# Acousto-optic tunable second harmonic generation in periodically poled $LiNbO_3$

**Zi-yan Yu, Fei Xu, Fei Leng, Xiao-shi Qian, Xiang-fei Chen and Yan-qing Lu***

*Department of Materials Science and Engineering and National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, P. R. China*

* *yqlu@nju.edu.cn*

**Abstract:** Acousto-optic (AO) tunable second harmonic generation (SHG) was proposed in periodically poled lithium niobate (PPLN). The acoustic wave could either be induced from an external transducer or self-generated in PPLN driving with a cross-field radio frequency field. The reciprocal vector of PPLN compensates the SHG wave-vector mismatch when quasi-phase-matching (QPM) condition is satisfied, while phonons with suitable frequencies may affect it by scattering photons to different polarization state. The QPM SHG and AO polarization rotation are coupled together. Second harmonic waves' intensities, polarization states and even phases thus could be manipulated instantly through AO interaction.



**OCIS codes:** (170.1065) Acousto-optics; (190.2620) Harmonic generation and mixing; (050.5298) Photonic crystals.

## References and links

1. E. Yablonovitch, "Inhibited spontaneous emission in solid-state physics and electronics," Phys. Rev. Lett. **58**, 2059-2062 (1987).
2. A. Sihvola, "Metamaterials in electromagnetics," Metmat. **1**, 2-11 (2007).
3. N. B. Ming, J. F. Hong, and D. Feng, "The growth striations and ferroelectric domain structures in Czochralski-grown $LiNbO_3$ single," J. Mater. Sci. **17**, 1663-1670 (1982).
4. M. M. Fejer, G. A. Margel, D. H. Jundt, and R. L. Byer, "Quasi-phase-matched second harmonic generation: tuning and tolerances," J. Quantum Electron. **28**, 2631-2654 (1992).
5. Y. Q. Lu, M. Xiao, and G. J. Salamo, "Coherent microwave generation in a nonlinear photonic crystal," J. Quantum Electron. **38**, 481-485 (2002).
6. V. Berger, "Nonlinear photonic crystals," Phys. Rev. Lett. **81**, 4136-4139 (1998).
7. Y. Q. Qin, C. Zhang, Y. Y. Zhu, X. P. Hu, and G. Zhao, "Wave-front engineering by huygens-fresnel principle for nonlinear optical interactions in domain engineered structures," Phys. Rev. Lett. **100**, 063902 (2008).
8. Y. Q. Lu, Y. Y. Zhu, Y. F. Chen, S. N. Zhu, N. B. Ming, and Y. J. Feng, "Optical properties of an ionic-type phononic crystal," Science **284**, 1822 (1999).
9. P. St. J. Russell and W. F. Liu, "Acousto-optic superlattice modulation in fiber Bragg gratings," J. Opt. Soc. Am. A **17**, 1421-1429 (2000).
10. S. Krishnamurthy and P. V. Santos, "Optical modulation in photonic band gap structures by surface acoustic waves," J. Appl. Phys. **96**, 1803 (2004).
11. H. Gnewuch, N. K. Zayer, C. N. Pannell, G. W. Ross, and P. G. R. Smith, "Broadband monolithic acousto-optic tunable filter," Opt. Lett. **25**, 305 (2000).
12. Y. Kong, B. Li, Y. Chen, Z. Huang, S. Chen, L. Zhang, S. Liu, J. Xu, H. Liu, Y. Wang, W. Yan, W. Zhang and G. Zhang, "The highly optical damage resistance of lithium niobate crystals doping with Mg near its second threshold," OSA TOPS **87,** 53-57 (2003).
13. Yariv and P. Yeh, *Optical Waves in Crystals* (John Wiley and Sons, New York, 1984), Chap. 9.
14. Y. Y. Zhu, N. B. Ming, W. H. Jiang, and Y. A. Shui, "Acoustic superlattice of $LiNbO_3$ crystals and its applications to bulk-wave transducers for ultrasonic generation and detection up to 800 MHz," Appl. Phys. Lett. **53**, 1381-1383 (1988).
15. Y. Y. Zhu, S. N. Zhu, Y. Q. Qin, and N. B. Ming, "Further studies on ultrasonic excitation in an acoustic superlattice," J. Appl. Phys. **79**, 2221-2224 (1996).
16. C. P. Huang, Q. J. Wang, and Y. Y. Zhu, "Cascaded frequency doubling and electro-optic coupling in a single optical superlattice," Appl. Phys. B **80**, 741-744 (2005).

