# Second-Harmonic Generation in AlGaAs/Al$_x$O$_y$ Artificial Birefringent Microring Resonators

Linsen Li, Junqiang Sun, and Tao Chen

***Abstract*—We propose a highly efficient second-harmonic generation (SHG) scheme based on AlGaAs/Al$_x$O$_y$ artificial birefringent microring resonators. This scheme can realize the quasi-phase-matching (QPM) between fundamental transverse-electric (TE) and transverse- magnetic (TM) mode in microring resonators. The theoretical analysis and numerical simulation demonstrate that the conversion efficiency of this model is considerable. The relationship of input power, total loss, and coupling constants with conversion efficiency has also been discussed.**

***Index Terms*—Artificial birefringent, conversion efficiency, microring resonators, quasi-phase-matching.**

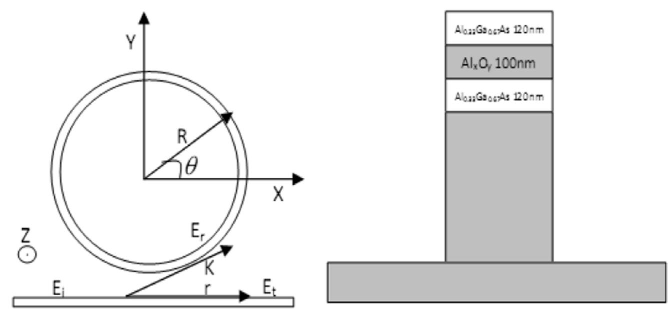


Fig. 1. Schematic of a doubly resonant artificial birefringent microring.

QUADRATIC optical interaction plays a very important role in frequency conversion, signal processing, high speed optical switch, quantum optics and so on [1], [2]. It has been intensively studied in the last three decades. A key of this field is how to improve the nonlinear conversion efficiency. In order to obtain highly efficient nonlinear conversion, choosing an appropriate material tends to be very important. The material with large second order nonlinear susceptibility is known to be the best choice. AlGaAs, as an easily integrated semiconductor material with huge nonlinear coefficient, has attracted much attention.

This letter focuses on second-harmonic generation (SHG) in AlGaAs. In the process of efficient frequency doubling, phase matching is a key technology. At present, phase matching can be grouped in two families, birefringent phase matching (BPM) and quasi-phase-matching (QPM). BPM is very popular and efficient in optically anisotropic crystal. Unfortunately, AlGaAs is optically isotropic crystal. In recent years, the scheme based on artificial birefringent waveguide structure to obtain phase matching has been reported [3], [4]. QPM, introduced by Armstrong *et al.* [5] in 1962, has been widely used in ferroelectric crystals, such as lithium niobate ($LiNO_3$). In AlGaAs, conventional QPM periodic domain inversion can be obtained by wafer bonding and epitaxial grown [6]–[8], however, this process is very complex and will cause large corrugation loss, thus having negative influences on the conversion efficiency.

Manuscript received November 16, 2010; revised January 10, 2011; accepted January 22, 2011. Date of publication January 28, 2011; date of current version March 23, 2011. This work was supported by the National Natural Science Foundation of China (Project 60977044).

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Digital Object Identifier 10.1109/LPT.2011.2109059

Dumeige *et al.* [9] proposed an angular quasi-phase-matching (AQPM) scheme to achieve second harmonic generation in AlGaAs microdisk. Yang *et al.* [10], [11] extended it to microring resonators and used it in quantum optics. This AQPM scheme avoids corrugation loss and reduces the nonlinear trigger threshold. Although this design has attracted much attention, there might be considered to its two disadvantages: one is the large bending loss will occur if the ring radius is too small; another is the phase matching obtains between different order mode fields, and as we know the mode coupling of different orders is very weak.

Here we propose second harmonic generation in AlGaAs/Al$_x$O$_y$ artificial birefringent microring resonators, which will solve those problems of previous microring model by the aid of birefringent structure. It realizes the QPM between fundamental TE and TM mode in microring resonators, at the same time, the matching radius can be enlarged by adjusting the effective mode index, which reduces the bending loss, and therefore, the conversion efficiency is improved. This model is shown in Fig. 1.

