Nonlinear directional coupler for polychromatic light

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We demonstrate that a nonlinear directional coupler with special bending of waveguide axes can be used for all-optical switching of polychromatic light with a very broad spectrum covering all of the visible region. The bandwidth of the suggested device is enhanced five times compared with conventional couplers. Our results suggest novel opportunities for the creation of all-optical logical gates and switches for polychromatic light with white-light and supercontinuum spectra. © 2007 Optical Society of America

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The directional waveguide coupler, which to our knowledge was first introduced by Jensen[1] and Maier,[2] has attracted a great deal of attention as a major candidate for the creation of ultrafast all-optical switches. This device utilizes light tunneling between two optical waveguides placed in close proximity to each other as schematically shown in Fig. 1(a). In the linear regime, light is switched from one waveguide to another at the distance called the coupling length. At high input powers, intensity-dependent change of the refractive index through optical nonlinearity creates detuning between the waveguides, which can suppress power transfer between coupler arms, such that light remains in the input waveguide. Since the first experimental demonstration of a subpicosecond nonlinear coupler switch in a dual-core fiber,[3] various aspects of switching in different coupler configurations have been extensively analyzed.[4–8]

In recent years, new sources of light with ultrabroad spectra have become available with a wide range of applications, including information transmission, spectroscopy, microscopy, and optical sensing. However, conventional couplers can perform only switching of signals with rather limited spectral bandwidth, because the coupling length depends on optical frequency, resulting in separation of different frequency components between the waveguides.

In this Letter, we propose a new configuration of directional coupler designed for nonlinear switching of polychromatic light such as light with supercontinuum frequency spectrum generated in photonic-crystal fibers and fiber tapers.[9,10] The spectral bandwidth of the suggested device is five times wider compared with conventional coupler structures, making it possible to collectively switch wavelengths covering almost all of the visible region.

We demonstrate that the operating bandwidth of a conventional coupler consisting of straight parallel waveguides [Fig. 1(a)] can be improved by introducing special bending of waveguide axes in the propagation direction as illustrated in Fig. 1(b). Nonlinear switching of polychromatic signals while preserving their spectral characteristics can be realized in media with slow nonlinear response, where the optically induced refractive index change is defined by the time-averaged light intensity of different spectral components.[11,12] Then, the evolution of polychromatic beams can be described by a set of normalized nonlinear equations for the spatial beam envelopes $A_m(x,z)$ at vacuum wavelengths λ_m,

$$i\frac{\partial A_m}{\partial z} + \frac{z_s\lambda_m}{4\pi n_0 x_s^2}\frac{\partial^2 A_m}{\partial x^2} + \frac{2\pi z_s}{\lambda_m}\{\nu[x - x_0(z)] + \mathcal{G}\}A_m = 0, \qquad (1)$$

where x and z are the transverse and propagation coordinates normalized to the characteristic values $x_s = 1\ \mu\text{m}$ and $z_s = 1$ mm, respectively; n_0 is the average

