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All-optical switching devices based on large nonlinear phase shifts from second harmonic generation

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We show that the large nonlinear phase shifts obtained from phase-mismatched second harmonic generation can be used to implement all-optical switching devices such as a nonlinear Mach–Zehnder interferometer and a nonlinear directional coupler.

It has proven difficult to find materials with large enough nonlinearities (n_2) combined with low enough losses (α) to make high throughput all-optical switching (AOS) devices responding on picosecond time scales.[1] Well-understood devices such as nonlinear Mach–Zehnder interferometers (NMZI) and directional couplers (NLDC) have been implemented successfully only in glass fibers,[2,3] and in AlGaAs channel waveguides operated with photon energies below half their band gap.[4,5] Recently it has been shown that the nonlinear phase shift experienced by a beam at the fundamental frequency during almost phase-matched second harmonic generation can achieve multiple values of $\pi/2$ without absorptive losses.[6–8] The evolution of this phase (and amplitude) of the fundamental with distance and power is quite different from that associated with an intensity-dependent refractive index n_2, and it has been an open question whether this source of nonlinear phase shift can be used in AOS devices.[7] In this letter we examine the response of two such devices using noncentrosymmetric media, a NMZI and a NLDC, and show that the special features associated with second order cascaded processes are indeed useful for geometries relying on nonlinear phase shifts.

The basic configuration of a Mach–Zehnder interferometer and a directional coupler are well known and are shown as insets of Figs. 2(a) and 3(c).[1] For the Mach–Zehnder, the incident beam is split into two, and both beams undergo independent phase shifts on propagation until they are recombined at the second stem to produce an output. The goal for an NMZI is to change the relative phase between the channels by changing input power. In order to ensure complete destructive interference at low powers (which requires a phase differences of π), we also introduce a phase offset element into one arm. For the NLDC there are two separate inputs, and the guides are sufficiently close to permit energy exchange between the fundamental beams in the two channels due to spatial beam overlap. Normally, for half beat length, a signal input into one channel exits from the second channel. For AOS, the relative channel outputs are changed by increasing the input power.

The starting point of the analysis is the usual coupled mode equations describing second harmonic generation in two lossless channels (for example, waveguides) which can be coupled (NLDC) or not (NMZI) by the spatial overlap of optical fields.[1–5] We write

$$\frac{d}{dz}a_{2\omega}(z)=-i\kappa(-2\omega;\omega,\omega)a_{\omega}^{2}(z)e^{i\Delta\beta z}, \tag{1}$$

$$\frac{d}{dz}a_{\omega}(z)=-i\kappa(-\omega;2\omega,-\omega)a_{2\omega}(z)a_{\omega}^{*}(z)\times e^{-i\Delta\beta z}+i\Gamma b_{\omega}(z), \tag{2}$$

$$\frac{d}{dz}b_{2\omega}(z)=-i\kappa(-2\omega;\omega,\omega)b_{\omega}^{2}(z)e^{i\Delta\beta' z}, \tag{3}$$

$$\frac{d}{dz}b_{\omega}(z)=-i\kappa(-\omega;2\omega,-\omega)b_{2\omega}(z)b_{\omega}^{*}(z)\times e^{-i\Delta\beta' z}+i\Gamma a_{\omega}(z). \tag{4}$$

We assume that an index or nonlinearity is spatially modulated along the direction of propagation in order to achieve quasi-phase-matching and that the wave vector mismatches $\Delta\beta=2k_{\mathrm{vac}}[n(2\omega)-n(\omega)]\pm K$ and $\Delta\beta'=2k_{\mathrm{vac}}[n(2\omega)-n(\omega)]\pm K'$ can be different for the two channels with $2\pi/K$ ($2\pi/K'$) the appropriate period of the modulation. The complex field amplitudes $a_{i\omega}(z)$ (channel 1) and $b_{i\omega}(z)$ (channel 2) are normalized so that $|a_{i\omega}(z)|^2$ and $|b_{i\omega}(z)|^2$ have the units of power. $\kappa=\kappa(-2\omega;\omega,\omega)=\kappa(-\omega;2\omega,-\omega)$ is an effective nonlinear coefficient far from any material resonances and accounts for the field transverse distributions. The subscript i indicates either the fundamental ($i=1$) or second harmonic ($i=2$). Γ quantifies the coupling between the waveguides due to field overlap of the fundamental beams.[1,2,4] Since the

