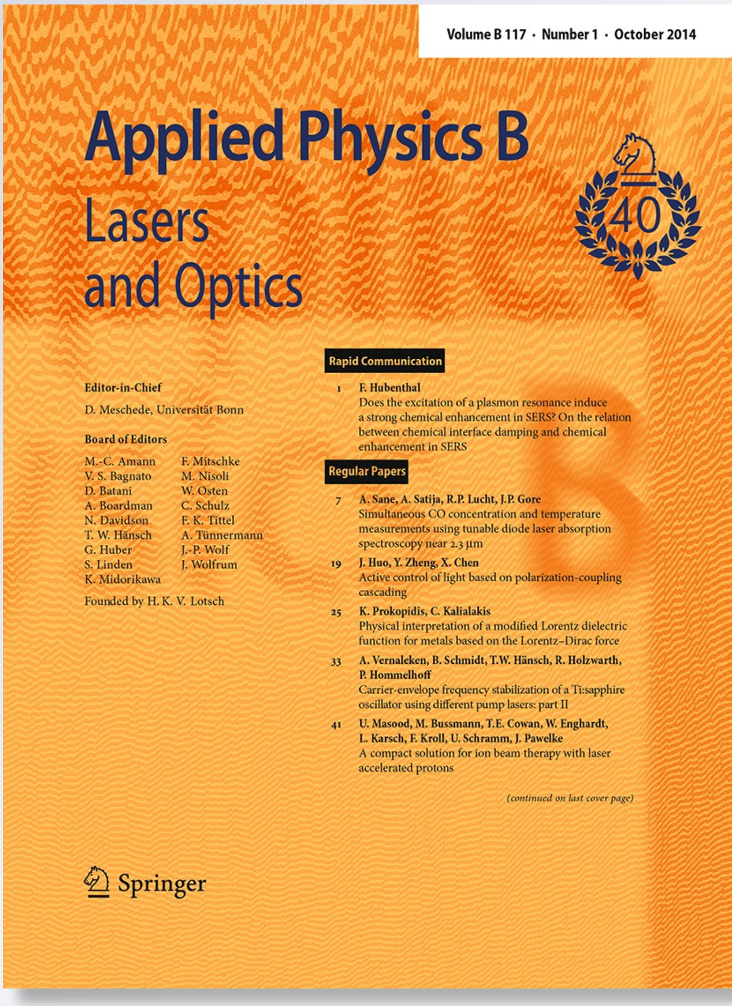
Active control of light based on polarization-coupling cascading

Juan Huo, Yuanlin Zheng & Xianfeng Chen

Applied Physics B
Lasers and Optics

ISSN 0946-2171
Volume 117
Number 1

Appl. Phys. B (2014) 117:19-23
DOI 10.1007/s00340-014-5793-2



Springer

Appl. Phys. B (2014) 117:19–23
DOI 10.1007/s00340-014-5793-2

Applied Physics B
Lasers and Optics

Active control of light based on polarization-coupling cascading

Juan Huo · Yuanlin Zheng · Xianfeng Chen

Received: 14 September 2013 / Accepted: 2 February 2014 / Published online: 15 February 2014

Abstract In this letter, we proposed a novel method for optical manipulation based on polarization-coupling cascading in MgO-doped periodically poled lithium niobate crystal. Polarization-coupling cascading, a series of energy exchanges between two orthogonally polarized beams close to phase matching condition, can also lead to phase shifts, in analogy with that in cascaded second-order nonlinearities. In addition, the parameters of light such as phase, amplitude, and group velocity can be modulated by changing the relative power ratio of the incident continuous wave beams. The phase control was demonstrated by Newton's rings experiment, which was in good agreement with the theoretical prediction.