The main idea of AQPM can be addressed by the effective nonlinear polarization periodic changes due to the angular variation. This effective nonlinear polarization can be written as below in cylindrical coordinates:

$$P_z = \varepsilon_0 d \left\{ 2E_{\bar{r}}^{\omega} E_{\bar{\theta}}^{\omega} \cos(2\theta) + \left[ \left(E_{\bar{r}}^{\omega}\right)^2 - \left(E_{\bar{\theta}}^{\omega}\right)^2 \right] \sin(2\theta) \right\} \tag{1}$$

where $E_{\bar{r}}^{\omega}, E_{\bar{\theta}}^{\omega}$ is radial and tangential field component inside the resonator, respectively, and $d = \chi^{(2)}/2$. This effective nonlinear polarization depends on the angular $\theta$, and this angular dependent effective nonlinear polarization can be used to reach the QPM condition.

As we have already emphasized that others realize AQPM between different order modes and the coupling efficiency is

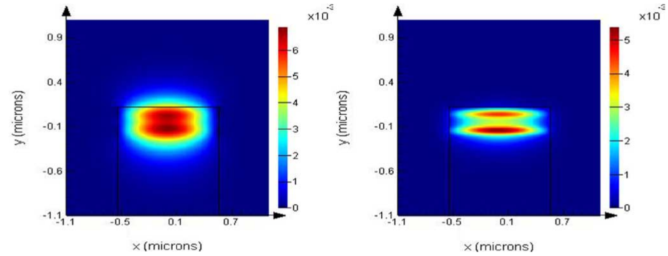


Fig. 2. Mode field of fundamental (a) FW TE and (b) SH TM.

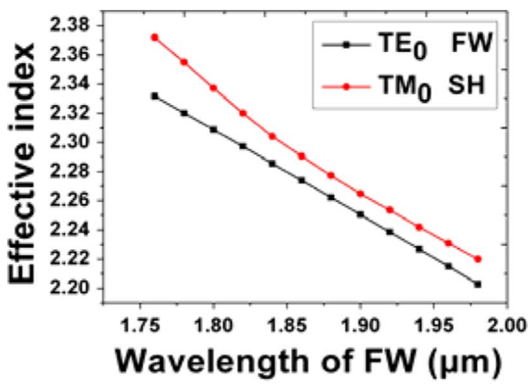


Fig. 3. TE and TM effective index at different wavelength.

very low. Our model is to use artificial birefringent doubly resonant microring cavity to realize AQPM in fundamental mode. In this model, The phase matching obtained between TE-polarized fundamental wave (FW) field at frequency $\omega$ and an out of plane TM-polarized second-harmonic (SH) field at frequency $2\omega$. Here Al composition we chosen is 0.33, so as to avoid two photonics absorption at FW frequency and at this condition $d = d_{14} \approx 108$ (pm/V).

The layer structure of our model is a multilayer core (120 nm $Al_{0.33}Ga_{0.67}As$/100 nm $Al_xO_y$/120 nm $Al_{0.33}$ $Ga_{0.67}$ As) on top of a 2.5 $\mu$m thick $Al_xO_y$, the thin $Al_xO_y$ layer does not significantly affect the TE mode profile at FW but generates large discontinuities in the electric field distribution of the TM mode at SH. The SH mode effective index is thus lowered enough to achieve phase matching. The width of the waveguide is 1100 nm. The distance $dl$ between the microring resonator and the bus waveguide can be adjusted to get an optimal coupling coefficient.

The layer structure can be grown by molecular beam epitaxy (MBE), where $Al_{0.92}Ga_{0.08}$ As is used for the cladding layer. E-beam lithography and then followed by the dry etching in chlorine plasma is used to obtain the ridge waveguide. The sample is then thermally oxidized to convert the $Al_{0.92}Ga_{0.08}$ As to $Al_xO_y$. The mode field of TE and TM in this model is shown in Fig. 2.

The effective index of fundamental TE and TM mode in different wavelength is shown in Fig. 3.

