Coherent Interactions for All-Optical Signal Processing via Quadratic Nonlinearities

Gaetano Assanto, George I. Stegeman, Mansoor Sheik-Bahae, and Eric VanStryland

Abstract—**Based on processes involving the cascading of two successive second-order nonlinear interactions, we show how novel, all-optical approaches to signal processing can be exploited by coherent interactions between three waves in noncentrosymmetric materials. Specifically, we emphasize the coherent seeding of the second-harmonic generation process with waves at one of the participating frequencies.**

ALL-OPTICAL signal processing, i.e., the ensemble of those effects leading to some optically-induced modification of the parameters describing an electromagnetic wave at optical frequencies, has generally been considered to be the realm of third-order phenomena and consequently requires third-order nonlinear susceptibilities and related materials [1]–[3]. Among the important effects are frequency degenerate interactions between one wave (with itself) or two waves which induce self- or cross-phase modulation. Operation at a single photon energy (i.e., optical frequency) is indeed a crucial requirement for cascadability and fan-out of single devices in a network for either processing or computing. Nonlinear phase modulation leads with propagation distance to a nonlinear phase shift, the key quantity in intensity-dependent switching [2]–[3]. The search for third-order materials able to provide large phase shifts at reasonable intensities and with short response times has been, and still is, a major effort in nonlinear optics.

A different approach exists for obtaining optically a nonlinear phase shift upon propagation. It was understood and had been observed previously that certain effects quadratic in the electric field lead to nonlinear phase distortion—shift in pulses—cw-waves propagating in noncentrosymmetric media and undergoing frequency conversion or, specifically, frequency doubling [4], [9]. In the early days of nonlinear optics such effects were included as an additional contribution to the third order susceptibility and evoked little interest because the second order susceptibilities available at that time were small [10]. More recently, the possibility of achieving large nonlinear phase-shifts of a fundamental-frequency (FF) input-wave, utilizing a cascaded process based on wavevector mismatched second-harmonic generation (SHG), has spurred novel ideas in the application of $\chi^{(2)}$ effects for the manipulation of optical signals [11]–[16]. This effect requires both processes, up conversion and down conversion to occur. The resulting nonlinear phase shift can, indeed, be used for the implementation of all-optical switching devices most of which had been originally conceived for implementation with cubic nonlinearities [13]–[16]. The key features of a cascaded quadratic nonlinearity employing a single beam have been outlined before [9] and large phase-shifts of the FF-wave have been measured in KTP crystals due to phase-mismatched SHG [17]–[18]. Phase shifts due to cascading in a DAN-single-crystal core fiber via Cerenkov SHG have been also reported [19]. Cascading in nondegenerate parametric interaction has also been discussed [20] and experimentally demonstrated [5], [21]–[22].

Here, we discuss some of the possibilities offered by a cascaded $\chi^{(2)}$ nonlinearity in the presence of an injected weak seed. Provided that the weak seed wave is temporally and spatially coherent with one of the waves undergoing conversion, i.e., the *fundamental* or *second harmonic* wave, a number of interactions can be considered, involving seeds either at the second harmonic or at the fundamental frequency, 2ω or ω respectively, or both. Since modulation can be considered in terms of either amplitude or phase of both the control and the output waves, this leads to a variety of interesting and potentially useful effects inherent to this interaction. While a detailed inspection of all of them goes beyond the scope of this paper, a qualitative overview of some of these novel processes involving just one control wave and a cw fundamental input is presented in Fig. 1. Even though cascaded effects are present also in the case of Type II SHG, without loss of generality here we will make explicit reference to Type I interactions only, i.e., those in which 2ω-photons result from pairs of ω-photons provided by a single eigenwave in the crystal [23]–[24]. In line with our previous considerations, only waves at the fundamental frequency are regarded as useful outputs of devices intended for use in a photonic system or network, while a 2ω-output is to be regarded as a nonlinear loss (equivalent to two-photon absorption). In general, phase (PM) or amplitude (AM) modulation impressed onto a coherent weak control beam leads to combined phase and amplitude modulation of the fundamental at the output, with the possibility of "small signal

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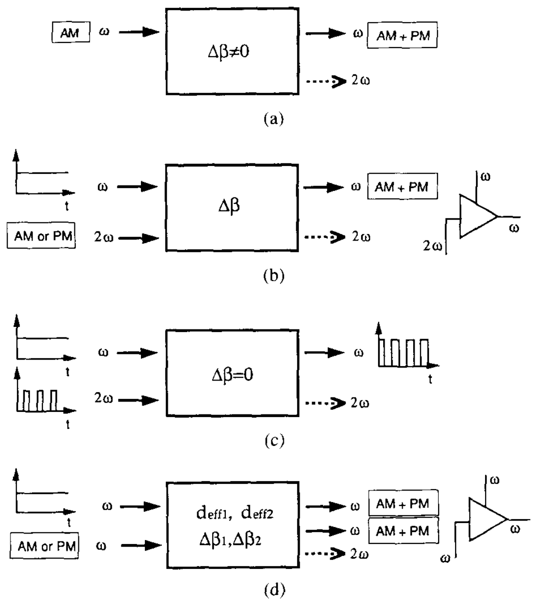