1 Introduction

Optical modulators play important roles in optical signal processing as well as in high-speed optical communication systems, where the manipulation is focused on the modulation of optical phase, amplitude, intensity, and group velocity. Recently, various types of modulation techniques based on various effects and media, such as liquid crystals [1], acousto-optic programmable dispersive filter (AOPDF) [2], manganite thin film [3], electro-optic effect [4–6], electro-optic polymer [7], optical waveguide switch [8], magneto-optics [9], and photonic crystals [10], have been investigated to obtain active control of light in optical transmission systems.

J. Huo · Y. Zheng · X. Chen (✉)
Department of Physics, The State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China
e-mail: xfchen@sjtu.edu.cn

In this paper, we investigate a novel optical modulation scheme, which can control the phase, amplitude, and group velocity of the lightwave. This is, to our best knowledge, the first study to demonstrate optical control of light based on polarization-coupling cascading in MgO-doped periodically poled lithium niobate crystal (MgO:PPLN) where we exhibit the phase shift of weak light. Polarization-coupling (PC) cascading, proposed in our previous research, is modeled after the second-harmonic generation (SHG) cascading [11]. In these cascading processes, energy oscillates between the two orthogonally polarized coupling beams near the condition of phase matching or quasi-phase matching [12]. Based on this PC cascading effect, our theory predicts that the phase, amplitude, and group velocity of the coupling light are related to the power ratio of the incident beams rather than the absolute light intensity. This means that the active control of light through PC cascading may open a door for broader scopes of applications in weak-light optical operation. Thanks to the short electro-optical response time, the proposed method would have a promise in high-speed operation capability [13, 14].

2 Theoretical analysis

When a transverse external dc electric field is applied along a Z-cut MgO:PPLN, the optical axis of each domain is alternately aligned at the angles of $+\theta$ and $-\theta$ with respect to the plane of polarization of the input light [15]. The folded dielectric axes structure resembles the birefringent plate stack in a Solc-type filter. Consider two orthogonally polarized light, ordinary wave (OW) and extraordinary wave (EW), incident into these folded domains, the PC cascading between OW and EW can be generated under non-quasi-phase matching (NQPM) condition [12]. As similar to SHG

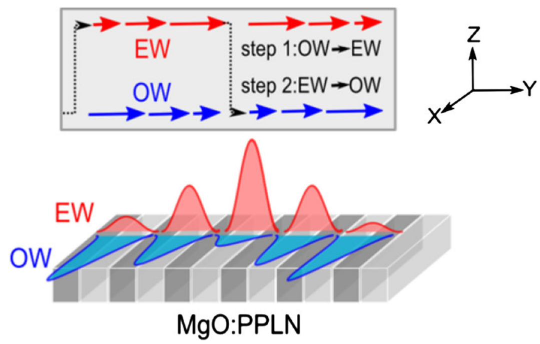


Fig. 1 Schematic illustration of PC cascaded processes

cascading [11], PC cascading could also be divided into two steps: Take OW incidence for example, the energy of OW flows to EW in the first coherent length, but does not cause complete depletion; then, energy flows back from EW into OW in the second coherence length. The regenerated OW is no longer in phase with the original, yielding a net OW phase shift, as schematically depicted in Fig. 1.

During the PC cascading in MgO:PPLN, the relative azimuth angle ($\pm\theta$) between the dielectric axes of two adjacent domains is given by $\theta \approx \gamma_{51}E_y/[(1/n_e^2) - (1/n_o^2)]$,where γ_{51} is the electro-optical coefficient (its value is referred to [15]), E_y is the intensity of the transverse dc electric field, and n_o and n_e are refractive indices for the ordinary and extraordinary waves, respectively. Calculations show that θ is a very small angle ($\ll 1°$); therefore, the periodic alternation of the azimuth can be considered as a small periodic perturbation. In this case, the coupled-mode equations of the ordinary and extraordinary waves are as follows[16]:

$$\begin{cases} dA_1/dz = -i\kappa A_2 e^{i\Delta\beta z} \\ dA_2/dz = -i\kappa^* A_1 e^{-i\Delta\beta z} \end{cases}, \quad (1)$$

