Intensity modulation of light by light in a periodically poled MgO-doped lithium niobate crystal

Ping Hu (胡 萍)[1,2], Guangzhen Li (李广珍)[1], Juan Huo (霍 娟)[3], Yuanlin Zheng (郑远林)[1,2], and Xianfeng Chen (陈险峰)[1,2,*]

[1]*State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*Key Laboratory for Laser Plasma (Ministry of Education), IFSA Collaborative Innovation Center, Shanghai Jiao Tong University, Shanghai 200240, China*
[3]*Quantum Engineering Research Center, Beijing Institute of Aerospace Control Devices, CASC, Beijing 100094, China*
**Corresponding author: xfchen@sjtu.edu.cn*

Received September 1, 2015; accepted October 27, 2015; posted online December 7, 2015

In this Letter, we investigate a method for controlling the intensity of a light by another light in a periodically poled MgO-doped lithium niobate (PPMgLN) crystal with a transverse applied external electric field. The power of the emergent light can be modulated by the power ratio of the incident ordinary and extraordinary beams. The light intensity control is experimentally demonstrated by the Mach–Zehnder interference configuration, and the results are in good agreement with the theoretical predictions.

OCIS codes: 190.4223, 230.6120.
doi: 10.3788/COL201513.121902.

With the development of high-speed optical communication technology, optical modulators, as important parts of an optical communication system, have begun to face the new challenges in recent years[1]. These challenges include how to meet the increasing requirements of communication technology, and how to expand the field of optical modulation, and have attracted advanced research attention. Many types of optical modulation techniques have been tried to realize the control of light via various structures, materials, and effects, such as double-layer graphene[2], photoresponsive-liquid crystals[3], silicon photonics[4,5], electro-optic polymers[6], metal-oxide semiconductors[7], Ti:LiNbO$_3$ crystals[8], GaAs/GaAlAs quantum wells[9–11], dye-sensitized nanocrystalline TiO$_2$ solar cells[12], Mach–Zehnder interference[13,14], and electro-optic effects[15–17]. Generally speaking, optical modulation focuses on the manipulation of light's phase, intensity, amplitude, and group velocity, among which the intensity modulation is the most mature field. Optical intensity modulation is mainly based on optical effects, such as the electro-optic effect, the magneto-optical effect, and the acousto-optic effect. Recently, two widely used methods of optical intensity-modulation technology are the electro-absorption modulator[18], and electro-optic modulation based on nonlinear optical crystals.

In our previous study, we demonstrated that the intensity modulation could be realized by rotating the linear polarization state through changing the external electric field[19]. In this Letter, we introduced a new method of optical intensity modulation by applying another control light based on the polarization-coupling (PC) cascading effect in an MgO-doped, periodically poled lithium niobate crystal (PPMgLN)[20–22]. In PC cascading, on the condition of the wavelengths disagreeing with the quasi-phase matching, energy oscillates between the two orthogonally polarized coupling beams. If we introduce a beam at one polarization, it is expected that it will the affect original energy oscillation and further realize the modulation of the light of the other polarization. We found that this energy transfer depends on the intensity of two input beams, which means the light intensity with a fixed linear polarization can be modulated by another light. It is interesting because this kind of light modulation can work in the weak-light region.

In the PPMgLN, the optical axis of each domain is alternately aligned at the angles of $+\theta$ and $-\theta$ with respect to the plane of polarization by the transverse external dc electric field. The angle θ is called the azimuth angle and is proportional to the electric field intensity. During the PC cascading, an ordinary wave (OW) and an extraordinary wave (EW) are two orthogonally polarized lights. The relative azimuth angle 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 n_o and n_e are the refractive indices of the OW and EW, E_y is the transverse dc electric field intensity, and γ_{51} is the electro-optic coefficient. It is estimated that θ is very small, so that the periodic alternation of the azimuth can be considered as a periodic perturbation. So, the coupled-wave equations of OW and EW are given by the following[23]:

$$dA_1/dz = -i\kappa A_2 \exp(i\Delta\beta z), \tag{1}$$

$$dA_2/dz = -i\kappa^* A_1 \exp(i\Delta\beta z), \tag{2}$$

with $\Delta\beta = \beta_1 - \beta_2 - G_m$, $G_m = 2\pi m/\Lambda$, and

$$\kappa = -\frac{\omega}{2c}\frac{n_o^2 n_e^2 \gamma_{51} E_y}{\sqrt{n_o n_e}}\frac{i(1-\cos m\pi)}{m\pi}, \quad (m = 1, 3, 5\ldots), \quad (3)$$

