All-optical switch with two periodically curved nonlinear waveguides

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We propose a type of all-optical switch which consists of two periodically curved nonlinear optical waveguides placed in parallel. Compared to the all-optical switch based on the traditional nonlinear directional coupler with straight waveguides, this all-optical switch has much lower switching threshold power and sharper switching width.

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I. INTRODUCTION

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 switching device. Its switching operation is based on the intensity-dependent power transfer between its two coupled waveguides. For a continuous-wave (CW) laser beam, the beam can be directed towards different output ports of the NLDC depending on whether the input power exceeds a threshold (or critical) power \(P_c\). At low input power, most of the light emerges from the neighboring waveguide; at high power above \(P_c\), most of the light remains in the launching waveguide. Therefore, the change in the input power can cause light to be switched from one waveguide to the other.

However, the application of the NLDC as an all-optical switch is limited by its high threshold on switching power. There were two approaches to improve its performance or to make it applicable. One approach is to use a pulsed beam to lower the overall demand on the laser power as a CW beam would. Both picosecond and femtosecond lasers have been used to successfully demonstrate the all-optical switching in a NLDC. 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 the case of CW beams. The other is to use materials with relatively larger Kerr nonlinearity but this usually leads to a slower response time.

In this paper, 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 periodically curved nonlinear waveguides placed in parallel. It can be regarded as a modification of the traditional NLDC which consists of two straight waveguides. Due to the effect of nonlinear coherent destruction of tunneling (NCDT), this modified NLDC can function as an all-optical switch at an appropriate length. This all-optical switch has lower critical power since the periodical bending of the nonlinear waveguides can effectively increase their nonlinearity. In addition, this device has sharper switching width. Such a curved switch permits in principle arbitrarily low switching threshold power; its only foreseeable drawback is longer coupling length. This work is motivated by a recent experiment with two coupled periodically curved linear waveguides and the theoretical extension to the nonlinear case.

II. STRAIGHT ALL-OPTICAL SWITCH

Before we fully discuss our proposed switch, we give a brief introduction to the traditional NLDC. This device is made of two straight nonlinear waveguides which are placed in parallel adjacent to each other so that they are coupled optically. The operation of the NLDC as an all-optical switching was studied in detail by Jensen. 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

\[
P_1(L) = \frac{P_0}{2} [1 + \text{cn}(\pi L/L_c|m)],
\]

where \(L\) is the length of the coupler and \(\text{cn}(\pi L/L_c|m)\) is the Jacobi elliptic function. The parameter \(L_c\) is called the coupling length representing the shortest length for the light switching from one waveguide to the other without nonlinearity. 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

\[
P_c = \lambda \sigma_{\text{eff}}/L_c n_2,
\]

where \(\lambda\) is the free space wavelength of the light, \(\sigma_{\text{eff}}\) is the effective cross-section of the waveguide, and \(n_2\) is the
Kerr nonlinear coefficient (or nonlinear refractive index \( \chi \)). 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 \( P_0 < P_c \).

III. PERIODICALLY CURVED ALL-OPTICAL SWITCH

Our proposed all-optical switch is a modification of the NLDC by replacing the two straight waveguides with two periodically curved nonlinear waveguides as shown in Fig. 1. In the following discussion, without loss of generality we focus on the case where the two waveguides are bent sinusoidally along the propagation direction \( z \). Specifically, the profile of the waveguide is given by \( x_0(z) = A \cos(2\pi z/\Lambda) \) with an amplitude \( A \) and a period \( \Lambda \).

Since the light is strongly localized in the \( y \) direction.\(^{11} \) In this case, the light propagation in this nonlinear directionally waveguides is described by an effective two-dimensional wave equation\(^{10,11,12} \)

\[
i\frac{\lambda}{2\pi} \frac{\partial \psi}{\partial z} = - \frac{\lambda^2}{8\pi^2 n_s} \frac{\partial^2 \psi}{\partial x^2} + V[x - x_0(z)]\psi - n_2|\psi|^2\psi, \tag{3}
\]

where \( V(x) = |n_s^2 - n_s^2(x)|/(2n_s) \approx n_s - n(x) \), where \( n(x) \) and \( n_s \) are, respectively, the effective refractive index profile of the waveguides and the substrate refractive index. For the coupled waveguides, \( n(x) \) and thus \( V(x) \) have a double-well structure. The scalar electric field is related to \( \psi \) through \( E(x, z, t) = (1/2)(n_s\epsilon_0\sigma_0/2)^{-1/2}[\psi(x, z) \exp(-ik_0t + ikn_s z) + c.c.] \), where \( k = 2\pi/\Lambda \), \( \sigma_0 \) is the speed of light, and \( \epsilon_0 \) is the dielectric constant in vacuum. The light intensity \( I \) (in \( W/m^2 \)) is given by \( I = |\psi|^2 = (n_s\epsilon_0\sigma_0/2)|E|^2 \). With the Kramers-Henneberger transformation\(^{11} \), \( x' = x - x_0(z), z' = z, \phi(x', z') = \psi(x', z') \exp[-i(2\pi n_s/\lambda)\tilde{x}_0(z')x' - i(n_s\pi/\lambda)\tilde{x}_0(z')\tilde{x}_0(z')|\tilde{x}_0(x')| \) (the dot indicates the derivative with respect to \( z' \)), we have