with $\Delta\beta = k_1 - k_2 - G_m$, $G_m = 2\pi m/\Lambda$ and $\kappa = -\frac{\omega}{2c}\frac{n_o^2 n_e^2 \gamma_{51} E_y}{\sqrt{n_o n_e}}\frac{i(1-\cos m\pi)}{m\pi}$, $(m = 1, 3, 5, 7\ldots)$, where A_1 and A_2 are normalized complex amplitudes of OW and EW, respectively. $\Delta\beta$ is the wave-vector mismatch; k_1 and $k_2$are the corresponding wave vectors; G_m is the mth reciprocal vector corresponding to the poling periodicity Λ. The solution of Eq. (1) is given by the following:

$$\begin{cases} A_1(z) = e^{i(\Delta\beta/2)z}\left\{[\cos sz - i\frac{\Delta\beta}{2s}\sin sz]A_1(0) - i\frac{\kappa}{s}\sin sz A_2(0)\right\} \\ A_2(z) = e^{-i(\Delta\beta/2)z}\left\{-i\frac{\kappa^*}{s}\sin sz A_1(0) + [\cos sz + i\frac{\Delta\beta}{2s}\sin sz]A_2(0)\right\} \end{cases}, \quad (2)$$

with $s^2 = \kappa\kappa^* + (\Delta\beta/2)^2$. Then, the phases of the two orthogonally polarized beams can be derived as follows:

$$\Phi_1(z) = \frac{\Delta\beta z}{2} + \arctan \times \left[\frac{-\sqrt{I_1/I_2}(\Delta\beta/2s)\sin(sz) + \mathrm{Im}(\kappa/s)\sin(sz)\sin(\delta_0)}{\sqrt{I_1/I_2}\cos(sz) + \mathrm{Im}(\kappa/s)\sin(sz)\cos(\delta_0)}\right] \quad (3)$$

$$\Phi_2(z) = -\frac{\Delta\beta z}{2} + \arctan \times \left[\frac{\cos(sz)\sin(\delta_0) + (\Delta\beta/2s)\sin(sz)\cos(\delta_0)}{\cos(sz)\cos(\delta_0) - (\Delta\beta/2s)\sin(sz)\sin(\delta_0) - \sqrt{I_1/I_2}\mathrm{Im}(\kappa/s)\sin(sz)}\right] \quad (4)$$

where I_1 and I_2 are incident light intensities of OW and EW, respectively; δ_0 is the initial relative phase difference between the incident beams. Equations (3) and (4) show that the phase of each beam can be controlled by the relative power ratio rather than their absolute power intensity.

Assume without the loss of generality that a 45-mm-long MgO:PPLN with period of 20.9 μm is employed to investigate such PC cascading. The relative phases of two orthogonally polarized lightwaves are shown in Fig. 2, with Fig. 2a–c for OW and Fig. 2d–f for EW during various mismatching. The applied electric field is 0.25 V/μm.

It is interesting to see that at some critical conditions (points P1, P2, P3, P4, P5, P6 in Fig. 2), tiny change of the relative power ratio $\sqrt{I_2}/\sqrt{I_1 + I_2}$ causes large nonlinear phase change. This feature may be used to design a new kind of phase modulator. Figure 3 suggests that the transmission can be controlled between exactly zero and almost 100 % by simply modulating the relative power ratio, serving as an amplitude modulator.

The ability to control the group velocity of light is also of great interest for its promising applications in telecommunication systems [17]; therefore, we consider the PC cascading in communication band. The phase shifts as the function of the wavelengths in communication band are shown in Fig. 4. In the simulation, we set δ_0= 0, E = 0.17V/μm and $B_2 = \sqrt{I_2/(I_1 + I_2)}$. Besides, a, c show the results of OW, and b, d present the results of EW. Figure 4 shows that the phase shifts (Fig. 4a, b) and their derivatives (Fig. 4c, d) can be tuned by the relative power ratio of B_2, which is considered to be very feasible and attractive. The derivative of the phase shift represents the group velocity, which indicates that slow light with its time delay controllable by relative power ratio is possible.

