All-optical switch with two periodically modulated nonlinear waveguides

Qiongtao Xie,[1,2,*] Xiaobing Luo,[1,3] and Biao Wu[1]
[1]Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
[2]Department of Physics, Hunan Normal University, Changsha 410081, China
[3]Department of Physics, Jinggangshan University, Ji'an 343009, China
*Corresponding author: xieqiongtao@yahoo.cn

Received November 3, 2009; revised December 21, 2009; accepted December 22, 2009; posted December 23, 2009 (Doc. ID 119251); published January 25, 2010

We propose a type of all-optical switch which consists of two periodically modulated nonlinear optical waveguides placed in parallel. Compared to the all-optical switch based on the traditional nonlinear directional coupler without periodic modulation, this all-optical switch has much lower switching threshold power and sharper switching width. © 2010 Optical Society of America

OCIS codes: 230.4320, 190.5530.

The nonlinear directional coupler (NLDC), a device consisting of two parallel straight nonlinear waveguides, has received much attention for its potential applications as a type of all-optical switch [1–4]. Its switching operation is based on the intensity-dependent power transfer between its two coupled waveguides. For a cw laser beam, at input power below threshold (or critical) power P_c, most of the light emerges from the neighboring waveguide over a coupling length; at high power above P_c, most of the light remains in the launching waveguide over the same length. Therefore, the change in the input power can cause light propagation to be switched from one waveguide to the other.

So far, the application of the NLDC as an all-optical switch is limited by its high threshold on switching power. One approach to lower the high switching power is to place the two waveguides with a certain special shape, such that the variable coupling coefficient NLDCs are obtained [5,6]. This method has one drawback. The length of the all-optical switch increases exponentially with the separation. Another approach, which has been tried experimentally [7–9], is to use a pulsed beam to lower the overall demand on the laser power as a cw beam would. But experimental results also showed some drawbacks. For example, an optical pulse usually breaks up at the output ports and the switching is not as sharp as for the case of cw beams. One can of course lower the switching power by using materials with larger Kerr nonlinearity. However, it is not easy to find this kind of material. At the same time, it is found that larger Kerr nonlinearity usually leads to a slower response time [10,11].

In this Letter, we propose a different type of all-optical switch with much lower threshold on switching power. As illustrated in Fig. 1, this device is made of two nonlinear waveguides placed in parallel with periodically modulated refractive index along the propagation direction. Such a modulated coupler, functioning as an all-optical switch at an appropriate length, has much lower critical power than the traditional NLDC, since the periodical modulation of the nonlinear waveguides can effectively increase their nonlinearity. In addition, this device has sharper switching width. This modulated switch permits in principle arbitrarily low switching threshold power; its only foreseeable drawback is longer coupling length. This work is motivated by the phenomenon of nonlinear coherent destruction of tunneling (NCDT) [12,13] and its recent experimental demonstration with two coupled periodically modulated nonlinear waveguides [14].

We first give a brief introduction to the traditional NLDC. This device is made of two straight nonlinear parallel waveguides which are adjacent to each other so that they are coupled optically. The operation of the NLDC as an all-optical switch was studied in detail by Jensen [1]. He showed that if all the light is initially shined into one waveguide with the input power P_0, then the amount of the light remaining in the launching waveguide is given by $P_1(L)=P_0[1+\mathrm{cn}(\pi L/L_c|m)]/2$, where L is the length of the coupler and $\mathrm{cn}(\pi L/L_c|m)$ is the Jacobi elliptic function [16]. The parameter $L_c=\pi/v$ is called the coupling length representing the shortest length for the light switching from one waveguide to the other without nonlinearity. Here, v is the coupling coefficient and the other parameter m is defined as $m=(P_0/P_c)^2$ with P_c being the threshold (or critical) power and given by $P_c=\lambda\sigma_{\mathrm{eff}}/L_c n_2$. Here, λ is the free-space wavelength of the light, σ_{eff} is the effective cross section of the waveguide, and n_2 is the Kerr nonlinear coefficient (or nonlinear refractive index). For NLDC to function as an all-optical device, the length L is usu-

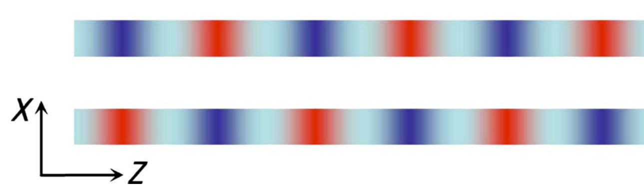

Fig. 1. (Color online) Schematic drawing of a periodically modulated all-optical switch. The two lines represent two waveguides, whose refractive indexes are out-of-phase modulated periodically along the z direction [14]. Periodic modulation can also be achieved by periodically curving both waveguides [15].

ally the coupling length L_c. The analysis of the elliptic function cn shows that the NLDC can function as a switch: most of light stays in the launching waveguide if the input power P_0 is above the critical power P_c and switch to the neighboring waveguide if $P_0 < P_c$.