Fig. 1. Summary of simple coherent interactions leading to phase and amplitude modulation of a beam at frequency ω in a 2nd-order nonlinear medium. Solid arrows indicate inputs and outputs of interest. $\Delta\beta$ is the wavevector mismatch between a fundamental and the SH-wave and d_{eff} is the effective nonlinear susceptibility. (a) the standard cascaded nonlinear interaction near wavevector matching, with one input and one relevant output at the same fundamental frequency. (b) Sketch of coherent interactions involving an SH seeding input, either phase (PM) or amplitude (AM) modulated. The ω-output will, in general, exhibit both phase and amplitude modulations, with the possibility of "small-signal" gain in transposing the signal from 2ω to ω. (c) A specific case of b) under phase-matching. A 2ω-signal digitally modulated in amplitude and with an appropriate constant phase will switch on and off the fundamental wave. (d) an interaction allowing two orthogonally polarized fundamental waves to couple with an SH-wave. The PM or AM signal will in general induce both PM and AM onto the "pump" fundamental, potentially with "small-signal" gain and amplification. No 2ω-inputs are involved.

amplification" and/or effective gain. By a judicious choice of the parameters defining the cascaded interaction (i.e., phase mismatch, geometry and interaction length, effective nonlinear coefficients, seed power and phase, etc.) "digital" operations and switching can be obtained.

The simplest interaction involves one input beam at ω, with the geometry chosen for SHG to be near (but not *at*) the phase-matching condition. A *cw* wave will in general produce output waves at ω and 2ω, with phases and amplitudes depending upon the level of initial excitation and the length of the interaction region. Changes in input power will then map into amplitude and phase variations in the fundamental wave leaving the crystal (Fig. 1(a)). A certain amount of coherently injected signal at 2ω affects this process away from phase-matching, imposing phase and/or amplitude modulation on the *cw* ω-wave by virtue of phase or amplitude changes in the seeding input. The two inputs at ω and 2ω would then correspond to pump and control beams, with their electric fields co- or orthogonally-polarized, depending upon the specific effective susceptibility involved. "Small signal" gain can be obtained between input and output waves with different carrier frequencies (Fig. 1(b)). On phase-matching this process can lead to transistor-like gain for the fundamental as suggested by St. J. Russell [25]. Fig. 1(c) specializes the previous interaction to the phase-matched case, such that complete switching can be imposed on the output by an on/off amplitude modulation of the 2ω-seed of appropriate (constant) phase. Finally, in Fig. 1(d) we sketch an interaction involving two orthogonal input waves at ω, two ω-outputs and two effective nonlinear susceptibilities. In the case of a strong *cw* pump and a weak signal carrying the information, the latter will affect phase and amplitude of both outputs, with small signal gain and amplification at the expense of the pump wave. This is the prototype of an all-optical "common emitter" amplifier, with base and collector corresponding to *cw* and signal FF inputs, respectively.

In the following, after briefly reviewing the fundamentals of a cascaded second-order nonlinearity via SHG, we will numerically demonstrate the richness of this "coherent" second-order approach to optical signal processing with examples for each of the interactions mentioned above. Some of these results can also be obtained analytically, using the approach outlined in [24] and [26]. Our goal here is to discuss these phenomena and underline their main features in a qualitative fashion, leaving "in-depth" descriptions to further publications. In particular, we will restrict ourselves to *cw* waves, neglecting time dynamics, dispersion, and the occurrence of three-wave mixing interactions due to additional spectral components induced by the modulation.

Considering a lossless noncentrosymmetric medium with a dominant nonzero effective second-order susceptibility for Type I SHG (extension to Type II is straightforward, see [23]), a set of two coupled-mode equations is readily written describing the evolution of normalized complex slowly-varying wave-amplitudes at ω and 2ω with propagation distance:

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

where $\Delta\beta = \beta(2\omega) - 2\beta(\omega)$ is the wavevector mismatch, β is the propagation constants and $\kappa(-2\omega;\, \omega,\, \omega) = \kappa^{*}(-\omega;\, 2\omega,\, -\omega) = \kappa$ is the effective strength of the nonlinearity far from material resonances. For plane waves $\kappa = 2\omega d_{\mathrm{eff}}^{(2)}/[2n^{2}(\omega)n(2\omega)\varepsilon_0 c^3]^{1/2}$, with the amplitudes in (1) normalized so that their square moduli $|a|^2$ express intensities. In the case of guided wave interactions in channel waveguides with propagation along z, $|a|^2$ are normalized to powers and the coefficient κ includes a spatial integral over the product of the modal transverse profiles $E_{\omega}(x,\, y)E_{\omega}(x,\, y)E_{2\omega}^{*}(x,\, y)$. The geometry of the interaction is included in d_{eff} and n refers to the refractive index.

Equations (1) describe standard second-harmonic generation when the initial conditions are set with a zero 2ω-amplitude at $z = 0$, and admit exact solutions in terms of Jacobi elliptic functions [24], [26]. Maximum conversion efficiency is attained for $\Delta\beta = 0$, i.e., when the wavefronts at the two frequencies travel at the same velocity along z. Otherwise, if synchronism is lacking (i.e., $\Delta\beta \neq 0$), the nonlinear polarization sources leading to (1) will no longer be in perfect

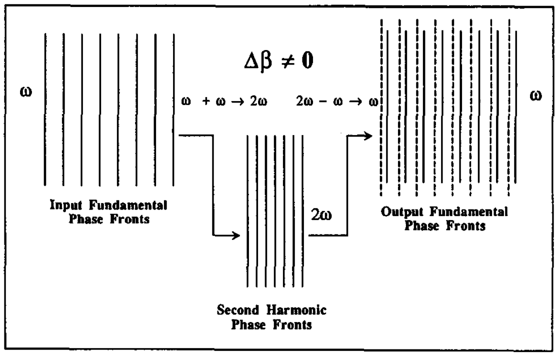


Fig. 2. Sketch of the cascaded nonlinear interaction. It involves up-conversion from ω to 2ω and down-conversion from 2ω to ω with nonzero wavevector mismatch. The phasefronts travel at different velocities at ω and 2ω, and the relative phase accumulated by the phasefronts upon down-conversion causes a net nonlinear phase-shift in the ω-output.