#111311 - $15.00 USD Received 12 May 2009; revised 26 Jun 2009; accepted 27 Jun 2009; published 30 Jun 2009

17. Y. Kong, X. F. Chen, and Y. Xia, "Competition of frequency conversion and polarization coupling in periodically poled lithium niobate," Appl. Phys. B **91**, 479-482 (2008).

## 1. Introduction

Wavelength scale artificial photonic microstructures have been hot topics in the past two decades [1, 2]. Among them, photonic crystal (PC) attracts most of the research interests. While in nonlinear optics regime, quasi-phase-matching (QPM) in periodic nonlinear media have been intensively studied [3-5]. As photons simultaneously exhibit particle and wave-type behavior, there are two ways to understand the mechanism of various photonic microstructures, either viewing from the quantum physics or from classical wave optics.

The quantum description reveals that photons exhibit similar characteristics like electrons. Concepts such as Brillouin zone, band gap thus could be introduced to photonic crystals. The energy conservation and momentum conservation laws give straightforward insight on photon-photon interaction in a PC. On the other hand, the wave optics describes PCs as dielectric or metallo-dielectric microstructures where electromagnetic waves propagating. Detailed properties could be deduced from Maxwell equations with the help of various analytical or numerical methods.

Although QPM is traditionally established on the wave picture [4], researches have adopted the photon description in QPM nonlinear optics gradually. Considering the similarity to PCs, QPM materials have been named nonlinear photonic crystals as well [5, 6]. Novel 2D QPM thus was proposed accordingly [6, 7]. People are expecting to "copy" more physical effects from PCs or crystals to QPM materials analogously. For example, the electron-phonon interaction plays an important role in electrons' state transition in a crystal. The photon-phonon interactions in photonic microstructures also have been investigated with some new "acousto-optic" (AO) properties, e.g., macro-polariton excitation and tunable band gap [8-10]. It would be also interesting to see how the photon-phonon interacts in nonlinear PCs, *i.e.*, artificial QPM microstructures. To the best of our knowledge, there is still rarely report on this topic. As QPM has a lot of advantages over the birefringence phase matching, studying the AO QPM nonlinear effects would have both fundamental interest in Physics and important technical applications.

In this paper, we studied the photon-phonon interaction in a typical QPM material, the periodically poled $LiNbO_3$ (PPLN). We found that the acoustic wave could affect the wave vector matching between fundamental wave (FW) and its second harmonic (SH). The frequency doubling is thus tunable by an externally induced acoustic wave. The power flow curves among the FW, SH and polarization rotated SH were investigated through coupling wave equations. Furthermore, we pointed out that the PPLN itself could work as an acoustic superlattice to generate high-frequency bulk acoustic wave. Therefore a radio frequency (RF) signal can be used to manipulate the second harmonic generation (SHG) directly though cascaded piezoelectric and AO processes in a PPLN. The related mechanism and future applications were discussed.

## 2. Theory and simulation

When an acoustic wave travels in a PPLN, it results in deformation so that the domain boundaries are displaced periodically. In addition, the refractive index also changes due to the traditional elasto-optic effect. As the elasto-optic coefficient is a forth-rank tensor, it keeps uniform in both positive and negative domain. The acoustic wave travels just like in a single-domain $LiNbO_3$ crystal, a periodic index modulation is built up in PPLN, which affects its optical properties. From the quantum point of view, the phonons may scatter photons strongly if the corresponding momentum (wave vector) conservation is satisfied. As the PPLN is a one-dimensional microstructure, the collinear-phonons only may scatter the photons toward the backward direction, *i.e.*, Bragg scattering, or, forward scattering with orthogonal polarization [11]. As the backward scattering requires extremely high acoustic frequency, here we only consider the acousto-optic polarization rotation and its effects. In this case, the wave vector difference depends on crystal's birefringence, it is relatively much lower than that of