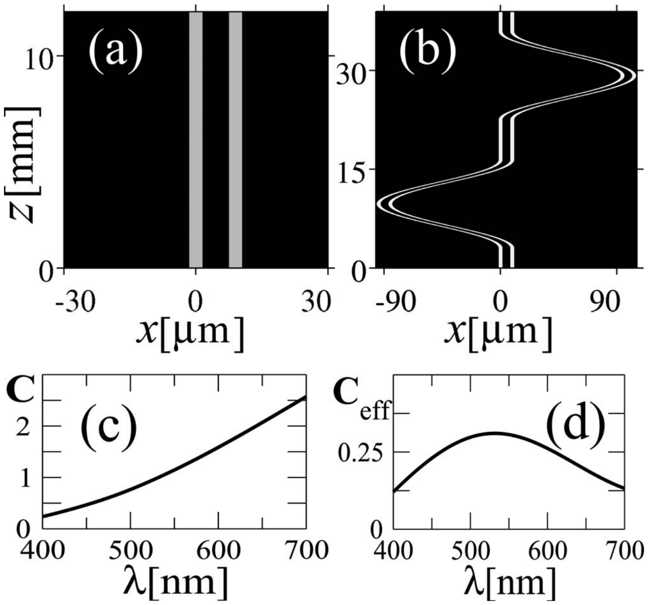

Fig. 1. (a) Conventional directional coupler composed of two evanescently coupled straight waveguides. (b) Polychromatic coupler with specially designed bending of the waveguide axes. (c) Wavelength dependence of the coupling coefficient between straight waveguides. (d) Effective coupling in the curved coupler shown in (b). Waveguide width and separation between waveguide axes are 3 and 9 μm, respectively. Refractive index contrast is $\Delta\nu = 8\times 10^{-4}$, and $n_0 = 2.35$.

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refractive index of the medium; $\nu(x)$ defines the transverse refractive index profile in cross section of the coupler; $x_0(z)$ is the longitudinal bending profile of the waveguide axes; $\mathcal{G}=\alpha M^{-1}\Sigma_{m=1}^{M}\gamma(\lambda_m)|A_m|^2$ defines the nonlinear change of refractive index; α is the nonlinear coefficient; and $\gamma(\lambda)$ accounts for dispersion of the nonlinear response. In numerical simulations, we choose a large number of components $M=50$ to model accurately the dynamics of beams with broadband spectrum.

As monochromatic light propagates in a directional coupler made of straight identical waveguides [Fig. 1(a)], the power is periodically exchanged between the two waveguides.[1] The period is defined by the coupling length, $Z_c=\pi/[2C(\lambda)]$, where $C(\lambda)$ is the coupling coefficient. Then, signal switching between output coupler arms is realized by choosing the device length as an odd number of coupling lengths. However, this condition cannot be simultaneously satisfied for all frequency components of polychromatic light, because the coupling coefficient depends on wavelength[1,13] and tends to increase at the red spectral edge [see Fig. 1(c)].

The effect of axes bending on light propagation in two coupled waveguides can be described in terms of the effective coupling coefficient C_{eff}. It was shown[14] that, in the limit when bending period (Z_b) is much smaller than the coupling length for straight waveguides (Z_c), the light distribution at the output of the curved coupler is the same as for straight structure with the coupling C_{eff} between the waveguides. We observe in numerical simulations that the effective coupling accurately describes the device operation for a broad class of bending profiles even when L, Z_b, and Z_c are of the same order, where L is the length of the structure. For bending profiles consisting of symmetric segments with $x_0(z-\tilde{z})=x_0(\tilde{z}-z)$, where $\tilde{z}$ is a coordinate shift, the modified coupling coefficient takes the same form as in periodic waveguide arrays[14,15]:

$$C_{\text{eff}}(\lambda)=C(\lambda)L^{-1}\int_0^L \cos[2\pi n_0 a\dot{x}_0(z)/\lambda]\mathrm{d}z.$$

Here, $C(\lambda)$ is the wavelength-dependent coupling coefficient between straight waveguides with the same separation a between their axes, and the dot stands for the derivative.