3 Experimental results

To investigate the relationship between the wave phase and the incident power ratio, a scheme of Mach–Zehnder interference is used, and the schematic of the experimental setup is shown in Fig. 5. The wavelength of the He–Ne

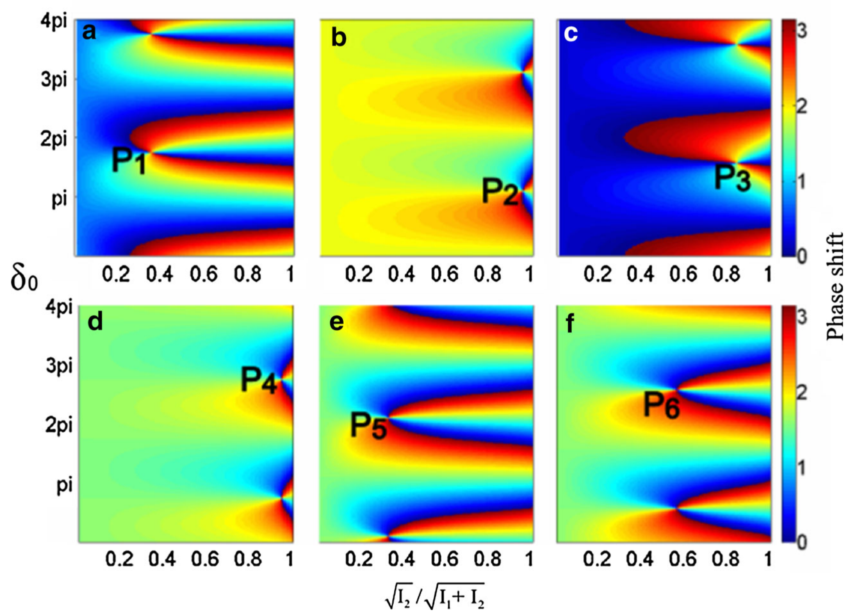


Fig. 2 Relative phase shifts as a function of the initial relative phase δ_0 and power ratio. $\Delta\beta = 16\ \pi/m$, in (**a**, **d**); $\Delta\beta = 55\ \pi/m$, in (**b**, **e**) and $\Delta\beta = 90\ \pi/m$, in (**c**, **f**)