Our proposed all-optical switch is a modification of the NLDC by modulating the two waveguides periodically. In the following discussion, we assume that the light is propagating along the z direction and strongly localized in the y direction. In this case, the light propagation in this nonlinear directional waveguides is described by an effective two-dimensional wave equation [12,14],

$$i\frac{\lambda}{2\pi}\frac{\partial\psi}{\partial z} = -\frac{\lambda^2}{8\pi^2 n_s}\frac{\partial^2\psi}{\partial x^2} + [V_0(x) + V_1(x,z) - n_2|\psi|^2]\psi, \quad (1)$$

where n_s is the substrate refractive index, $V_0(x)$ is the effective refractive index profile of the waveguides along the x direction with a symmetric double-well structure, and $V_1(x,z)$ describes the periodic modulation of the waveguides along the z direction. This periodic modulation can be realized by an out-of-phase harmonic modulation of the refractive index [14,17,18] or the periodic curvature in the coupled waveguides along the propagation direction [15,19–21]. In the current experiments [14,15,17–21], $V_1(x,z)$ can be written in the form $V_1(x,z)=V_1'(x)f(z)$ with $V_1'(-x)=-V_1'(x)$.

Owing to the symmetric double-well structure of $V_0(x)$, we apply the two-mode approximation [12] and write $\psi(x,z)=[c_1(z)u_1(x)+c_2(z)u_2(x)]\exp(-2i\pi E_0 z/\lambda)$, where u_1 and u_2 are localized waves in the two waveguides and the two coefficients are normalized to one, $|c_1|^2+|c_2|^2=1$. E_0 is defined as $E_0 = \int u_{1,2}^* H_0 u_{1,2} dx$ with $H_0=-\lambda^2/(8\pi^2 n_s)\partial^2/\partial x^2+V_0(x)$. It is reasonable to assume that the localized wave is a Gaussian, $u_{1,2}(x)=\sqrt{D}\exp[-(x\pm a/2)^2/2b^2]$, where a is the distance between the two waveguides, b is the half-width of each waveguide, and D is related to the input power of the system P_0 as $D=P_0/(\sqrt{\pi}b)$. P_0 has the unit of W/m. Strictly, the width of $u_{1,2}$ changes due to the modulation of the refractive index. However, the resulting effects is likely secondary as the theoretical predictions made with this approximation agree with the experiments quite well [14]. The variation of the width b is thus not considered here. This two-mode approximation eventually simplifies Eq. (1) to

$$i\dot{c}_1 = \frac{v}{2}c_2 - \frac{S(z)}{2}c_1 - \chi|c_1|^2 c_1, \quad (2)$$

$$i\dot{c}_2 = \frac{v}{2}c_1 + \frac{S(z)}{2}c_2 - \chi|c_2|^2 c_2, \quad (3)$$

where $S(z)=-4\pi(\int u_1^* V_1(x,z)u_1 dx)/\lambda$, $v=4\pi \times(\int u_1^* H_0 u_2 dx)/\lambda$, and $\chi=\sqrt{2\pi}n_2P_0/(\lambda b)$. Since the real waveguide is three dimensional, we replace b in χ with $\sigma_{\rm eff}$ to relate our nonlinear parameter χ to real experimental parameters and write $\chi=2\pi n_2 P_0/\lambda\sigma_{\rm eff}$ [1,2], where P_0 has the unit of W. When $S=0$, Eqs. (2) and (3) are reduced to the well-known Jensen equation, where the critical power is defined as $P_c=2vP_0/\chi$ [1].