We note that the integral in the expression for the effective coupling coefficient depends on the wavelength λ. This makes it possible to compensate for the wavelength dependence of the coupling coefficient $C(\lambda)$ with the geometrical bending-induced dispersion. We find that wavelength-insensitive effective coupling around the central wavelength λ_0 can be realized in a hybrid structure consisting of alternating straight and sinusoidal segments [see Fig. 1(b)]: $x_0(z)=0$ for $0\leqslant z\leqslant z_0$, $x_0(z)=A\{\cos[2\pi(z-z_0)/(z_1-z_0)]-1\}$ for $z_0\leqslant z\leqslant z_1$, $x_0(z)=0$ for $z_1\leqslant z\leqslant L/2$, and $x_0(z)=-x_0(z-L/2)$ for $L/2\leqslant z\leqslant L$. We set $A=\xi_2(z_1-z_0)\lambda_0(4\pi^2 n_0 a)^{-1}$ and $z_1=L/2-z_0$, where $\xi_2\simeq 5.52$ is the second root of the equation $J_0(\tilde{\xi})=0$ and J_m is the Bessel function of the first kind of the order m. Effective coupling in this structure is $C_{\text{eff}}(\lambda)=C(\lambda)L^{-1}[4z_0+(L-4z_0)J_0(\xi_2\lambda_0/\lambda)]$, and the condition of wavelength-insensitive coupling $\mathrm{d}C_{\text{eff}}(\lambda)/\mathrm{d}\lambda|_{\lambda=\lambda_0}=0$ is satisfied for $z_0=(L/4)\{1-C_1[\xi_2 J_1(\xi_2)C_0]^{-1}\}^{-1}$. Here, the coefficients $C_0=C(\lambda_0)$ and $C_1=\lambda_0\mathrm{d}C(\lambda)/\mathrm{d}\lambda|_{\lambda=\lambda_0}$ characterize coupling dispersion for straight waveguides. In numerical simulations, we choose $\lambda_0=532$ nm and find the coupling dispersion for waveguides shown in Fig. 1(a) as $C_0\simeq 0.13\ \text{mm}^{-1}$ and $C_1\simeq 0.52\ \text{mm}^{-1}$. Then, we calculate the optimal parameters of the curved coupler and obtain almost constant coupling $C_{\text{eff}}(\lambda\simeq\lambda_0)\simeq 0.31C_0$ in a broad spectral region [see Fig. 1(d)].

The optimized curved coupler can be used to collectively switch all spectral components around the central wavelength λ_0 from one waveguide at the input to the other waveguide at the output. This regime is realized when the device length is matched to the effective coupling length; i.e., $L=\pi/[2C_{\text{eff}}(\lambda_0)]\simeq 39$ mm. We have verified that the effective coupling approximation provides very accurate results with less than 1% deviation from exact solutions of coupled-mode equations[14] in the vicinity of central wavelength. We then perform numerical simulations based on full-model Eq. (1) and confirm that the proposed coupler

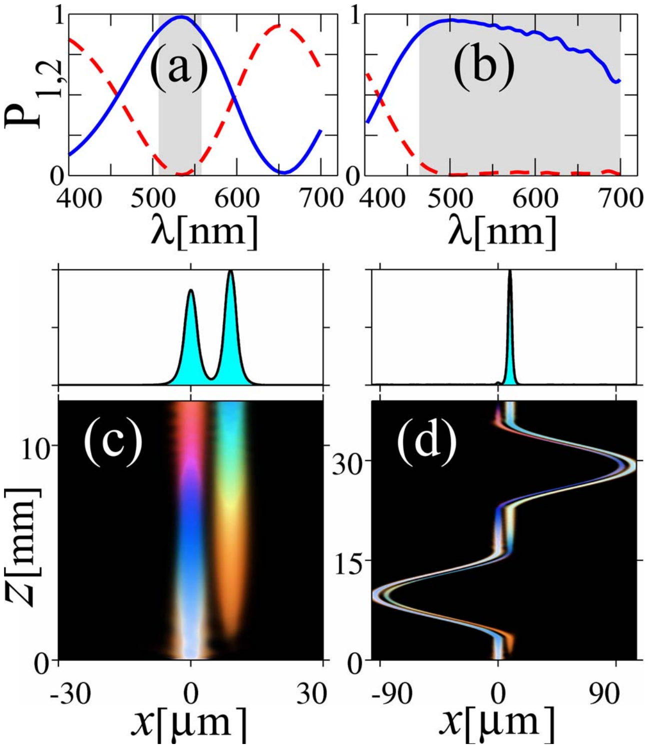

Fig. 2. (Color online) (a), (b) Wavelength dependence of linear transmission characteristics for straight and optimized curved couplers, respectively. Shown are output powers in the left (dashed curve, P_1) and right (solid curve, P_2) coupler arms, when light is fed into the left arm of the coupler. Shading marks spectral regions where the switching ratio P_2/P_1 is larger than 10. (c), (d) Evolution of polychromatic light with flat spectrum covering 450–700 nm in the straight and in the optimized curved structures, respectively. Top panels in (c) and (d) show the total intensity distributions at the output.