In the rest of this letter, the FW we chosen is 1.84 $\mu$m and the SH is 0.92 $\mu$m, at this condition, the effective index for fundamental TE and TM is $n_\omega = 2.285568$ and $n_{2\omega} = 2.30411$ [12] respectively. For achieving angular dependent QPM in microring resonators, the matching condition that results as

$$k_{2\omega} - 2k_\omega = 2/R \tag{2}$$

where $k_{\omega,2\omega} = (\omega, 2\omega \times n_{\omega,2\omega})/c$, $R$ is the microring radius. In this assumed condition, $R = 15.7936$ $\mu$m. Of course, it needs to ensure the FW and the SH resonance in microring.

In microring resonators, the loss exponentially increases with the decrease of the ring radius $R$ [13], [14]. And this loss is associated with conversion efficiency, which will be addressed later.

As it has been mentioned before, the conversion efficiency is in close relation with coupling coefficient while the coupling coefficient is related with the distance $dl$ between the bus waveguide and the microring resonator. Generally, the coupling coefficient is not as the same for different wavelength and mode at a fixed $dl$, but here for simplicity, we assume the coupling coefficient is the same for fundamental TE-FW and TM-SH. In microring, at steady and resonance state, the transmission-transfer function of the resonator can be written as [15]:

$$\frac{E_t}{E_i} = \frac{r - ae^{j\phi}}{1 - rae^{j\phi}} \tag{3}$$

The ratio of the circulating field to the input field is given by:

$$\frac{E_r}{E_i} = \frac{-jk}{1 - rae^{j\phi}} \tag{4}$$

where $E_i, E_t$ is the input and throughput field at the bus waveguide respectively, $E_r$ is the field inside the resonator. $\phi = k_{\omega,2\omega}L$ is the resonator round trip phase, $L = 2\pi R$ is the circumference of the ring, $a = e^{-\alpha_0 L/2}$ is the round trip field transmission, $\alpha_0$ is the total loss (contain bending loss and interface loss) of the microring, $k$ and $r$ are the field coupling and transmission coefficients between the bus waveguide and the microring resonator such that $k^2 + r^2 = 1$.

We define the "conversion efficiency" as the ratio of output SH intensity to the input FW intensity, in the case of small signal model, and taking into account of the light intensity increase and the effective nonlinear polarization periodic variation in microring, it can be written by:

$$\eta = \frac{8\omega^2 d_{\text{eff}}^2 L^2 k^6 I_{i\omega}}{\varepsilon_0 c^3 n_{2\omega} n_\omega^2 (1 - ra)^6} \sin c^2 \left(\frac{\Delta k_{\text{SHG}} L}{2}\right) \tag{5}$$

where $\Delta k_{\text{SHG}} = k_{2\omega} - 2k_\omega - 2/R$ represents the phase mismatching in the microring. $I_{i\omega} = |E_{i\omega}|^2$ is the intensity of input power, here $d_{\text{eff}} = \overline{|v(\theta)|} \cdot d \cdot 2/\pi$ and $v(\theta) \propto P_z, v(\theta)$ represents the effective nonlinear polarization variation with $\theta$. If link these parameters to $Q$ factors, and the $Q$ factors is defined as [15] $Q = (\pi n_{\omega,2\omega} L \cdot \sqrt{ar})/[\lambda_{\omega,2\omega} \cdot (1 - ar)]$, then the conversion efficiency can be written by

$$\eta = \frac{8\omega^2 d_{\text{eff}}^2 L^2 (1 - (C_Q/a)^2)^3 I_{i\omega}}{\varepsilon_0 c^3 n_{2\omega} n_\omega^2 (1 - C_Q)^6} \sin c^2 \left(\frac{\Delta k_{\text{SHG}} L}{2}\right) \tag{6}$$

where

$$C_Q = \frac{1}{2}\left[\left(\frac{\pi n_{\omega,2\omega} L}{Q\lambda_{\omega,2\omega}}\right)^2 + 2\right] - \sqrt{\frac{1}{4}\left(\frac{\pi n_{\omega,2\omega} L}{Q\lambda_{\omega,2\omega}}\right)^4 + \left(\frac{\pi n_{\omega,2\omega} L}{Q\lambda_{\omega,2\omega}}\right)^2}$$