The presence of the periodic modulation in the two coupled waveguides strongly affects the behavior of the all-optical switch. To investigate this effect, we solve Eqs. (2) and (3) numerically for the following form of $S(z)=S\cos(\omega z)$ [12–15,17–21]. Here, S and ω are the amplitude and frequency of the modulation. Our numerical results are shown in Fig. 2, where the relative output power (to the total power) is plotted as a function of the input power for three different values of the ratio S/ω with certain fixed ratio of ω/v. We observe two important trends for this case. As the ratio S/ω is increased (1) the threshold switching power P_c' decreases and (2) the width of the switching step becomes smaller. This demonstrates that by increasing the amplitude of the periodic modulation one can improve the performance of the all-optical switch in two aspects: lowering the threshold switching power and sharpening the switching. We have computed numerically how the critical switching power changes with S/ω for two different values of ratio ω/v. The results are plotted in Fig. 3(a), showing a significant lowering of threshold switching power as S/ω increases. To measure the width of the switching steps in Fig. 2, we introduce a new quantity ΔP, which is the distance between the two positions of the input power where the relative output powers are 25% and 75%, respectively. Figure 3(b) shows that the switching width ΔP becomes smaller with increasing S/ω, i.e., the switching becomes sharper and sharper as S/ω increases.

To better understand the above results, we consider the high frequency limit, $\omega \gg \max\{v,\chi\}$, which is the case for the current experiment with optical waveguides [14]. We take advantage of the transformation $c_{1,2}=c_{1,2}'\exp[\pm iS\sin(\omega z)/2\omega]$. After averaging

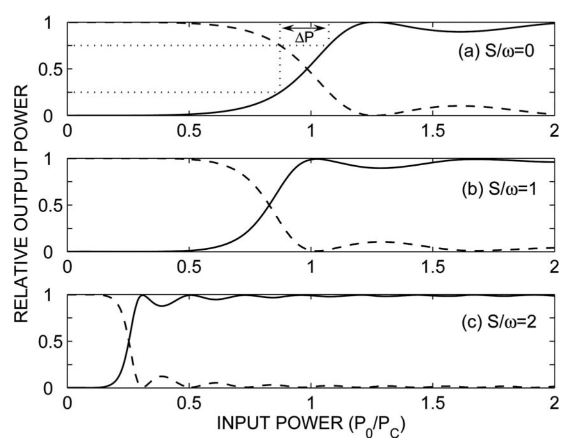

Fig. 2. Relative output powers as functions of the input power for three different values of S/ω at $\omega/v=10$ for $S(z)=S\cos(\omega z)$. The solid lines are for the launching waveguide, while the dashed lines are for the neighboring waveguide. The input power P_0 is scaled by the threshold switching power P_c.

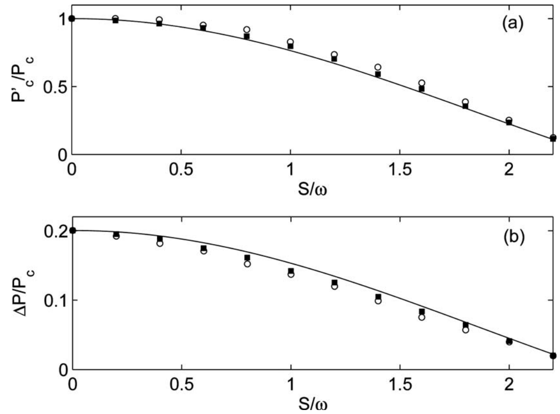

Fig. 3. (a) Threshold switching power as a function of the ratio S/ω. (b) Switching width as a function of the ratio S/ω. This is for the case of $S(z)=S\cos(\omega z)$. The open circles are for $\omega/v=10$, the squares are for $\omega/v=20$, and the solid lines represent the theoretical results at the high-frequency limit.

out the high frequency terms, we arrive at a nondriving nonlinear model [12,19]

$$i\dot{c}_1' = \frac{v}{2}J_0(S/\omega)c_2' - \chi|c_1'|^2c_1', \tag{4}$$

$$i\dot{c}_2' = \frac{v}{2}J_0(S/\omega)c_1' - \chi|c_2'|^2c_2', \tag{5}$$

where $J_0(x)$ is the zeroth-order Bessel function. These two equations are exactly the Jensen equations, except that the coupling constant v is renormalized by a factor of $J_0(S/\omega)$. This shows that all the effect of the periodic modulation, $S(z)=S\cos(\omega z)$, is manifested in the renormalized factor $J_0(S/\omega)$. Consequently, the nonlinear parameter χ is effectively increased by a factor of $1/J_0(S/\omega)$ and the threshold power P_c' is lowered by a factor of $J_0(S/\omega)$, i.e., $P_c'=P_cJ_0(S/\omega)$. This implies that arbitrarily low switching powers may be obtained when the ratio S/ω is chosen to be close to the first zero of the Bessel function $J_0(S/\omega)$. This analytical result is compared to our previous numerical results in Fig. 2(a). The switching width can also be computed by combining L_c and P_c'. The results agree very well with our previous numerical results, as seen in Fig. 2(b).