where A_1 and A_2 are the normalized amplitudes of the OW and EW, β_1 and β_2 are the corresponding wave vectors, $\Delta\beta$ is the wave-vector mismatch, Λ is the period of the PPMgLN, and G_m is the mth reciprocal vector corresponding to Λ. The solutions of the coupled-wave Eqs. (1) and (2) are given by:

$$A_1(z) = e^{i(\Delta\beta/2)z}\left\{\left[\cos(sz) - i\frac{\Delta\beta}{2s}\sin(sz)\right]A_1(0) - i\frac{\kappa}{s} \times \sin(sz)A_2(0)e^{i\delta_0}\right\}, \quad (4)$$

$$A_2(z) = e^{-i(\Delta\beta/2)z}\left\{-i\frac{\kappa^*}{s}\sin(sz)A_1(0) + \left[\cos(sz) + i\frac{\Delta\beta}{2s} \times \sin(sz)\right]A_2(0)e^{i\delta_0}\right\}. \quad (5)$$

With $s^2 = \kappa\kappa^* + (\Delta\beta/2)^2$, δ_0 is the initial relative phase difference between the OW and EW. Considering the intensity of the input beams (A_1 (0) (OW) and A_2 (EW)) as I_1 and I_2, respectively, Eqs. (4) and (5) can be written as

$$A_1(z) = e^{i(\Delta\beta/2)z}\left\{\left[\cos(sz) - i\frac{\Delta\beta}{2s}\sin(sz)\right]\sqrt{1-B_2^2} - i\frac{\kappa}{s}\sin(sz)B_2 e^{i\delta_0}\right\}, \quad (6)$$

$$A_2(z) = e^{-i(\Delta\beta/2)z}\left\{-i\frac{\kappa^*}{s}\sin(sz)\sqrt{1-B_2^2} + \left[\cos(sz) + i\frac{\Delta\beta}{2s}\sin(sz)\right]B_2 e^{i\delta_0}\right\}, \quad (7)$$

where $B_2 = \sqrt{I_2/(I_1+I_2)}$, is the input beams' power ratio. We can see that the both the OW and EW beams' amplitudes are determined by the input beams' power ratio. When the intensity of one beam is given, its output amplitude will be controlled only by the intensity of the other beam.

We consider a 40 mm-long PPMgLN without loss of generality. The wavelength of the input light is 632.8 nm, and the period of PPMgLN crystal is 21.1 μm, which almost meets the third-order quasi-phase-matching condition. The thickness of the PPMgLN is 0.5 mm and the width is 1 cm. Here the applied voltage is fixed at 3.3 kV, so the external electric field E_y is fixed at 0.33 V/μm. The transmission of the OW and EW as a function of the initial relative phase and power ratio is shown in Fig. 1, with Figs. 1(a)–1(c) showing the EW and Figs. 1(d)–1(f) showing the OW with different mismatch conditions. The wave-vector mismatches are 100π for Figs. 1(a) and 1(d), 40π for Figs. 1(b) and 1(e), and 26π for Figs. 1(c) and 1(f). We can see that the transmission could be modulated almost from 0% to 100% by the initial relative phase and power ratio.

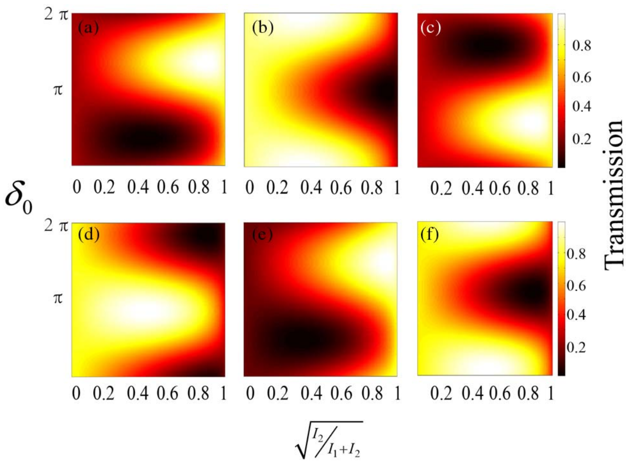

Fig. 1. Transmission as a function of the initial relative phase δ_0 and power ratio B_2.