\[
i\frac{\lambda}{2\pi} \frac{\partial \phi}{\partial z'} = H_0\phi - n_2|\phi|^2\phi + x'F(z')\phi, \tag{4}
\]

where \( H_0 = -\frac{\lambda^2}{8\pi^2 n_s} \frac{\partial^2}{\partial x'^2} + V(x') + F(z') \approx n_s\tilde{x}_0(z') = (4\pi^2 A n_s/\Lambda^2) \cos(2\pi z'/\Lambda) \) can be regarded as a “force” induced by the bending waveguide.

Due to the double-well structure of \( V(z') \), we apply the two-mode approximation\(^{11,13} \) and write \( \phi(x', z') = e^{-i\phi_0} c_1(z')u_1(x') + c_2(z')u_2(x') \), where \( u_1 \) and \( u_2 \) are localized waves in the two waveguides and the two coefficients are normalized to one, \( |c_1|^2 + |c_2|^2 = 1 \). \( \phi_0 \) is defined as \( \phi_0 = \int u_1^* H_0 u_1 dx' \). It is reasonable to assume that the localized wave is a Gaussian, \( u_{1,2}(x') = \sqrt{D}\exp[-(x' \pm a/2)^2/b^2]\), 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 \( W/m \). This two-mode approximation eventually simplifies Eq. (4) to

\[
i c_1 = \frac{\psi}{\sqrt{2}}c_2 - \frac{S}{2}\cos(\omega z')c_1 - \chi|c_1|^2c_1, \tag{5}
\]

\[
i c_2 = \frac{\psi}{\sqrt{2}}c_1 + \frac{S}{2}\cos(\omega z')c_2 - \chi|c_2|^2c_2, \tag{6}
\]

where \( S = 8\pi^3 a A n_s/\Lambda^3 \), \( v = 4\pi(\int u_1^* H_0 u_2 dx)/\lambda \), \( \omega = 2\pi/\Lambda \), and \( \chi = \sqrt{2\pi n_b P_0/\lambda b} \). Since the real waveguide is 3D, we replace \( b \) in \( \chi \) with \( \sigma_{eff} \) to relate our nonlinear parameter \( \chi \) to real experimental parameters and write \( \chi = 2\pi n_b bP_0/\lambda\sigma_{eff} \), where \( P_0 \) has the unit of \( W \). When \( S = 0 \), Eqs. (5) and (6) are reduced to the well-known Jensen equation, where the critical power is defined as \( P_c = 2vP_0/\chi \) and the coupling length \( L_c \) is related to \( v \) through \( L_c = \pi/v^2 \). Combination of these relations leads to the critical power \( P_c \) in Eq. (2).

\[
\begin{align*}
(a) S/\omega=0 & \\
(b) S/\omega=1 & \\
(c) S/\omega=2 & \\
\end{align*}
\]

FIG. 2: Relative output powers as functions of the input power for three different values of \( S/\omega \) at \( \omega/v = 10 \). 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 \( P_c \).

The presence of the periodical curvature in the two coupled waveguides strongly affect the behavior of the all-optical switch. To investigate this effect, we solve Eqs. (5) and (6) numerically. Figure 2 shows the relative output power (to the total power) as a function of the input power for three different values of the ratio \( S/\omega \) with \( \omega/v = 10 \). We observe two trends as the ratio \( S/\omega \) is increased. First, the threshold switching power \( P_c \) decreases. Second, the width of the switching step becomes smaller. This demonstrates that by increasing the amplitude of the periodic curvature 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 \( S/\omega \).
As an example, we take the experimental parameters in Refs. 14,15 to estimate our theoretical values in Eqs. 4 and 10 for a given ratio of $S/\omega$. In this experiment, the wavelength of the laser light is $\lambda = 0.62 \mu m$, the effective cross-section area of the waveguide is $\sigma_{\text{eff}} = 15 \mu m^2$, the nonlinear index $n_2 = 3.2 \times 10^{-16} \text{cm}^2/\text{W}$, and the coupling length $L = L_c = 5 \text{mm}$. The critical power is thus $P_c = 60 \text{ kW}$. For the periodically bent coupler, we choose $S/\omega \approx 2.38$, which means $J_0(2.38) \approx 0.01$. As a result, the threshold switching power is lower by a factor of 100 and becomes $P'_c \approx 600 \text{W}$ while the switch length of the coupler is $L' = 0.5 \text{m}$.

IV. CONCLUSION

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

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