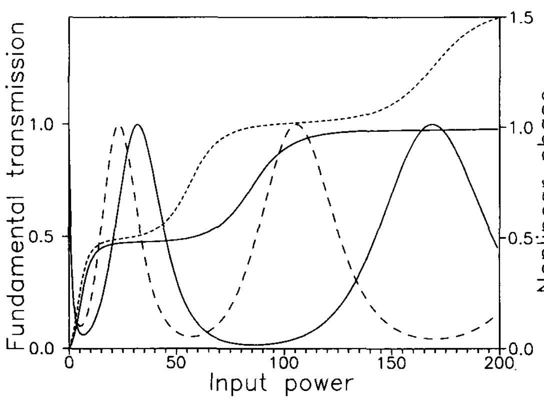


Fig. 3. Fundamental transmission and nonlinear phase (units of π) versus input excitation at ω, for $\kappa L = 1$ and $\Delta\beta L = 0.1\pi$, without (solid lines) and with 0.1% seeding at 2ω (dashed lines). The seed relative phase $\Delta\phi$ is π.

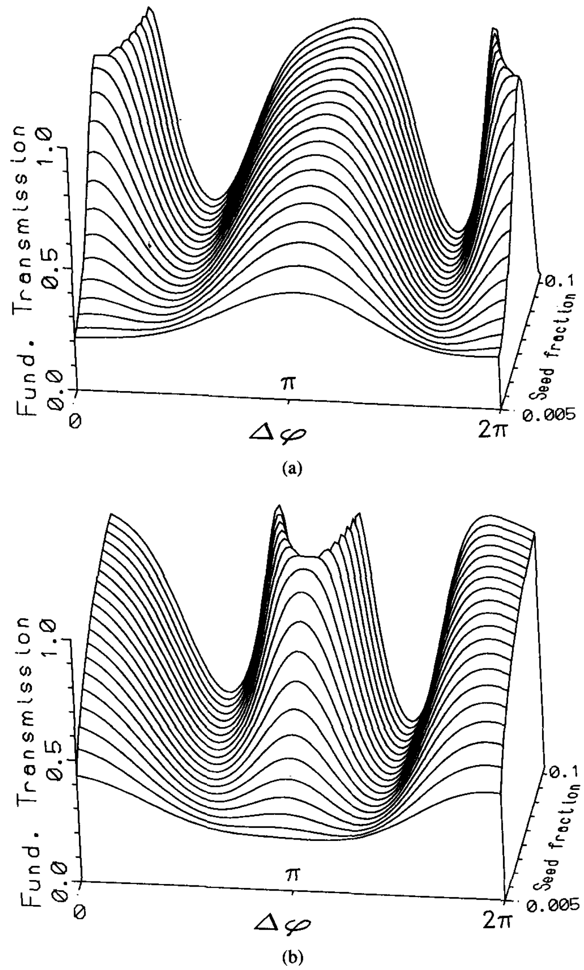


Fig. 4. Fundamental throughput in a 2ω-seeded interaction versus relative phase $\Delta\phi$ and seeding fraction, for $\kappa L = 1$ and $|a_\omega(0)|^2 = 25$, with (a) $\Delta\beta L = \pi$ and (b) $\Delta\beta L = -\pi$.

quadrature with the fields, leading to destructive interference in the growth of the SH wave. As a result, the second harmonic converts back into the fundamental (down conversion). Because the phase velocities of the fundamental and the harmonic are unequal, the downconverted photons returning to the fundamental are out of phase with the fundamental beam and hence retard or advance its phase, depending on the sign of $\Delta\beta$. Note that the propagation aspect of this phenomenon makes it nonlocal. It leads to the accumulation of nonlinear phase in the fundamental frequency wave. This mechanism is sketched in Fig. 2, showing by dashed lines the FF phasefronts after up- and down-conversion through the $(\omega + \omega \rightarrow 2\omega) + (2\omega - \omega \rightarrow \omega)$ cascade process. The total phase of the fundamental field is shifted, retarded in the case shown. Thus terminating the interaction at $z = L$ such that the total energy has been reconverted back into the fundamental, the nonlinearity will simply contribute an intensity-dependent phase to the input wave, resembling the optical Kerr effect (i.e., self-phase modulation) due to a third-order susceptibility. This phenomenon is generally referred to as a "cascaded nonlinear effect," since it can be envisioned as the cascading of two three-wave interactions utilizing $\chi^{(2)}(-2\omega;\, \omega, \omega)$ and $\chi^{(2)}(-\omega;\, 2\omega, -\omega)$ for up- and down-conversion of the fundamental, respectively.