#111311 - $15.00 USD Received 12 May 2009; revised 26 Jun 2009; accepted 27 Jun 2009; published 30 Jun 2009

backward Bragg scattering. In another word, the phonon's wave vector could compensate the wave vector mismatch between ordinary and extraordinary beams. This polarization rotation effect may be realized for either FWs or SHs depending on the phonon's frequency. As QPM relies on lights' polarization states, the phonon induced polarization change should affect the SHG accordingly. Let's assume the SH wave's polarization is rotated, thus the FW, original SH and the polarization rotated SH are coupled together. Here a Z-polarized FW is adopted to utilize the largest nonlinear coefficient $d_{33}$ of $LiNbO_3$. The coupling equations can be deduced under the plane-wave approximation with consideration of both SHG and AO interactions.

$$\begin{cases} \dfrac{dE_{1z}}{dx} = -i\dfrac{\omega_1 d_{33}(x)}{n_{1z}c} E_{2z}E_{1z}^* e^{i\Delta\beta_1 x} \\ \dfrac{dE_{2z}}{dx} = -i\dfrac{\omega_2}{4n_{2z}c}\left(2d_{33}(x)E_{1z}^2 e^{-i\Delta\beta_1 x} + n_{2y}^2 n_{2z}^2 p_{41} S E_{2y} e^{i\Delta\beta_2 x}\right) \\ \dfrac{dE_{2y}}{dx} = -i\dfrac{\omega_2}{4n_{2y}c} n_{2y}^2 n_{2z}^2 p_{41} S E_{2z} e^{-i\Delta\beta_2 x} \end{cases}. \quad (1)$$

Where $E_{j\xi}$, $\omega_{j\xi}$, $k_{j\xi}$ and $n_{j\xi}$ (the subscripts j = 1, 2 refer to the FW and SH, respectively, and $\xi$ = y, z represent the polarization) are the electric fields, the angular frequencies, the wave-vectors and the refractive indices, respectively. c is the speed of light in vacuum. $\omega_2 = 2\omega_1$ is the doubled light frequency. $d_{33}(x) = d_{33}f(x)$ is the modulated nonlinear coefficient. $\Delta\beta_1 = k_{2z} - 2k_{1z}$, $\Delta\beta_2 = k_{2y} - k_{2z} - H$ are the wave vector mismatch for SHG and polarization rotation, respectively, where H is the acoustic wave vector. S = HA is the amplitude of acoustic wave induced strain [13], where A is the maximal displacement of a mass point in PPLN when acoustic wave propagates in it. A longitudinal acoustic wave along X-direction is considered. $P_{41}$ is the corresponding elasto-optic coefficient.

In a PPLN, the structure function f(x) changes its sign from +1 to -1 periodically in different domains. It can be expanded as Fourier series, $f(x) = \sum_m g_m \exp(-iG_m x)$, where $G_m$ are the reciprocal vectors and gm are the amplitudes of the reciprocal vectors. Without loss of generality, the reciprocal vector $G_1$ is adopted to compensate the nonlinear phase mismatch as $\Delta\beta_1 = k_{2z} - 2k_{1z} = G_1$. Then the acoustic frequency is fine tuned to realize the AO polarization rotation at $\Delta\beta_2 = 0$. In this case, the coupling Eqs. (1) can be simplified as:

$$\begin{cases} \dfrac{dA_{1z}}{dx} = -iK_1 A_{1z}^* A_{2z} \\ \dfrac{dA_{2z}}{dx} = -\dfrac{1}{2}K_1 A_{1z}^2 - iK_2 A_{2y} \\ \dfrac{dA_{2y}}{dx} = -iK_2^* A_{2z} \end{cases} \quad (2)$$

with $A_j = \sqrt{\dfrac{n_j}{\omega_j}} E_j, K_1 = \dfrac{d_{33}g_1}{c}\sqrt{\dfrac{\omega_{1z}^2\omega_{2z}}{n_{1z}^2 n_{2z}}}, K_2 = \dfrac{\omega_2 (n_{2y}n_{2z})^{\frac{3}{2}} p_{41} S}{4c}$

In this phase matching case, the SHG and AO polarization rotation no longer proceed alone but are coupled together, which leads to a continuous energy transfer among the FW and SHs. As seen from Eq. (2), the right-hand side of the second equation is composed of two terms: one represents the SHG and another is for polarization rotation. A frequency doubled photon could either splits back to two FW photons or be scattered to another polarization state. The competition between these two processes is governed by the coupling coefficients $K_1$ and $K_2$ and their ratio. Numerical solution to Eq. (2) was done to study this coupled SHG-AO effect. We set the wavelength of FW at 1550 nm and working temperature T at 20°C. $\Lambda$ = 18.98 μm to satisfy the QPM condition. $d_{33}$ = 25.2 pm/V, $p_{41}$ = -0.05. Note that $p_{41}$ at this wavelength is approximately a third of that published value at $\lambda$ = 0.633μm [11]. Considering of the optical damage threshold of a Near-stoichiometric $LiNbO_3$ crystal, the pumping FW intensity is set to be 10 $MW/cm^2$ [12].