The schematic of the experimental setup is shown in Fig. 2. The transmission as a function of the initial relative phase and power ratio is investigated by a scheme of Mach–Zehnder interference. The wavelength of the He–Ne laser used is 632.8 nm with a power of 6 mW. The period of the PPMgLN is 21.1 μm, and the external electric field E_y is 0.33 V/μm. At the temperature of 21.1°C, the vector mismatch is around 45π.

The light from the He–Ne laser was separated by a polarizing beam splitter (PBS) and became two orthogonally polarized beams, the OW and the EW. The intensity of one beam was changed by an attenuator. Therefore, the power ratio could be changed by rotating the attenuator. We utilized a PBS to choose the output light polarization and measured the emergent light power with a power meter. The high voltage is used to supply the transverse electric field. It is worth mentioning that the fixed transverse electric field was used to compel the relative azimuth angle rather than modulating the light. When we changed the

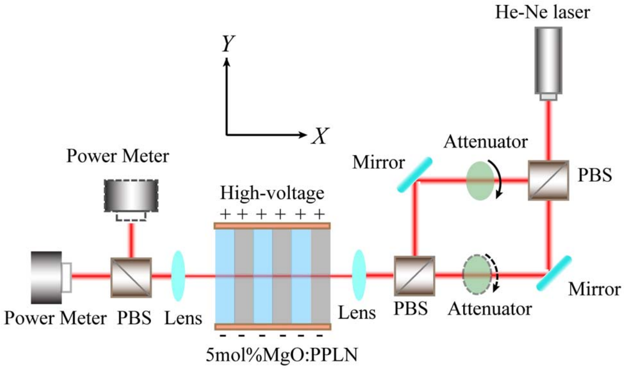

Fig. 2. Experimental setup for demonstrating the light intensity modulation. The period of PPMgLN is 21.1 μm with the length of 40 mm. A uniform electric field is applied along the y-axis of the PPMgLN.

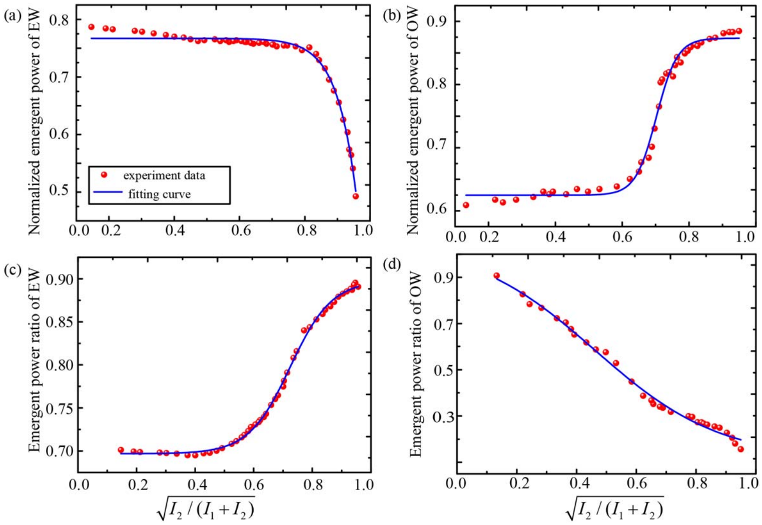

Fig. 3. Normalized emergent optical power of (a) the EW, and (b) the OW as a function of the incident optical power ratio. (c) and (d) are the emergent power ratios of the EW and OW as a function of the incident optical power ratio, respectively. I_1 is the incident optical intensity of the OW, and I_2 is the incident optical intensity of the EW.

incident extraordinary light power and fixed the incident ordinary light power, the incident light power ratio could be changed. Based on above, the polarization state of the light in the PPMgLN will be rotated by polarization coupling and the emergent ordinary light intensity would be changed. Similarly, we also changed the incident ordinary light power and fixed the incident extraordinary light power.