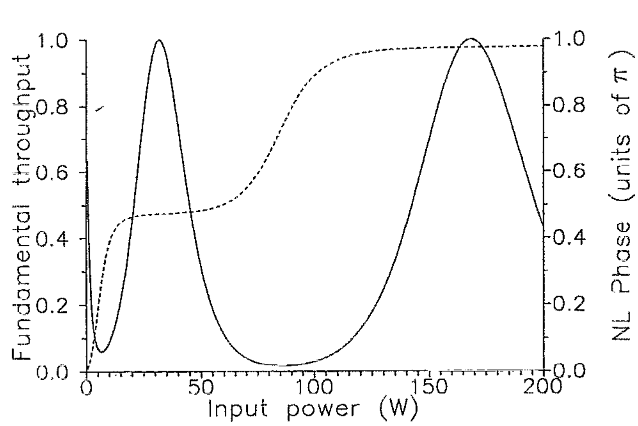

FIG. 1. Nonlinear phase (dashed line) and throughput (solid line) of the fundamental beam vs cw input power in a channel with $\kappa L=1$ and $\Delta\beta L=0.1$. The phase is graphed in units of π.

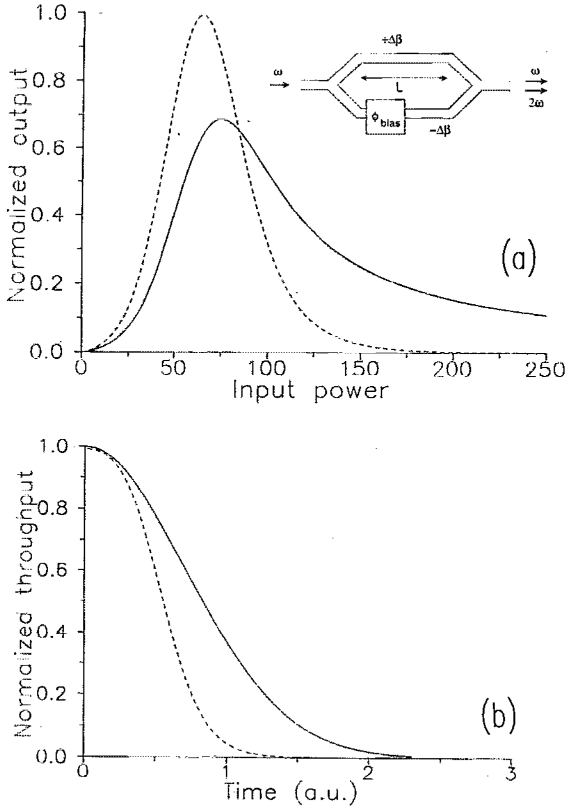

FIG. 2. Mach–Zehnder interferometer: (a) transmission vs input fundamental powers for cw (dashed line) and pulsed (solid) inputs; in the pulsed case, the horizontal axis represents the peak power of the Gaussian pulses. A sketch of the NMZI is shown in the inset. (b) Time response for a single pulse with a peak power of 65 W. The device is characterized by the same parameters listed in Fig. 1, with phase mismatches of opposite signs in the two arms and a phase offset of π.