The cascaded nonlinearity, although it does not rely on any changes in the refractive index, under the appropriate conditions can provide a pure nonlinear phase change without amplitude modulation. For this reason it has attracted a great deal of interest for prospective applications in all-optical switching devices, which require a large nonlinear phase change upon propagation [13]–[16]. The following are among the most relevant features of the cascaded $\chi^{(2)}$ nonlinearity [12]:

1) the nonlinear phase $\Phi_\omega^{NL}(|a_\omega|)$ grows stepwise with propagation distance and input excitation, exhibiting regions of constant value (plateaus) for small phase-mismatch;
2) the amplitude of the fundamental wave oscillates with both z and excitation, the smaller the mismatch $\Delta\beta$ the deeper the modulation. This behaviour is, however, periodic with distance and unity transmission can be restored by appropriate choice of crystal length L and/or input level;

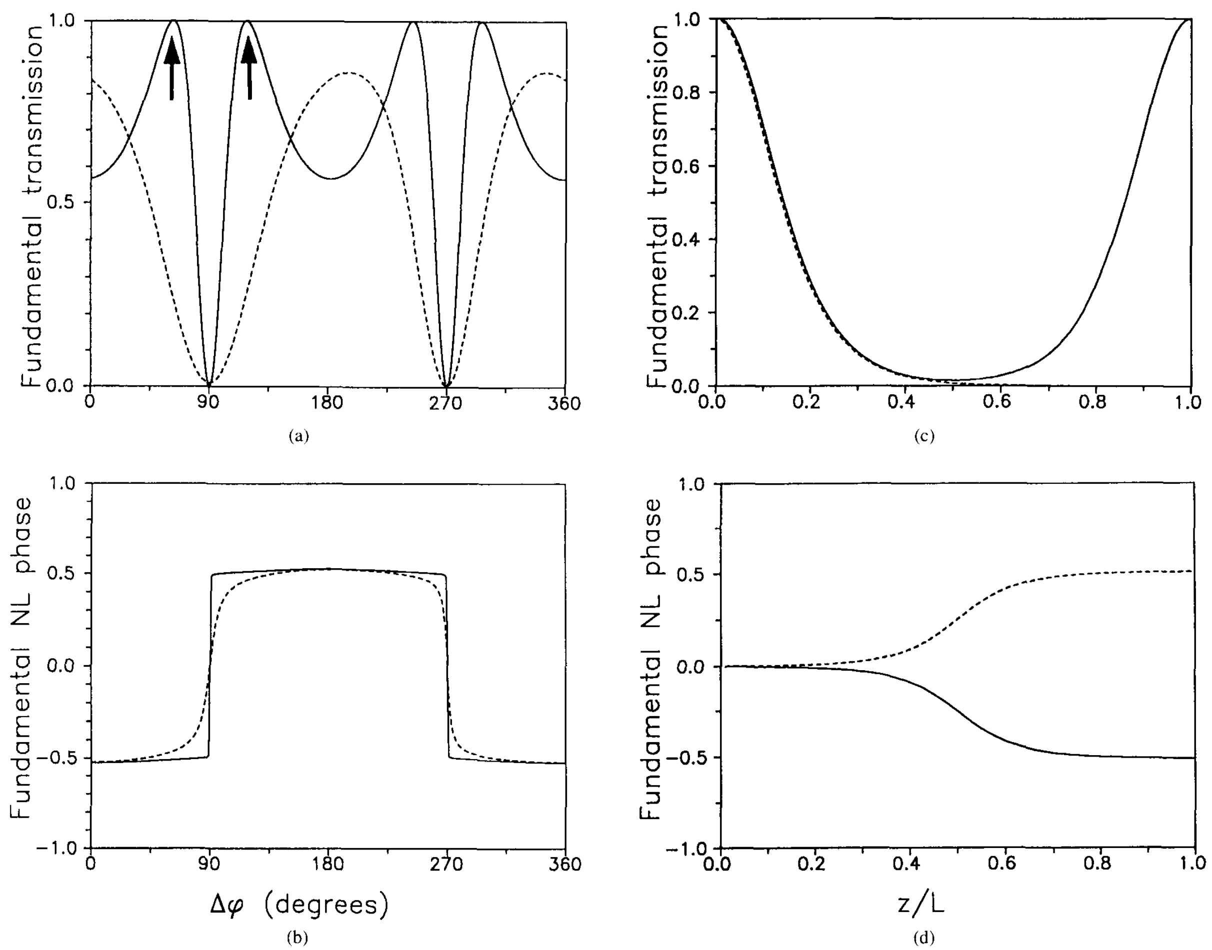


Fig. 5. 2ω-seeded interaction under wavevector matching conditions. Here $|a_\omega(0)|^2 = 10, \kappa L = 2, \Delta\beta L = 0$ and the seed fraction is 0.1% for (a)→ (d). The dashed lines in (a) and (b) refer to $\kappa L = 1$, $|a_\omega(0)|^2 = 10$, $\Delta\beta L = 0$ and the seed fraction is 5%. (a) Fundamental throughput and (b) nonlinear phase (units of π) versus $\Delta\phi$. (c) Fundamental transmission and (d) nonlinear phase versus normalized propagation distance for $\Delta\phi = 62°$ (solid line) and $\Delta\phi = 118°$ (dashed line in (d)), corresponding to the two values indicated by arrows in (a). In (c), the dashed line represents the fundamental transmission without any seed.

3) the nonlinear phase shift is positive or negative depending upon the sign of the linear wavevector mismatch. Both self-focussing and -defocussing can be emulated by proper relative orientation of electric field and crystal axes, without any actual modifications in the refractive indices.

The interaction described above is of a coherent nature, and this can be exploited in controlling its outcome with the phase and/or amplitude of an injected weak signal (*control* beam). This concept is a familiar one in the area of parametric conversion [27]. Specifically, it is instructive to consider the effects of a weak second-harmonic signal injected at the input together with the fundamental for a given relative phase $\Delta\phi$ between them [11], [13], [28]. In general, the linear polarization source associated with this additional 2ω-wave at $z = 0$ need not be aligned with the nonlinear polarization normally obtained for $a_{2\omega}(0) = 0$, and the two waves will end up exchanging energy with propagation, the details depending upon their initial phases. In fact, varying this relative phase (i.e., phase modulation) leads to dramatic changes in the fundamental output. Fig. 3 shows examples of the throughput and nonlinear phase of a fundamental frequency wave due to cascading without (solid lines) and with the injection of a weaker (1000 times smaller than the fundamental) 2ω-seed with a relative phase $\Delta\phi = \pi$. The plots elucidate the first two features listed above. Notice the variations in both output power and phase induced by the control wave. While an evolution similar to the case $a_{2\omega}(0) = 0$ (solid lines) is to be expected for $\Delta\phi = \pm\pi/2$, a nonlinear phase will be accumulated in the fundamental, even for the wavevector-matched case, provided the initial 2ω-seed induces a phase rotation in the field radiated into the fundamental by the nonlinear polarization driven dipole array (2nd equation in (1)). That is, in the presence of seeding, a nonlinear phase shift can also occur in the phase-matched case.