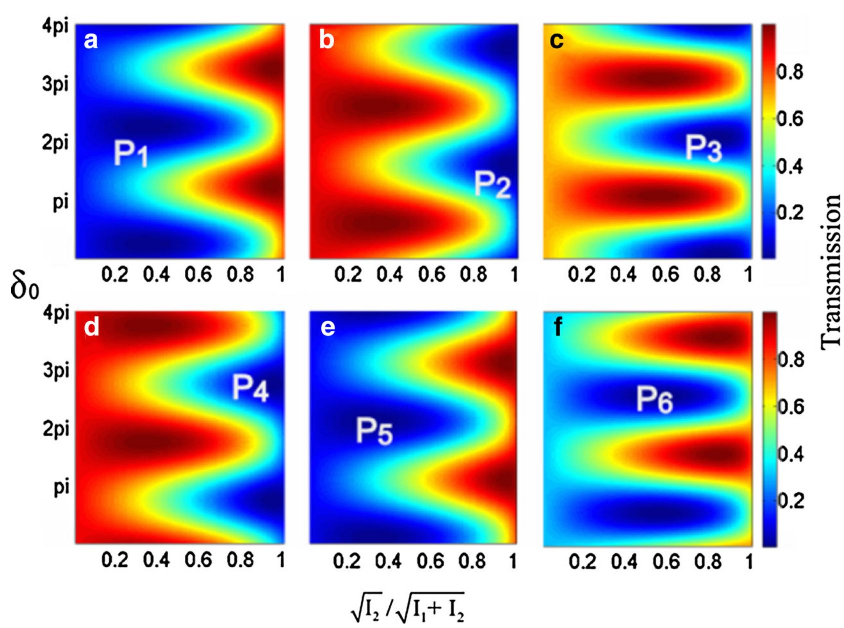


Fig. 3 Transmission as a function of the initial relative phase and power ratio

laser source is close to the third-order quasi-phase-matching condition with MgO:PPLN poling period of 20.9 μm. The laser power is about 8 mW, and the transverse electric field is fixed at 0.22 V/μm. The inserted figure shows the working principle of the polarizer. Here, β is the angle between the directions of polarizer and OW, and sin β is used to calculate the relative power ratio ($\sin\beta = \sqrt{I_2}/\sqrt{I_1+I_2}$.) Therefore, the relative power ratio can be modulated by rotating the polarizer. Then, the light is separated by a beam splitter (BS) with one beam passing through MgO:PPLN in one arm and the other in the space with a polarization beam splitter (PBS) in the pathway. The two beams experience interference after the second BS and form Newton's rings in the far field. Here, the PBS is used to align the polarization of the free-space arm of the interferometer along horizontal or vertical direction, which means we can get the interference patterns of OW and EW separately by flipping the PBS.

First, we used a MgO:PPLN sample with poling period of 20.9 μm in the experiment to observe the phase modulation by changing the incident power ratio. The results are shown in Fig 6a–f, with Fig. 6a–c for EW and Fig. 6d–f for OW. By rotating the polarizer, we found that the interference fringes "light–dark" changed at different

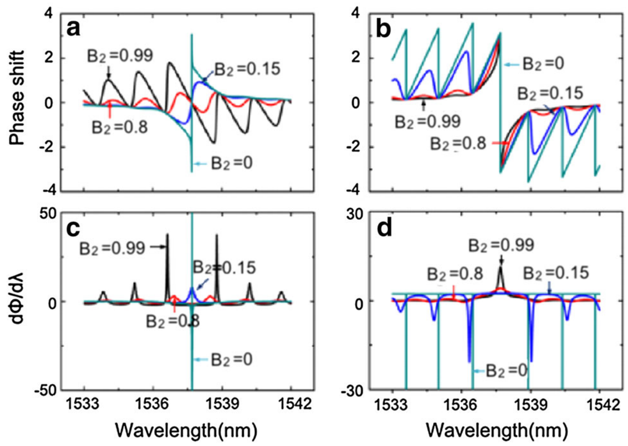


Fig. 4 Variation of the phase shifts against wavelengths at different power ratio

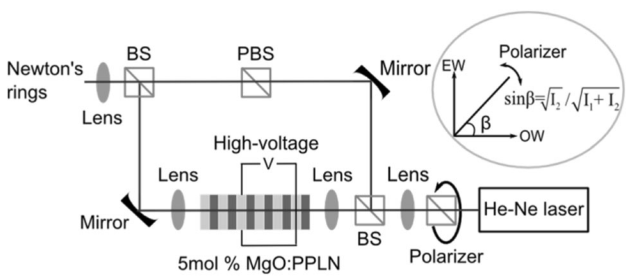


Fig. 5 Experimental setup for demonstrating the phase shifts yielded in PC cascading. A 5 mol% MgO:PPLN crystal with the length of 45 mm. High voltage is used to supply transverse electric fields