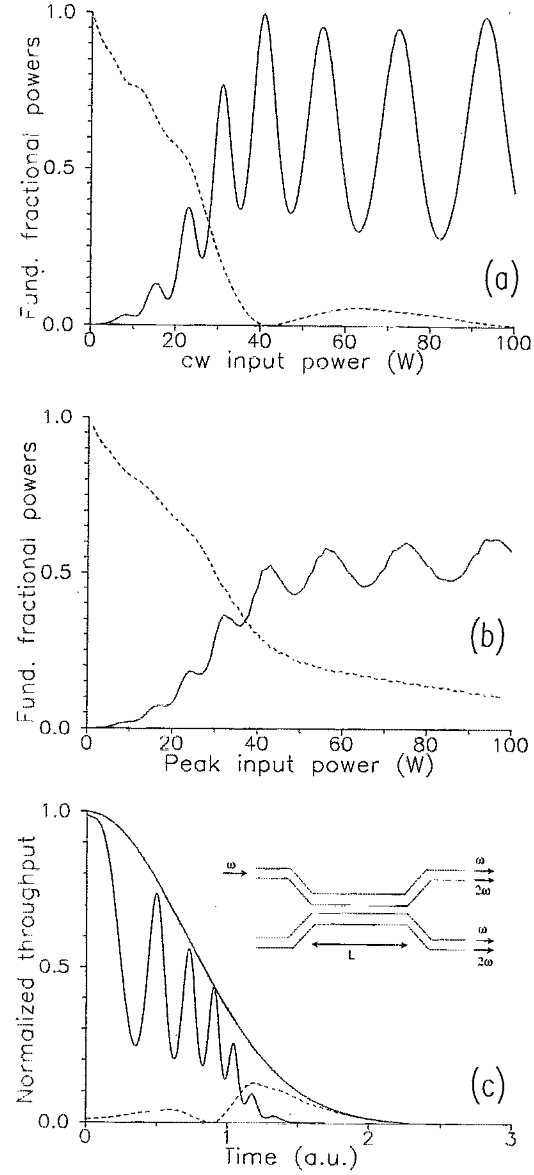

FIG. 3. Nonlinear directional coupler: (a) cross (solid) and bar (dashed) fractional output vs cw input power; (b) same as in (a) for pulsed excitation. The horizontal axis represents peak power. (c) Temporal profile of the output pulse in bar (solid) and cross (dash) channels for an input peak value of 93 W. A schematic of the NLDC is shown in the inset. The half-beat-length NLDC is characterized by $\kappa L=4$ and $\Delta\beta L=8$ in both guides.

harmonic fields are more tightly bound to the individual waveguides than the fundamental, we assume that the pertinent $\Gamma(2\omega)$ for the harmonic waves can be neglected. While the assumption is valid in most practical situations, the inclusion of a small $\Gamma(2\omega)$ does not alter significantly our numerical results. For NMZI, $\Gamma=0$ because there is no power (energy) exchange between the two arms.

A typical example of the fundamental's nonlinear phase shift and power throughout in single channels is shown in Fig. 1. For small detuning $\Delta\beta L$, the novel feature is the plateau in the phase shift versus input intensity. Note that to obtain large phase shifts at the smallest powers possible, large modulation in the output fundamental has to be dealt with. On the other hand, for large detunings the fundamental power is almost a constant, although higher input powers are needed for substantial phase shifts.[8]

First we discuss the NMZI with opposite $\Delta\beta$ in the two arms, i.e., $\Delta\beta' L=-\Delta\beta L$. Therefore the net *differential* phase shift achievable within one plateau is $\pi=[+\pi/2-(-\pi/2)]$, enough for switching the output of this device from off to on or vice versa. If a phase offset of π is introduced into one channel (for example electro-optically or via a difference in channel lengths) the net phase shift can be 0 when operating on the first plateau. The resulting cw response is shown in Fig. 2(a) (dashed line) and exhibits strong modulation versus input power. Since most AOS systems operate with pulse inputs, this response is of most interest. For pulses Gaussian in time, the energy throughput is also plotted in Fig. 2(a) (solid line) vs peak power. For a peak power at the maximum of the cw fundamental throughput, the output signal vs time for a single Gaussian pulse is shown in Fig. 2(b). Note that complete switching is obtained at the peak of the pulse, as well as pulse narrowing. Essentially no pulse break-up is obtained for these operating parameters, in contrast to similar devices based on electronic n_2 nonlinearities.[1] Note that to avoid pulse break-up with a third-order process temporal solitons (realizable only in fibers) or square pulses (difficult to synthesize) have to be used.[9,10]

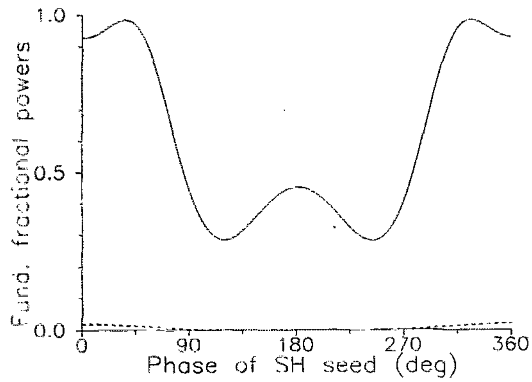

FIG. 4. NLDC with seeding signal at the second harmonic in the input channel. Fractional powers in the bar (solid) and cross (dashed) ports vs initial phase of the seed. Parameters are as listed in Fig. 3, input and seeding powers are 100 and 0.1 W, respectively.