Controlling the outcome of the interaction with a weak coherent wave introduces extra degrees of freedom and flexibility in exploiting the effects of a cascaded nonlinearity. What we suggest is more general than the proposed use of the eigenmodes of the nonlinear system, for example, where a large 2ω-amplitude is injected at the entrance face and propagates without a net exchange of energy with the fundamental [29], [30]. Fig. 4(a)–(b) show two examples of the amplitude modulation which one can impress onto the fundamental simply by phase modulating the 2ω-seed. The curves are plotted (for opposite wavevector mismatches in (a) and (b)) versus $\Delta\phi$ and for increasing fractions of seed-input in order to emphasize how both the amplitude and phase of the seed affect the ω-wave. These particular examples demonstrate the transposition of PM into AM and AM–AM transfer between the two beams via a wavevector-mismatched interaction. For larger seeding fractions the curves exhibit an asymmetry with respect to $\Delta\phi = \pi$, especially in the case b) where the mismatch has a negative sign. This is in agreement with our description of the process based on vectorial addition of field components. Due to the large AM possible on the fundamental, the AM–AM transfer is reminiscent of transistor action with "small signal" amplification between the two frequencies, although the use of phase control seems more appealing in terms of its experimental implementation. This latter case has been recently demonstrated in a KTP crystal at $\lambda = 1.064$ μm, with 4.6:1 modulation depth of the FF fluence [28].

More dramatic features, i.e., larger changes in output for small input changes in the relative phase, are present for a wavevector-matched interaction, when complete (or substantial) up-conversion occurs. Fig. 5(a)–(b) shows examples of the throughput and phase of a fundamental wave under wavevector-matching conditions versus relative phase $\Delta\phi$ for two different conditions. For a large enough nonlinearity* length product, almost complete conversion is achieved into the 2ω-beam when the phase is $\pm\pi/2$ (solid line) and, more importantly, a digital-like change occurs in the phase of the ω-signal when $\Delta\phi$ is changed (Fig. 5(b)). Such an abrupt phase variation at the output is simply the outcome of different phase evolutions during propagation, as demonstrated for two specific $\Delta\phi$ values in Fig. 5(c)–(d). The two values for $\Delta\phi$ are indicated by arrows in Fig. 5(a), and were selected in order to obtain unity transmission of the fundamental, with nonlinear phase shifts differing by π. Furthermore, as shown by the dashed lines in Fig. 5(a)–(b) for a different set of conditions, this does not correspond simply to a change in sign of the fundamental amplitude as it passes nearly through zero. The initial position of the seeding phasor in the complex plane determines the rotation direction of the ω-phasor. Larger nonlinear coefficients and/or input excitations introduce extra features, with the appearance of additional zeros in the throughput at ω and additional variations in the phase after/before the abrupt π changes visible in Fig. 5(b) or 5(d). Although a phase-matched interaction may not be easily realizable in practice, quasi-phase-matched geometries could allow for the implementation of these effects. It is worth emphasizing that, for the κL values used, the absence of a seeding input at 2ω would lead to complete depletion of the fundamental (dashed line in Fig. 5(c)), i.e., complete *digital* on/off switching could be achieved on the ω-wave by switching on and off the weak coherent beam at 2ω.

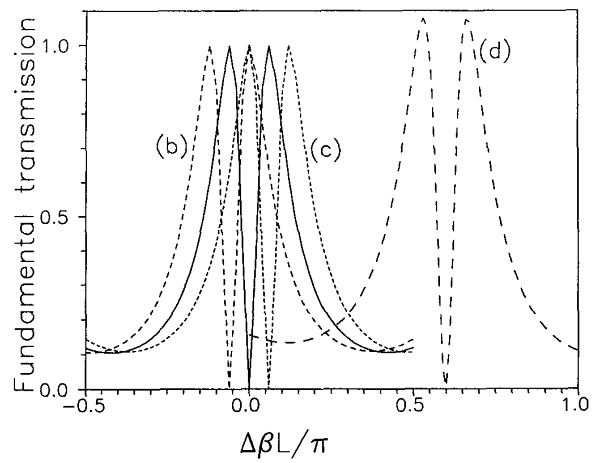


Fig. 6. 2ω-seeded interaction versus initial wavevector mismatch $\Delta\beta L$. Parameters are the same as in Fig. 4, with (a) no seed (solid line), (b) 0.1% seed with $\Delta\phi = 118°$, (c) 0.1% seed with $\Delta\phi = 62°$, (d) 10% seed with $\Delta\phi = 62°$.