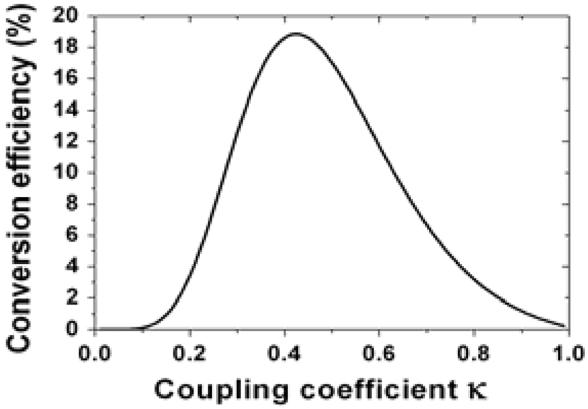


Fig. 4. Conversion efficiency at different coupling coefficients.

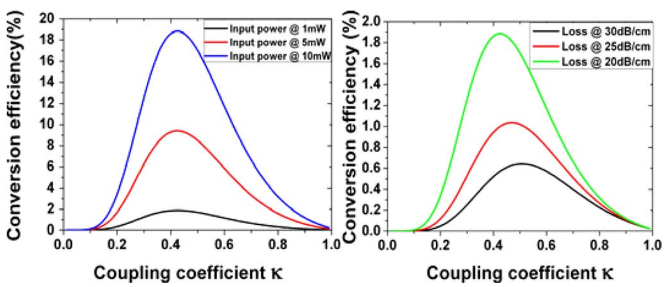


Fig. 5. Efficiency at different (a) input power and (b) total loss.

We calculated the conversion efficiency with different coupling coefficients ($k$ from 0 to 1) and the result is shown in Fig. 4.

The calculation condition is input power at 10 mW and total loss at 20 dB·cm$^{-1}$. The calculated result shows that when the coupling coefficient is $k = 0.42$, the $Q$ factors is $Q_\omega \approx 1.95 \times 10^3$ and $Q_{2\omega} \approx 3.93 \times 10^3$ respectively. The conversion efficiency reaches the peak, it is 18.83%, which means when the input power (FW) is 10 mW, it can get an 1.883 mW (SH) output power. Provided the total loss remains constant, keeping at 20 dB·cm$^{-1}$, Then we calculated conversion efficiency at different input power, it is found that the conversion efficiency linearly increases with the input power, and the optimal coupling coefficient remains unchanged, the maximum efficiency still appears at $k = 0.42$, the result is shown in Fig. 5(a). We also calculated the conversion efficiency at different total loss, and it is indicated that the efficiency exponentially increases with the decrease of the total loss, for instance, when the input power is kept at 1 mW, the loss is 20 dB·cm $^{-1}$, the conversion efficiency is 1.88% and the optimal coupling coefficient $k$ is 0.42; while when the loss is 30 dB·cm$^{-1}$, the conversion efficiency is 0.64% and optimal coupling coefficient $k$ is 0.51. The result is shown in Fig. 5(b).

It can be concluded that the total loss severely affects the conversion efficiency. So it is significative to use artificial birefringent structure to enlarge the microring matching radius and reduce the total loss. It is also demonstrated that when the total loss varies, the optimal coupling coefficients varies correspondingly.

In conclusion, it is proposed that utilizing the artificial birefringent microring resonators to realize second harming generation in III–V semiconductors is feasible. This model keeps the merits of the microring to realize nonlinear conversion, which is not relied on material periodic domain inversion to obtain quasi phase matching, and the microring resonance enhance the light intensity, thus the trigger power is reduced. Not only for this, compared with the previous reported nonlinear interaction that obtained in different order mode, our model, aiming at improving the conversion efficiency, is designed to make the nonlinear interaction obtained between fundamental TM and TE, because the mode coupling in the same order is more competitive. Moreover, considering the great impact of the total loss on conversion efficiency, our model is aimed to reduce the total loss by enlarging the microring matching radius; therefore, the conversion efficiency is extensively improved.