As in the traditional NLDC, an appropriate length has to be chosen for our device to function as an all-optical device. The appropriate length, which may be called switch length, is given by $L_c'=L_c/J_0(S/\omega)$. This indicates that to lower the threshold switching power we have to make a sacrifice by using longer waveguides. In fact, if one wants to lower the critical switching power by a factor, then one has to use waveguides that are longer by the same factor.

In conclusion, we have proposed a modification to the traditional NLDC by modulating the nonlinear waveguides periodically. When this device functions as an all-optical switch, it has much lower threshold switching power and sharping switching.

This work is supported by the National Science Foundation of China (NSFC) (grants 10825417, 10905019, and 10965001), and the MOST of China (2005CB724500 and 2006CB921400).

References

1. S. M. Jensen, IEEE J. Quantum Electron. **18**, 1580 (1982).
2. A. A. Maier, Sov. J. Quantum Electron. **12**, 1490 (1982).
3. G. P. Agrawal, *Applications of Nonlinear Fiber Optics* (Academic, 2001).
4. D. D. Gusovskii, E. M. Dianov, A. A. Maier, V. B. Neustruev, E. I. Shklovskii, and I. A. Shcherbakov, Sov. J. Quantum Electron. **15**, 1523 (1985).
5. V. Leutheuser, U. Langbein, and F. Lederer, Opt. Commun. **75**, 251 (1990).
6. G. J. Liu, B. M. Liang, G. L. Jin, and Q. Li, J. Lightwave Technol. **22**, 1591 (2004).
7. S. R. Friberg, Y. Silberberg, M. K. Oliver, M. J. Andrejco, M. A. Saifi, and P. W. Smith, Appl. Phys. Lett. **51**, 1135 (1987).
8. S. R. Friberg, A. M. Weiner, Y. Silberberg, B. G. Sfez, and P. W. Smith, Opt. Lett. **13**, 904 (1988).
9. A. M. Weiner, Y. Silberberg, H. Fouckhardt, D. E. Leaird, M. A. Saifi, M. J. Andrejco, and P. W. Smith, IEEE J. Quantum Electron. **25**, 2648 (1989).
10. S. R. Vigil, Z. Zhou, B. K. Canfield, J. Tostenrude, and M. G. Kuzyk, J. Opt. Soc. Am. B **15**, 895 (1998).
11. D. Marchese, M. De Sairo, A. Jha, A. K. Kar, and E. C. Smith, J. Opt. Soc. Am. B **15**, 2361 (1998).
12. X. Luo, Q. Xie, and B. Wu, Phys. Rev. A **76**, 051802(R) (2007).
13. X. Luo, Q. Xie, and B. Wu, Phys. Rev. A **77**, 053601 (2008).
14. A. Szameit, Y. V. Kartashov, M. Heinrich, F. Dreisow, R. Keil, S. Nolte, A. Tünnermann, V. A. Vysloukh, F. Lederer, and L. Torner, Opt. Lett. **34**, 2700 (2009).
15. G. Della Valle, M. Ornigotti, E. Cianci, V. Foglietti, P. Laporta, and S. Longhi, Phys. Rev. Lett. **98**, 263601 (2007).
16. *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*, M. Abramowitz and I. A. Stegun eds. (Dover, 1972).
17. A. Szameit, Y. V. Kartashov, F. Dreisow, M. Heinrich, T. Pertsch, S. Nolte, A. Tünnermann, V. A. Vysloukh, F. Lederer, and L. Torner, Phys. Rev. Lett. **102**, 153901 (2009).
18. Y. V. Kartashov, A. Szameit, V. A. Vysloukh, and L. Torner, Opt. Lett. **34**, 2906 (2009).
19. S. Longhi, Phys. Rev. A **71**, 065801 (2005).
20. A. Szameit, I. L. Garanovich, M. Heinrich, A. Minovich, F. Dreisow, A. A. Sukhorukov, T. Pertsch, D. N. Neshev, S. Nolte, W. Krolikowski, A. Tünnermann, A. Mitchell, and Y. S. Kivshar, Phys. Rev. A **78**, 031801 (2008).
21. A. Szameit, I. L. Garanovich, M. Heinrich, A. A. Sukhorukov, F. Dreisow, T. Pertsch, S. Nolte, A. Tünnermann, and Y. S. Kivshar, Nat. Phys. **5**, 271 (2009).