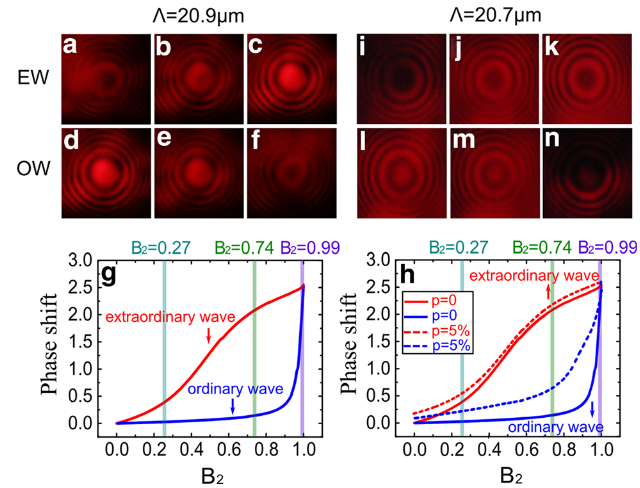


Fig. 6 The comparison of experimental results and theoretical simulation for demonstrating the enhanced phase shifts yielded in PC cascading; (**a**–**f**), the center experiences "*dark-light*" changes with the sample periodicity of 20.9 μm. $B_2 = 0.27$, in (**a**, **d**); $B_2 = 0.74$, in (**b**, **e**); and $B_2 = 0.99$ in (**c**, **f**). (**g**), the simulated curve (**h**), error analysis about B_2 (**i**–**n**) the contrast experiment results with the sample periodicity of 20.7 μm. $B_2 = 0.27$, in (**i**, **l**); $B_2 = 0.74$, in (**j**, **m**); and $B_2 = 0.99$, in (**k**, **n**)

relative power ratios. For EW, varying B_2 from 0.27 to 0.74, the interference fringes almost experienced a "light–dark" change (see Fig. 6a, b), which mean the phase shift was nearly close to π. Then, varying B_2 from 0.74 to 0.99, the Newton's rings had little variation (see Fig. 6b, c). While for OW, the fringes were nearly invariable before B_2 reached 0.74, (see Fig. 6d, e); then, the interference fringes experienced a "light–dark" change (see Fig. 6e, f) when B_2 was beyond 0.74. Figure 6g shows the simulated results of the EW (red curve) and OW (blue curve). For EW, the curve is steep during $B_2 = 0.27$ to 0.74, and the phase difference is close to π; then, the curve increases relatively gently; these processes are reversed for OW. Therefore, we can consider that the experimental data well fit the simulated curves with acceptable discrepancy, taking into account some unavoidable errors; for instance, the refractive indices of the MgO:PPLN sample we used are not consistent with the simulated values.

Considering the practical operation, the value of the coefficient B_2 may have error. In order to investigate the effect of the operation error, we use p as the parameter to indicate the deviation of B_2. The simulation results with $p = 5\ \%$ are shown in Fig. 6 h in dash curves (red one for EW and blue one for OW). It can be seem that B_2 has high tolerance. Comparing with the phase measurement, B_2 has enough high accuracy, which means little error of B_2 has almost no effect on this phase modulation.

Then, we presented a contrast experiment. We chose a MgO:PPLN sample with poling period of 20.7 μm and repeated the experiment under the same condition. The results were shown in Fig 6i–n, with Fig. 6i–k for EW and Fig. 6l–n for OW. The Newton's rings had no "light–dark" change. That is, because the phase mismatch is very large, which would cause the PC cascading to be too inefficient or prevent it from happening. By this token, the phase shift has nothing to do with the particular material but governed by PC cascading in MgO:PPLN.

It should be noted that in this experiment, the measurement of phase shift by observing the interference pattern was only a rough estimation, and we just need to tell a π phase shift, and the M–Z interference was quite stable. For practical consideration, some method [18, 19] can be used to realize high stabilization, which means the precision of the modulation could be improved. Beyond that, in our experiment, bulk MgO:PPLN was employed to demonstrate the optical control by polarization-coupling cascading. For practical consideration, the PPLN waveguide [20] can be used where the gap between the electrodes can be scaled to

10 μm, so that only several Volts is enough to generate desirable large phase shifts.