The cw response of a NLDC for the parameters listed in the caption is shown in Fig. 3(a). Note that the output from the cross state decreases to zero with increasing input power and the power reverts back to the bar (input) channel. The oscillation in the fundamental power occurs due to exchange of power with the second harmonic. This oscillation can be reduced, but not eliminated, by optimizing the parameters. The pulsed response as a function of peak power is shown in Fig. 3(b). The oscillations are damped out because of the averaging, however, there is still a strong modulation of the output pulses, as shown in Fig. 3(c) for a single Gaussian temporal profile.

Due to the coherent nature of the SHG process, the outcome of the interaction is sensitive to the amplitude and phase of any other signal input at ω or 2ω. Such sensitivity is enhanced at high powers due to the related bandwidth reduction of the SHG process. In a NLDC, for instance, a weak signal at 2ω can be used to control its operation. In particular, the phase of a second harmonic seed (0.1% of the fundamental beam in our simulations) input through the same bar channel as the fundamental is able to switch the cw fractional bar output of the strong beam, as shown in Fig. 4. A seed at ω into the cross channel can also act as a control signal. A study of these devices in the presence of a seeding signal for cw and pulsed excitations will be presented elsewhere.

In summary, second order processes, for example second harmonic generation, can be used to generate the large nonlinear phase shifts needed for AOS devices. In fact, we predict that switching without pulse break-up should be possible in a Mach–Zehnder interferometer. Switching is also predicted in nonlinear directional couplers with pulse modulation different from that obtained when employing a Kerr n_2. Although this approach to switching is limited to second order noncentrosymmetric media, a number of appropriate materials already exist in waveguide formats to make such devices possible with switching powers of tens of watts and sub-cm lengths.[11–13]

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[1] G. I. Stegeman and E. M. Wright, J. Opt. Quantum Electron. **22**, 95 (1990); G. Assanto, in *Guided Wave Nonlinear Optics*, edited by B. Ostrowsky and R. Reinisch (Kluwer, Dordrecht, 1992), NATO ASI Vol. 214, p. 257.
[2] D. S. Gusovskii, E. M. Dianov, A. A. Maier, V. B. Neustruev, V. V. Osoko, A. M. Prokhorov, K. Yu. Sitarskii, and I. A. Shcherbakov, Sov. J. Quantum Electron. **17**, 724 (1987); S. R. Friberg, A. M. Weiner, Y. Silberberg, B. G. Sfez, and P. W. Smith, Opt. Lett. **13**, 904 (1988).
[3] B. K. Nayar, N. Finlayson, N. J. Doran, S. T. Davey, D. L. Williams, and J. W. Arkwrigth, Opt. Lett. **16**, 408 (1991).
[4] A. Villeneuve, C. C. Yang, P. J. Wigley, G. I. Stegeman, J. S. Aitcheson, and C. N. Ironside, Appl. Phys. Lett. **61**, 147 (1992).
[5] K. Al-hemyari, J. S. Aitchison, C. N. Ironside, G. T. Kennedy, R. S. Grant, and W. Sibbett, Electron. Lett. **28**, 1091 (1992).
[6] N. R. Belashenkov, S. V. Gagarskii, and M. V. Inochkin, Opt. Spectrosc. **66**, 1383 (1989).
[7] R. DeSalvo, D. J. Hagan, M. Sheik-Bahae, G. Stegeman, and E. W. Van Stryland, Opt. Lett. **17**, 28 (1992).
[8] G. I. Stegeman, M. Sheik-Bahae, E. Van Stryland, and G. Assanto, Opt. Lett. **18**, 13 (1993).
[9] S. Trillo, S. Wabnitz, E. M. Wright, and G. I. Stegeman, Opt. Lett. **13**, 672 (1988).
[10] 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).
[11] G. L. J. A. Rikken, C. J. E. Seppen, A. H. J. VenHuizen, S. Nijhuisen, and E. G. J. Staring, Philips J. Res. **46**, 215 (1992).
[12] J. D. Bierlein, Technical Digest of Compact Blue-Green Lasers, Digest Series Vol. 6, Opt. Soc. Am., p. 119 (1992).
[13] K. Yamamoto, K. Mizuuchi, and T. Taniuchi, IEEE J. Quantum Electron. **28**, 1909 (1992).