The experimental measurements of emergent light power in different conditions are shown in Fig. 3. Figure 3(a) shows that the normalized emergent extraordinary light power is modulated by changing the input light power ratio via modulating the incident ordinary light power, and Fig. 3(b) shows the normalized emergent ordinary light power is modulated by changing the input light power ratio via modulating the incident extraordinary light power. Figures 3(c) and 3(d) are the relationship between the emergent light power ratio of the EW and OW and the incident light power ratio, respectively. Clearly, from Fig. 3, we can see that when we change the power ratio of incident lights, the normalized emergent light power is modulated.

Then, we switched on and off one of the incident lights in order to clarify that the light intensity modulation was only because of the incident light power ratio instead of the birefringent crystal itself. From Fig. 4(a), we can see that when the incident extraordinary light power was zero, no matter how much the incident ordinary light power changed, the variation of the emergent extraordinary light was very small. From Fig. 4(b), similarly, we can see that when we switch off the incident ordinary light, changing the incident extraordinary light power has little influence on the emergent ordinary light. Thus, we can conclude that the variation of the emergent light intensity was only controlled by the incident light power ratio. The simulation results of the emergent light intensity as a function of the incident light power ratio are shown in Figs. 5(a) and 5(b). The emergent light power ratio of the EW and the OW changed by the incident light power ratio through the simulation are shown in

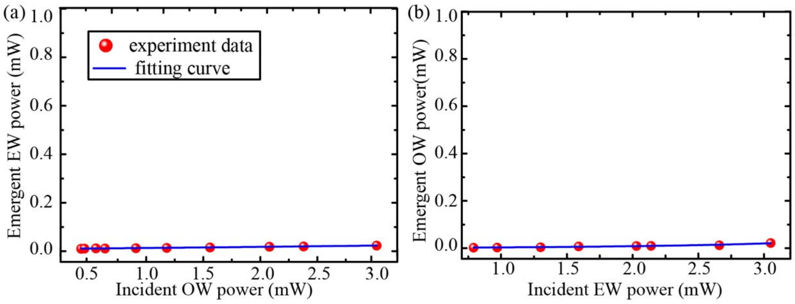

Fig. 4. Results of comparing the experiments. (a) The variation of the emergent EW by changing the incident OW power when the incident light is OW only. (b) The variation of the emergent OW by changing the incident EW power when the incident light is EW only.

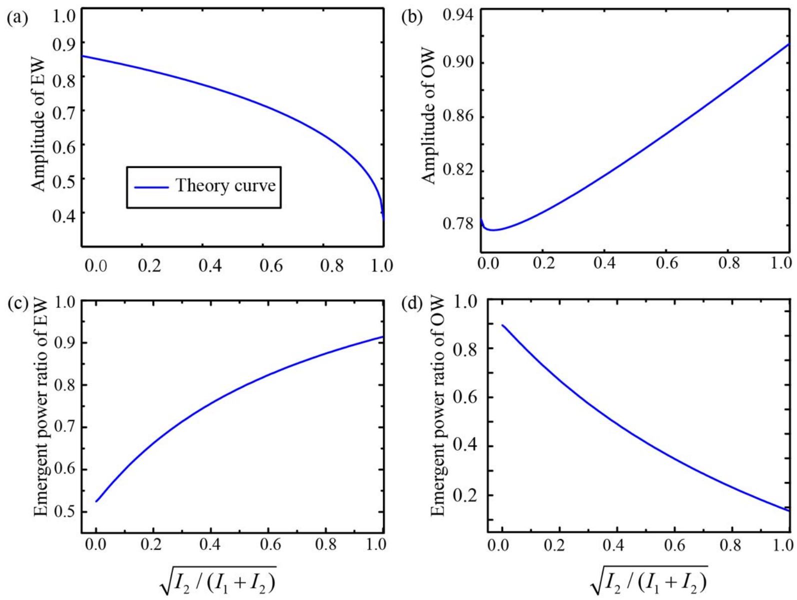

Fig. 5. Theoretical simulations for the relationship between transmission and incident light power ratio. (a) The variation of emergent EW power when varying the incident light power ratio by changing the incident OW power. (b) The variation of emergent OW power when varying the incident light power ratio by changing the incident EW power. (c) The emergent power ratio of EW changed by the incident power ratio. (d) The emergent power ratio of OW changed by the incident power ratio.