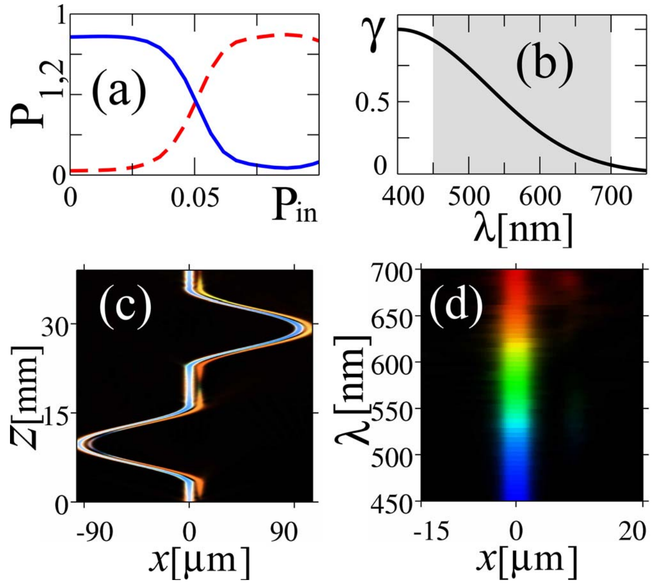

Fig. 3. (Color online) Nonlinear switching of polychromatic light. (a) Power distribution at the output ports of the coupler as a function of the input power. Polychromatic input is the same as in Figs. 2(c) and 2(d). Solid and dashed curves show power in the left (P_1) and in the right (P_2) output coupler ports, respectively. (b) Sensitivity function γ describing wavelength dispersion of the nonlinear response. (c), (d) Propagation dynamics and output spectrum, respectively, in the nonlinear switched state realized at the total input power $P_{\text{in}}=0.085$. Nonlinear coefficient is $\alpha=10$.

structure indeed exhibits extremely efficient switching into the crossed state simultaneously in a very broad spectral region of about 450–700 nm, which covers almost all visible [see Figs. 2(b) and 2(d)]. This is in a sharp contrast to the conventional straight coupler [Figs. 2(a) and 2(c)] that can operate only in the spectral region of ~510–560 nm, which is about five time less than that for the proposed curved coupler. We note that the slight decrease of the output power at the red edge of the spectrum for the curved coupler [Fig. 2(b)] is caused by the radiation at the waveguide bends,[14] but such losses do not affect the broadband switching behavior.

At high input powers, nonlinear change of the refractive index modifies waveguide propagation constant and decouples waveguides from each other similar to other nonlinear coupler structures studied before.[1,3,13] This causes switching from the crossed state into the parallel state as shown in Figs. 3(a), 3(c), and 3(d). Remarkably, nonlinear switching also takes place in a very broad spectral region of ~450–700 nm, which enables the coupler to act as an all-optical digital switch for polychromatic light. In these simulations, we consider the case of a photorefractive medium, such as $LiNbO_3$, where optical waveguides of arbitrary configuration can be fabricated by titanium indiffusion.[16,17] The photosensitivity of $LiNbO_3$ is approximated as $\gamma(\lambda)=\exp[-\log(2)(\lambda-\lambda_b)^2/\lambda_w^2]$, where $\lambda_b=400$ nm and $\lambda_w=150$ nm [Fig. 3(b)]. The switching behavior of the coupler remains essentially the same for other values of λ_w, which primarily affect the quantitative characteristics such as the switching power.

In conclusion, we demonstrated that optimized curved directional coupler can be used to perform switching of polychromatic light with extremely broad spectrum covering almost all visible. Similar principles can be applied to create broadband switches for other spectral regions. Suggested devices can be fabricated in planar waveguiding structures, offering novel opportunities for creating all-optical logical gates and switches for polychromatic signals with white-light or supercontinuum spectrum.

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