#111311 - $15.00 USD Received 12 May 2009; revised 26 Jun 2009; accepted 27 Jun 2009; published 30 Jun 2009

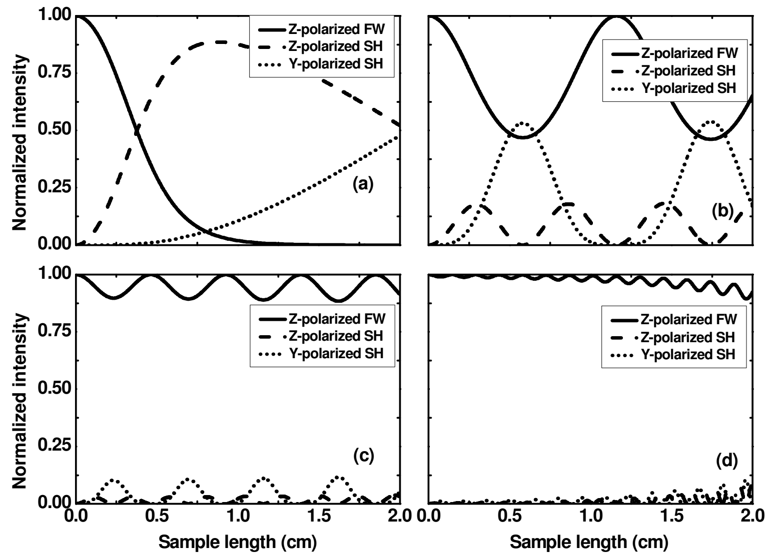


Fig. 1. Normalized light intensities versus the PPLN sample length at different $K_1/K_2$ ratios: (a) 10, (b) 1, (c) 0.33, (d) 0.1. Solid, dash and dot curves represent FW, Z-polarized SH, and Y-polarized SH, respectively.

Figure 1 shows the simulations results, where the following cases are categorized.

(a) $K_1/K_2 >> 1$. In this case, SHG is much stronger than AO polarization rotation. Fig. 1(a) illustrates the result when $K_1/K_2 = 10$. It can be seen that the majority of the energy stored in the Z-polarized FW is transferred to the Z-polarized SH along the crystal. 89% power could be transferred to Z-polarized SH with a 0.87 cm PPLN. Then its power drops slowly and is gradually converted to Y-polarized SH. If the crystal is 2 cm, there is almost no FW left while Y and Z-polarized SH shares the light power.

(b) $K_2$ increases while $K_1$ remains unchanged, so the $K_1/ K_2$ ratio becomes smaller. Fig. 1(b) shows the numerical solution when $K_1/ K_2 = 1$. The energy change between the Z-polarized SH and the Y-polarized SH goes faster, while the maximum SHG efficiency cannot reach 100% anymore. There is always FW left even with a longer PPLN length. This is quite different from pure QPM SHG where the FW and SH may totally swap their powers in theory. The lower SHG efficiency means the generated SH cannot interference constructively even the PPLN reciprocal vector may fully compensate the SHG wave vector mismatch. In other words, the AO interaction influences QPM. One simple explanation might be, the stronger acoustic field results in frequent SH polarization change, then further changes the phase of Z-polarized SH. The original QPM condition thus is broken and lowered the efficiency.

(c), (d) In the case of $K_1/K_2 < 1$, the AO polarization coupling process overcomes the frequency doubling process. Fig. 2(c) shows the case when $K_1/K_2 = 0.33$. As we just discussed, the stronger $K_2$ diminishes the SHG remarkably. Only up to 10% of the SH could be frequency doubled. When $K_1/K_2 << 1$, as shown in Fig. 2(d), $K_1/K_2 = 0.1$, the frequency doubling process is weaker. The period of the AO polarization coupling process is shorter.

