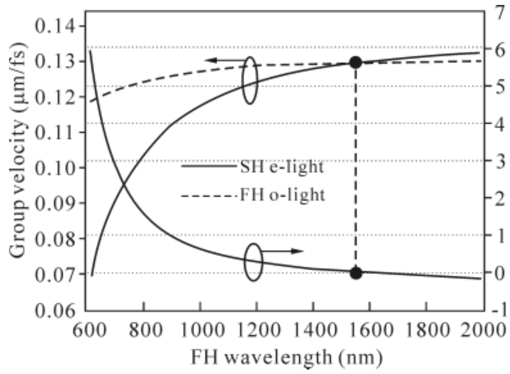

Fig.2 Group velocity and GVM as a function of FH wavelength

However, the width of the waveguide should have great influence on the conversion efficiency of the SHG[10]. We investigate both the center wavelength and the QPM period as a function of the waveguide width, shown in Fig.3 and Fig.4 respectively. With an increase of the waveguide width, the center wavelength of the SHG has a blue shift and the QPM period becomes shorter.

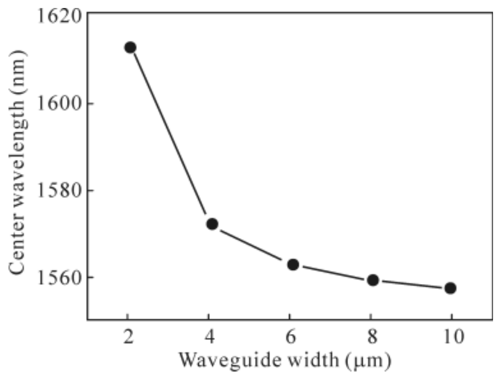

Fig.3 Center wavelength of the SHG as a function of waveguide width

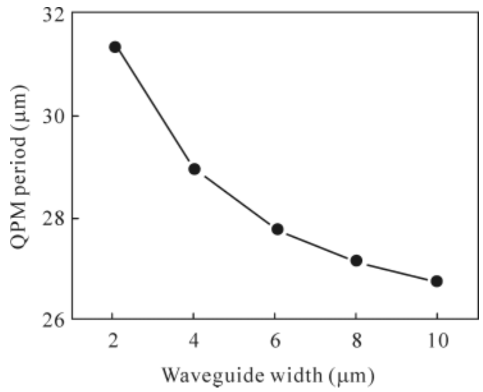

Fig.4 QPM period as a function of waveguide width

In summary, we theoretically investigate type-I broadband SHG in Ti-diffused MgO: $LiNbO_3$ channel waveguide. The effective refractive index is calculated by means of variational method. The broadband SHG has a center wavelength around 1550 nm and the bandwidth is as wide as 50 nm.

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