## REFERENCES

[1] Y. R. Shen, *The Principles of Nonlinear Optics*. New York: Wiley, 1984.

[2] J. Wang, J. Sun, Q. Sun, D. Wang, M. Zhou, X. Zhang, D. Huang, and M. M. Fejer, “All-optical format conversion using a periodically poled lithium niobate waveguide and a reflective semiconductor optical amplifier,” *Appl. Phys. Lett.*, vol. 91, p. 051107-3, 2007.

[3] L. Scaccabarozzi, M. M. Fejer, Y. Huo, S. Fan, X. Yu, and J. S. Harris, “Enhanced second-harmonic generation in AlGaAs/AlxOy tightly confining waveguides and resonant cavities,” *Opt. Lett.*, vol. 31, pp. 3626–3628, 2006.

[4] J. B. Khurgin, M. W. Pruessner, T. H. Stievater, and W. S. Rabinovich, “Suspended AlGaAs waveguides for tunable difference frequency generation in mid-infrared,” *Opt. Lett.*, vol. 33, pp. 2904–2906, 2008.

[5] J. A. Armstrong, N. Bloembergen, J. Ducuing, and P. S. Pershan, “Interactions between light waves in a nonlinear dielectric,” *Phys. Rev.*, vol. 127, pp. 1918–1939, 1962.

[6] E. U. Rafailov, P. Loza-Alvarez, C. T. A. Brown, W. Sibbett, R. M. De La Rue, P. Millar, D. A. Yanson, J. S. Roberts, and P. A. Houston, “Second-harmonic generation from a first-order quasi-phase-matched GaAs/AlGaAs waveguide crystal,” *Opt. Lett.*, vol. 26, pp. 1984–1986, 2001.

[7] S. J. B. Yoo, R. Bhat, C. Caneau, and M. A. Koza, “Quasi-phase-matched second-harmonic generation in AlGaAs waveguides with periodic domain inversion achieved by wafer-bonding,” *Appl. Phys. Lett.*, vol. 66, pp. 3410–3412, 2007.

[8] X. Yu, L. Scaccabarozzi, J. S. Harris, Jr., P. S. Kuo, and M. M. Fejer, “Efficient continuous wave second harmonic generation pumped at 1.55 $\mu$m in quasi-phase-matched AlGaAs waveguides,” *Opt. Express*, vol. 13, pp. 10742–10748, 2005.

[9] Y. Dumeige and P. Féron, “Whispering-gallery-mode analysis of phase-matched doubly resonant second-harmonic generation,” *Phys. Rev. A*, vol. 74, p. 063804-7, 2006.

[10] Z. Yang, P. Chak, A. D. Bristow, H. M. van Driel, R. Iyer, J. S. Aitchison, A. L. Smirl, and J. E. Sipe, “Enhanced second-harmonic generation in AlGaAs microring resonators,” *Opt. Lett.*, vol. 32, pp. 826–828, 2007.

[11] Z. Yang and J. E. Sipe, “Generating entangled photons via enhanced spontaneous parametric downconversion in AlGaAs microring resonators,” *Opt. Lett.*, vol. 32, pp. 3296–3298, 2007.

[12] Software: Mode Solutions. ver. 2.0.3, Lumerical Solution, Inc.

[13] V. Subramaniam, G. N. De Brabander, and D. H. Naghski, “Measurement of mode field profiles and bending and transition losses in curved optical channel waveguides,” *J. Lightw. Technol.*, vol. 15, no. 6, pp. 990–997, Jun. 1997.

[14] B. M. A. Rahman, D. M. H. Leung, S. S. A. Obayya, and K. T. V. Grattan, “Numerical analysis of bent waveguides: Bending loss, transmission loss, mode coupling, and polarization coupling,” *Appl. Opt.*, vol. 47, pp. 2961–2970, 2008.

[15] T. A. Ibrahim, “Nonlinear Optical Semiconductor Mirco-Ring Resonators,” Ph.D. Thesis, University of Maryland, College Park, MD, 2003.