Figs. 5(c) and 5(d). By comparing Figs. 3(a)–3(b) and Figs. 5(a)–5(b), we find that the theoretical simulation and the experimental results of the emergent light power and incident light power ratio are almost the same. Even so, there is a discrepancy between the numerical value of the theoretical simulation and experimental results. First, an initial rotation angle exists in the PPMgLN structure, which may be caused by the strain-optical effect because of the process of the photovoltaic effect or polarization. Second, in the experiment, we used a pair of parallel copper plates to produce the external electric field, and the real transverse electric field intensity may be different from the theoretical numerical value.

We have clarified that the polarization coupling effect in a PPMgLN can lead to the intensity modulation of light by the incident light power ratio. Because the mechanism behind this is the energy transfer between the OW and EW, it can work in the weak-light region and be applied in all-optical devices. In order to verify the sensibility of the wavelength for the intensity modulation, we also calculated the wavelength bandwidth, which is 0.189 nm.

In conclusion, a method is demonstrated for light intensity modulation by light through PC cascading processes. We experimentally demonstrate that the relative power ratio of the incident beams can modulate intensity of light in a PPMgLN. These results have potential applications in future all-optical information processing and optical communications.

This work was supported in part by the National Basic Research Program of China (No. 2011CB808101), the National Natural Science Foundation of China (Nos. 61125503 and 61235009), and the Foundation for the Development of Science and Technology of Shanghai (No. 13JC1408300).

References

1. H. Jensen, J. Schellman, and T. Troxell, Appl. Spectrosc. **32**, 192 (1978).
2. M. Liu, X. Yin, and X. Zhang, Nano Lett. **12**, 1482 (2012).
3. V. K. Hsiao, Y. B. Zheng, B. K. Juluri, and T. J. Huang, Adv. Mater. **20**, 3528 (2008).
4. A. Liu, L. Liao, D. Rubin, H. Nguyen, B. Ciftcioglu, Y. Chetrit, N. Izhaky, and M. Paniccia, Opt. Express **15**, 660 (2007).
5. Z. Yong, W. Wanjun, S. Haifeng, Y. Jianyi, W. Minghua, and J. Xiaoqing, J. Semicond. **33**, 014009 (2012).
6. M. Lee, H. E. Katz, C. Erben, D. M. Gill, P. Gopalan, J. D. Heber, and D. J. McGee, Science **298**, 1401 (2002).
7. A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, Nature **427**, 615 (2004).
8. K. Noguchi, O. Mitomi, and H. Miyazawa, J. Lightwave Technol. **16**, 615 (1998).
9. T. Wood, C. Burrus, D. Miller, D. Chemla, T. Damen, A. Gossard, and W. Wiegmann, Appl. Phys. Lett. **44**, 16 (1984).
10. J. Zucker, T. Hendrickson, and C. Burrus, Appl. Phys. Lett. **52**, 945 (1988).
11. S. Noda, T. Uemura, T. Yamashita, and A. Sasaki, J. Appl. Phys. **68**, 6529 (1990).
12. J. Van de Lagemaat, N.-G. Park, and A. Frank, J. Phys. Chem. B **104**, 2044 (2000).
13. M. Kolesik, M. Matus, and J. Moloney, Photon. Technol. Lett. **15**, 78 (2003).
14. N. Courjal, A. Martinez, and H. Porte, in *Proceeding Integrated Photonic Research*, IFA4 (2002).
15. S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
16. Q. Xu, B. Schmidt, S. Pradhan, and M. Lipson, Nature **435**, 325 (2005).
17. X. Gu, X. Chen, Y. Chen, Y. Xia, and Y. Chen, Chin. Opt. Lett. **1**, 671 (2003).

18. J. Liu, M. Beals, A. Pomerene, S. Bernardis, R. Sun, J. Cheng, L. C. Kimerling, and J. Michel, Nat. Photon. **2**, 433 (2008).
19. K. Liu, J. Shi, and X. Chen, Appl. Phys. Lett. **94**, 101106 (2009).
20. J. Huo, Y. Zheng, and X. Chen, Appl. Phys. B **117**, 19 (2014).
21. J. Huo and X. Chen, Opt. Express **20**, 13419 (2012).
22. K. Liu, W. Lu, Y. Chen, and X. Chen, Appl. Phys. Lett. **97**, 071104 (2010).
23. A. Yariv and P. YEH, *Optical Waves in Crystals: Propagation and Control of Laser Radiation* (Wiley, 1984).