4 Conclusion

A method was demonstrated to achieve optical operation with weak light through cascaded polarization-coupling processes. The phase, amplitude, and group velocity were determined by the relative power ratio of the incident beams, and phase modulation based on PC cascading was demonstrated in MgO:PPLN experimentally. With a different physical understanding in polarization coupling as well as an advanced technological application in optical communications, these results are of interest for researches, including nonlinear optics, ultrafast optics, and all-optical communications.

Acknowledgments This research was supported by the National Natural Science Foundation of China (Grant No. 61125503, 61078009), the National Basic Research Program "973" of China (Grant No. 2011CB808101), the Foundation for Development of Science and Technology of Shanghai (Grant No. 11XD1402600).

References

1. L. De Sio, L. Ricciardi, S. Serak, M. La Deda, N. Tabiryan, C. Umeton, J. Mater. Chem. **22**, 6669–6673 (2012)
2. F. Verluise, V. Laude, Z. Cheng, C. Spielmann, P. Tournois, Opt. Lett. **25**, 575–577 (2000)
3. N. Takubo, Y. Ogimoto, M. Nakamura, H. Tamaru, M. Izumi, K. Miyano, Phys. Rev. Lett. **95**, 17404 (2005)
4. T. Kawanishi, T. Sakamoto, M. Izutsu, IEEE J. **13**, 79–91 (2007)
5. J. Noda, N. Uchida, S. Saito, T. Saku, M. Minakata, Appl. Phys. Lett. **27**, 19–21 (1975)
6. K. Liu, W. Lu, Y. Chen, X. Chen: Appl. Phys. Lett. **97**, 071104-071104-071103 (2010)
7. M. Hikita, Y. Shuto, M. Amano, R. Yoshimura, S. Tomaru, H. Kozawaguchi, Appl. Phys. Lett. **63**, 1161–1163 (1993)
8. S. Korotky, G. Eisenstein, R. Tucker, J. Veselka, G. Raybon, Appl. Phys. Lett. **50**, 1631–1633 (1987)
9. D. Budker, D. Kimball, S. Rochester, V. Yashchuk, Phys. Rev. Lett. **83**, 1767–1770 (1999)
10. Y.A. Vlasov, M. O'Boyle, H.F. Hamann, S.J. McNab, Nature **438**, 65–69 (2005)
11. G. Stegeman, D. Hagan, L. Torner, Opt. Quantum Electron. **28**, 1691–1740 (1996)
12. J. Huo, X. Chen, Opt. Express **20**, 13419–13424 (2012)
13. J. Huo, K. Liu, X. Chen, Opt. Express **18**, 15603–15608 (2010)
14. Y. Chen, Y. Huang, Opt. Lett. **28**, 1460–1462 (2003)
15. Y.Q. Lu, Z.L. Wan, Q. Wang, Y.X. Xi, N.B. Ming, Appl. Phys. Lett. **77**, 3719–3721 (2000)
16. A. Yariv, P. Yeh, *Optical Waves in Crystals: Propagation and Control of Laser Radiation* (Wiley, New York, 1984)
17. Y. Okawachi, M.S. Bigelow, J.E. Sharping, Z. Zhu, A. Schweinsberg, D.J. Gauthier, R.W. Boyd, A.L. Gaeta, Phys. Rev. Lett. **94**, 153902 (2005)
18. J. Frejlich, L. Cescato, G.F. Mendes, Appl. Opt. **27**, 1967–1976 (1988)
19. L. De Sio, A. Veltri, A. Tedesco, R. Caputo, C. Umeton, A.V. Sukhov, Appl. Opt. **47**, 1363–1367 (2008)
20. Y. Lee, N. Yu, C.S. Kee, D.K. Ko, Y.C. Noh, B.A. Yu, W. Shin, T.J. Eom, K. Oh, J. Lee, Elect. Lett. **44**, 30–32 (2008)