Since SHG strongly relies on the coupling coefficients and their ratio, a simple method to tune the frequency doubling efficiency can be suggested. That is, adjusting the acoustic intensity, the coupling coefficient ratio changes, then a required SH intensity could be obtained. The lights' phases and polarizations are manipulated consequently.

In our simulation above, we assume the collinear propagated acoustic wave is coupled from an external transducer, which could be bonded directly to a PPLN. However, in addition to nonlinear optical coefficient, the piezoelectric coefficient changes its sign periodically in a PPLN, it also could act as an acoustic superlattice to generate high-frequency bulk acoustic waves [14]. One unique advantage of acoustic superlattice is cross-field excitation. The RF driving signals are applied at the sides of PPLN sample so that the refractive index and sound

#111311 - $15.00 USD Received 12 May 2009; revised 26 Jun 2009; accepted 27 Jun 2009; published 30 Jun 2009

velocity mismatching between the transducer and PPLN are solved [15]. Normal metal electrodes could be used instead of transparent ones to get a simple and more reliable setup.

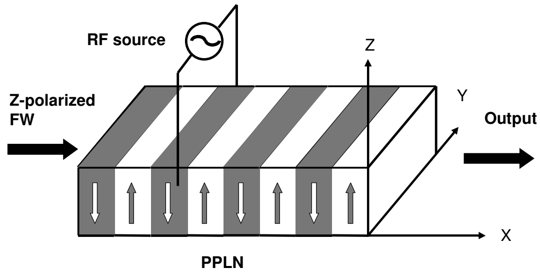


Fig. 2. Schematic diagram of an integrated PPLN AO tunable frequency doubler with cross-field RF driving.

Figure 2 shows the schematic diagram of the new configuration. A cross-field RF driving signal is applied at the Y-side surfaces to excite longitudinal wave along X-axis [15]. According to Zhu's acoustic superlattice theory [14, 15], the generated peak acoustic frequency is $f = v/\Lambda$, where v is acoustic velocity. When the phase-matching condition is satisfied for both the AO polarization coupling and the QPM frequency doubling simultaneously, the two processes are coupled together, *i.e.*, $\Delta\beta_1 = k_{2z} - 2k_{1z} = G_1$, $\Delta\beta_2 = k_{2y} - k_{2z} - H = 0$. Obviously these conditions are difficult to satisfy, giving tight constrains on working temperature, wavelength and superlattice geometrical parameters. At room temperature 20°C, a 4.95 μm period PPLN is selected for a 961 nm FW. The corresponding acoustic frequency is $f = v/\Lambda = 1.33$ GHz. To realize this approach at other wavelengths, temperature tuning is an effective way. The tuning rate is calculated to be ~ 0.5nm/°C. Employing third-order or high order QPM may further loose these constrains and release the sample fabrication difficulty [4].

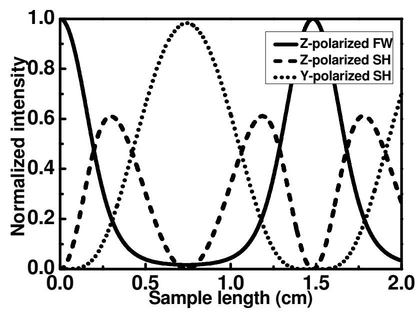


Fig. 3. Normalized light intensities of the FW and SHs as a function of PPLN sample length under the phase-matching conditions. The PPLN is driven by a cross-field RF signal to generate acoustic wave with $K_1/K_2 = 3.37$.

Figure 3 shows the calculated three-wave conversion efficiency in this situation. $K_1/K_2 = 3.37$. The FW and SHs couple tightly in the crystal. With the increase of PPLN length and giving a suitable acoustic wave intensity, different SHG efficiency and different SH polarization states are obtained. In this case, the driving RF signal amplitude determines the generated acoustic wave's intensity. $K_1/K_2$ ratio thus could be tuned instantly to affect SHG and AO polarization rotation. Figure 4 shows the results. The PPLN length is 7.5 mm and the corresponding SHG efficiency is 100% when there is no acoustic field. The Z-polarized SH occupies whole light power at the beginning. However, when the acoustic field becomes stronger, QPM is affected, the Z-polarized SH drops quickly and the power mainly transfers back to Y-polarized SH. When the acoustic intensity keeps going higher, $K_1/K_2$ ratio becomes smaller. The FW takes all light power back. Stronger acoustic wave destroys the satisfied

#111311 - $15.00 USD Received 12 May 2009; revised 26 Jun 2009; accepted 27 Jun 2009; published 30 Jun 2009

QPM condition, SHG efficiency becomes lower and lower just like in Fig. 1(c). A compact tunable SHG is thus achieved.