More insight in the effect of a coherent seed can be gained by considering the spectral response of the SHG process, i.e., the fundamental throughput versus cumulative phase detuning $\Delta\beta L$. Whenever $\Delta\phi = \pm\pi/2$, the central dip (maximum depletion or up-conversion efficiency) gets shifted from the phase-matching condition $\Delta\beta L = 0$, the shift depending on the relative phase $\Delta\phi$. Varying $\Delta\phi$ can impose a large modulation or switching onto the fundamental throughput for a particular $\Delta\beta$. This is demonstrated numerically in Fig. 6 for $\kappa L = 2$ and a 0.1% seed. Notice also that the larger the intensity or equivalently the nonlinearity, the more dramatic the effect due to a reduction in the bandwidth of the SHG process. Finally, as expected, larger seeding fractions produce larger effects on the fundamental via larger spectral detuning (Fig. 6, curve d).

Another important possibility for coherently controlling the fundamental wave in a cascaded interaction is offered by exploiting the tensorial nature of the susceptibility $\chi^{(2)}$. In general, due to the structure of the tensor it is possible that orthogonal polarization components at ω will interact with the same 2ω-eigenmode. In particular, in order to illustrate this concept, we consider two scalar type I SHG interactions as described by (1), allowing two orthogonally-polarized electric fields at ω (or two orthogonal modes in a guided-wave structure) to be coupled to the same 2ω-eigenwave. Notice that this is quite different from a type II SHG interaction (such as considered in [20]), where a tensorial product mixes an equal number of photons from the two fundamental wave-components to generate 2ω-photons. Here we simply consider 2ω-photons coupled to different polarization components at ω, letting the same 2ω-wave exchange energy with the two fundamental eigenmodes each of which is independently close to phase-match. This could be accomplished, for instance, by employing a combination of quasi-phase-matching (in order to utilize a diagonal $\chi^{(2)}$ component) and birefringence or temperature tuning. In this case, then, the two fundamental waves can be regarded as pump and signal or probe, since

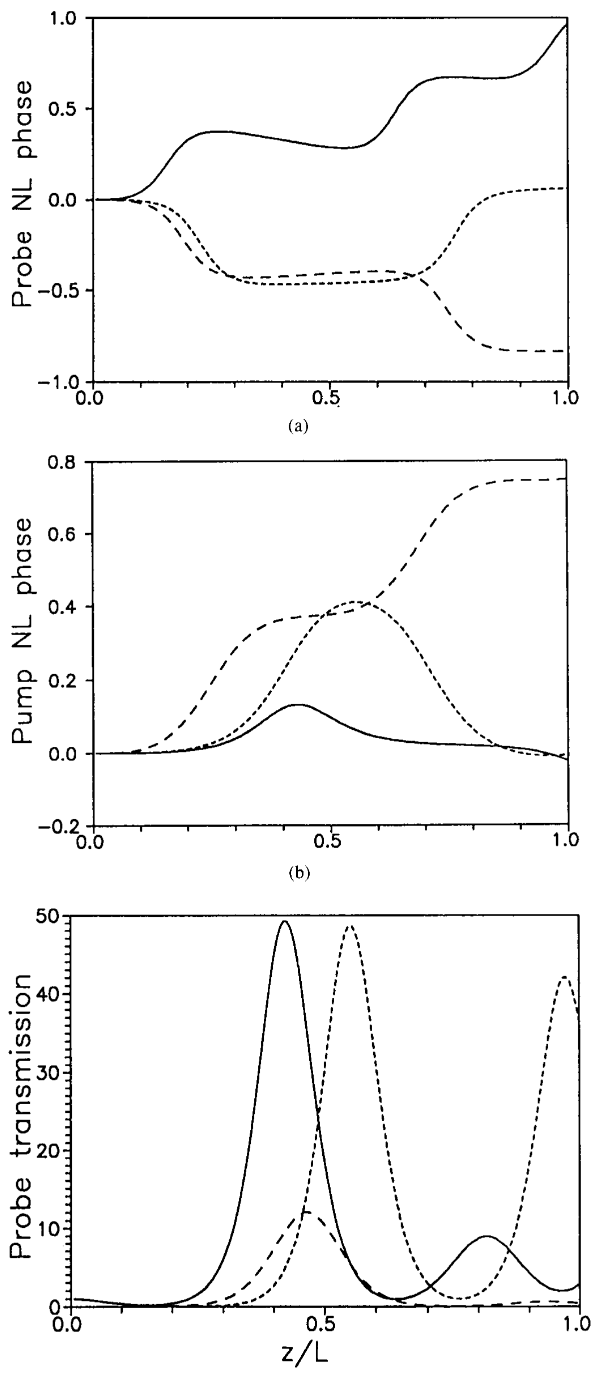


Fig. 7. Coherent interaction in the presence of an additional weak ω-wave. (a) Probe and (b) pump nonlinear phases (units of π) and (c) probe throughput versus normalized propagation distance for $|a_1(0)|^2 = 50$ (pump), $|a_2(0)|^2 = 1$, $\kappa_1 L = 1$, $\kappa_2 L = 2$, with $\Delta\beta_1 L = 0.1\pi$ and $\Delta\beta_2 L = \pi$ (solid lines), $\Delta\beta_1 L = 0.1\pi$ and $\Delta\beta_2 L = -0.1\pi$ (short dashes), $\Delta\beta_1 L = \pi$ and $\Delta\beta_2 L = 0.1\pi$ (long dashes).

they need not carry the same power. Because of coupling to the same 2ω-eigensolution, however, they are able to exchange energy and affect each other's phases.