Comparing the external acoustic wave driving with direct RF controlling, the latter one is more compact, simple and efficient, but the PPLN domain structure should be carefully designed to satisfy all phase matching conditions. We should emphasis here that RF electric field driving is different from electro-optic (EO) tuning. For EO tunable QPM [16, 17], a DC field is applied, while RF driving requires high frequency AC signals. RF driving is a cascaded physical effect, *i.e.*, piezoelectric effect to generate ultrasonic wave, elasto-optic effect to redistribute refractive index, and at last AO polarization rotation to affect QPM SHG. All these processes take place in a single versatile PPLN.

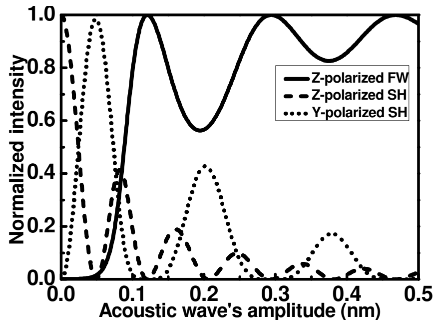


Fig. 4. Normalized light intensities as a function of the acoustic wave's amplitude in a 7.5 mm-long PPLN sample.

From Fig. 4, when the acoustic wave's amplitude A is 0.05 nm, Y-polarized SH reaches is maxima. The corresponding acoustic intensity is $I_a = \rho v^3 |HA|^2 / 2 = 2.65 W/mm^2$ [13], where $\rho = 4640$ kg/m$^3$, v = 6570 m/s are used for calculation. Assume a 0.5 x 0.5 mm$^2$ sample cross-section, the minimum required RF power is only 0.66 W, agreeing with the reported AO polarization rotation experiment in a PPLN [11]. If the input impedance is 50 Ω, the driving voltage is only 5.76 $V_{rms}$. In comparison with the 490 V/mm electric field for EO SHG tuning [16], the cross-field excited AO driving voltage is greatly reduced. As for the in-field excitation with an external transducer, the RF power should be at the same level but slightly higher because of the loss due to sound velocity mismatching. In addition, as our AO tuning is contributed by photon-phonon interaction, there should be a light frequency shift along with the polarization rotation. Some interesting applications may be expected.

In our simulation above, we only considered SH polarization rotation. Actually the acoustic frequency can be tuned to rotate FW's polarization as well. In addition to SHG, our AO tuning approach could be applied to other nonlinear optical processes, such as sum frequency generation, difference frequency generation etc. Even it may be applied to self-frequency doubling, where some interesting AO tuning or AO Q-switching can be realized.

## 3. Conclusion

In summary, we studied the photon-phonon interactions in PPLN, a kind of nonlinear photonic crystal. When an acoustic wave travels in a PPLN during frequency doubling, the phonons may scatter the photons to an orthogonal polarization state then further strongly affects SHG. A three-wave-coupling approach is proposed to study the optical power transferring among the FW and SHs. The dependency of SHG efficiency on acoustic wave's intensity is investigated. An AO tunable SHG in PPLN is thus analyzed. Two effective ways to induce the acoustic waves were proposed, either importing from an external transducer or self-generation in a PPLN acoustic superlattice. The external source solution is very flexible but the latter one is more efficient and convenient. The related physical mechanism, characteristics and possible applications were discussed.

#111311 - $15.00 USD Received 12 May 2009; revised 26 Jun 2009; accepted 27 Jun 2009; published 30 Jun 2009

**Acknowledgments**

This work was sponsored by NSFC program under contract No. 10874080, 863 program under contract No. 2006AA03Z417, the Nature Science Foundation of Jiangsu Province under contract No. BK2007712 and quantum manipulation program under contract No. 2006CB921805. Yan-qing Lu acknowledges the support from China MOE for new century and Changjiang scholars program.

#111311 - $15.00 USD Received 12 May 2009; revised 26 Jun 2009; accepted 27 Jun 2009; published 30 Jun 2009