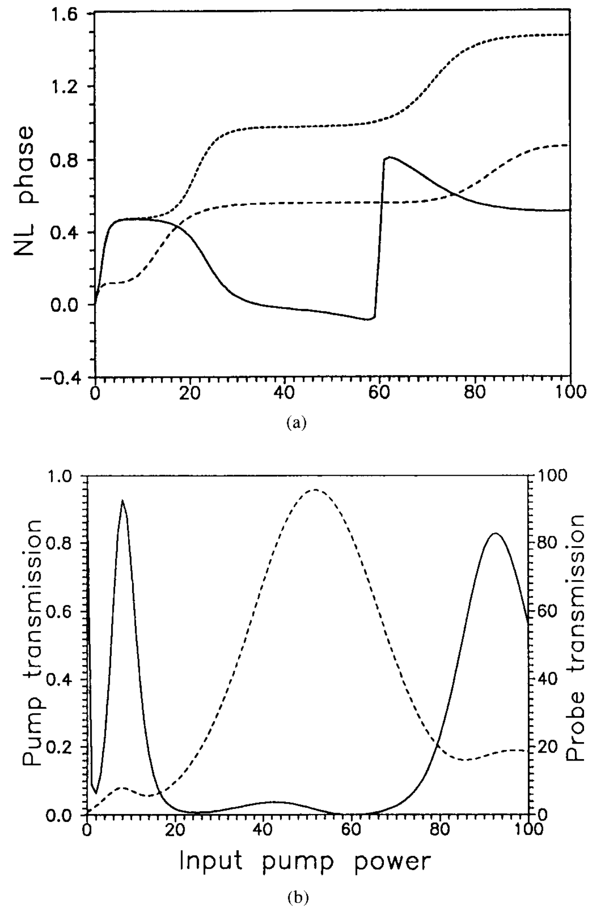


Fig. 8. Coherent interaction in the presence of an additional weak ω-wave. a) Nonlinear phases (units of π) and b) transmissions of pump (solid lines) and probe (dashed lines) versus $|a_1(0)|^2$ for $\kappa_1 L = 2$, $\kappa_2 L = 1$, $\Delta\beta_1 L = 0.1\pi$, $\Delta\beta_2 L = \pi$ and $|a_1(0)|^2/|a_2(0)|^2 = 100$. In a) the short dashes refer to the standard single input cascaded case ($|a_2(0)|^2 = 0$).

Using subscripts 1 and 2 for the two FF waves, and 3 for the field at 2ω, a set of three coupled equations similar to (1) is readily reduced to:

$$\frac{d|a_1|^2}{dz} = -2\kappa_1 |a_3|\, |a_1^2 \sin(2\phi_1 - \phi_3 + \Delta\beta_1 z)$$

$$\frac{d|a_2|^2}{dz} = -2\kappa_2 |a_3|\, |a_2|^2 \sin(2\phi_2 - \phi_3 + \Delta\beta_2 z) \qquad (2)$$

for the fundamental intensities/powers, having defined κ_1 and κ_2 as proportional to the two relevant effective $\chi^{(2)}$ components and $\Delta\beta_1$ and $\Delta\beta_2$ as the wavevector-mismatches. The z-dependence has been dropped for notational convenience.

This nonlinear system has a larger number of degrees of freedom, and is nonintegrable, and its exact analysis is therefore more difficult than in the previous case [31]. Here we want to focus on the potential for phase and amplitude control of one beam by the other, i.e., transfer of information and/or energy from pump to signal or vice versa. To that extent we

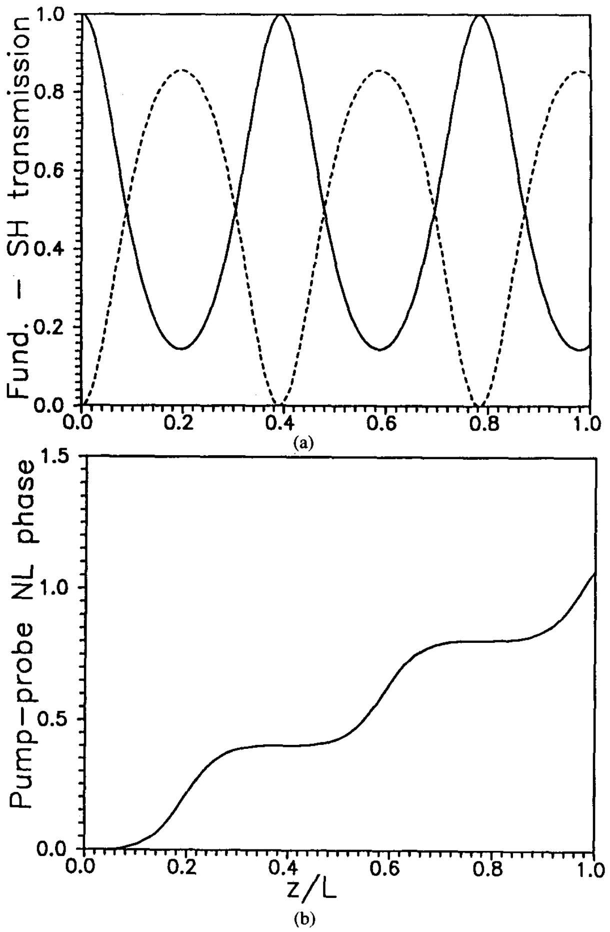


Fig. 9. (a) Nonlinear phases (units of π) of the fundamentals and (b) normalized transmission of the two fundamentals (solid line) and of the second-harmonic wave (dashed line) versus propagation distance for $\kappa_1 L = \kappa_2 L = 1$ and $\Delta\beta_1 = \Delta\beta_2 = \pi/L$. It is $|a_1(0)|^2/|a_2(0)|^2 = 100$.

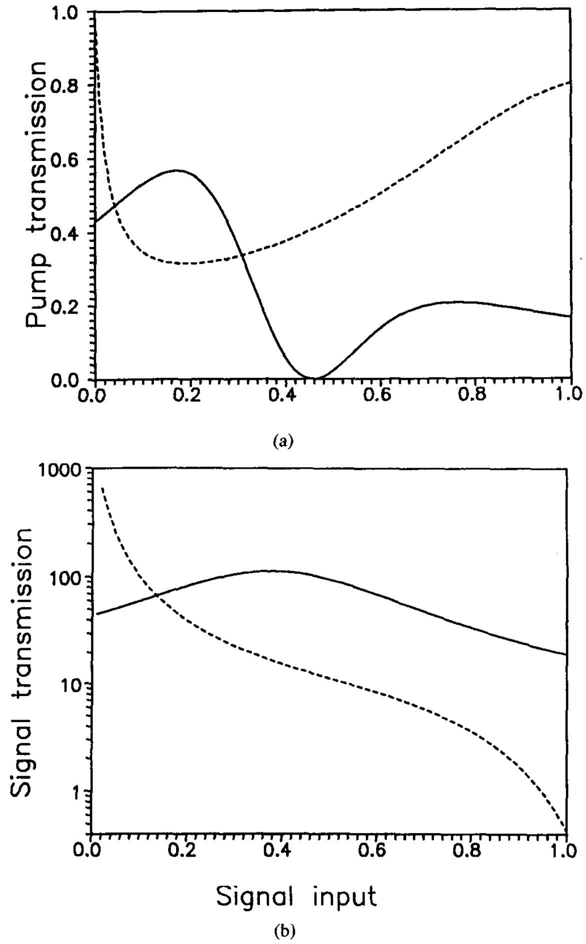


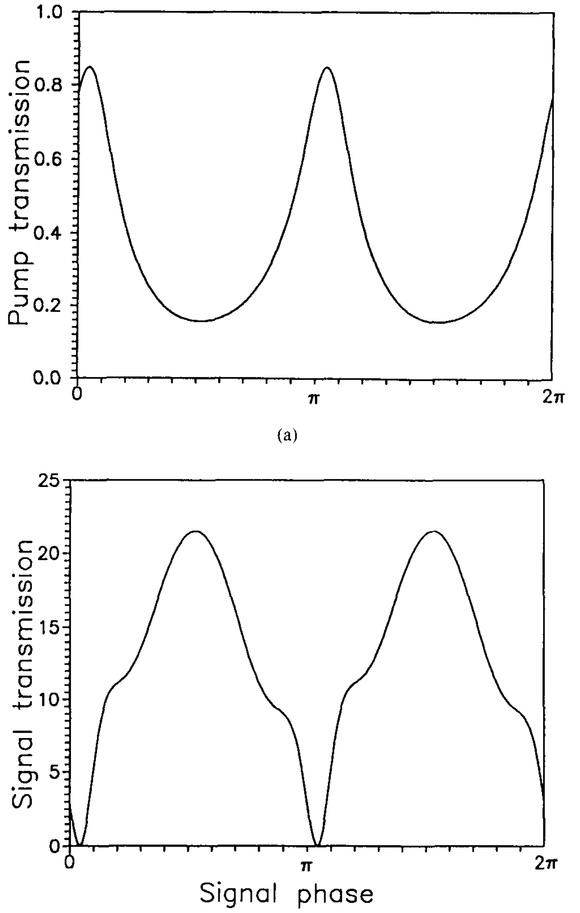
Fig. 10. All-optical transistor operation. (a) Pump and (b) signal throughputs versus $|a_2(0)|^2$ normalized to their initial values, for $\kappa_1 L = 2$, $\kappa_2 L = 1$, $\Delta\beta_1 L = 0.1\pi$, $\Delta\beta_2 L = \pi$ (solid lines) and for $\kappa_1 L = 1$, $\kappa_2 L = 2$, $\Delta\beta_1 L = \pi$, $\Delta\beta_2 L = 0.1\pi$ (dashed lines). Here $|a_1(0)|^2 = 50$.

will show some interesting features which occur for specific values of the parameters, referring the interested reader to a more comprehensive treatment to appear elsewhere for a more detailed analysis [32].

Fig. 7 shows some examples of energy transfer between the two fundamental beams versus propagation distance, assuming an intensity ratio of 50:1, $\kappa_2 L = 2\kappa_1 L = 2$ and various detunings $\Delta\beta_1$ and $\Delta\beta_2$ (see caption). Graphed in Fig. 7(c) is the probe throughput normalized to its initial value at $z = 0$. A substantial transfer of power takes place versus z, with the weak beam being amplified up to the level of the pump. Fig. 7(a) and (b) show the nonlinear phases vs z in both FF waves. The energy transfer from pump to second harmonic to probe imprints different signatures onto the phase evolution for differing initial wavevector mismatches.

Figs. 8 and 9 demonstrate the energy transfer between pump and probe versus excitation intensity for two different conditions. In Fig. 8, a fixed ratio of 100:1 is assumed between the inputs at the entrance face of the crystal, $\kappa_1 L = 2\kappa_2 L = 2$ and $\Delta\beta_2 L = 10\Delta\beta_1 L = \pi$. Large gain and a substantial modification of the phase evolution indicate an efficient cross-coupling between the two ω-waves. Another case is that of identical nonlinear coefficients and wavevector-mismatches for the two input beams, as pictured in Fig. 9 for $\kappa_1 L = \kappa_2 L = 1$ and $\Delta\beta_1 = \Delta\beta_2 = \pi/L$. The two fundamental components undergo periodic amplitude evolution without exchanging energy, i.e., coupling only to the same SH wave. This is accomplished because their phases are effectively locked together during propagation. Since the interaction is driven by the wave carrying the largest energy, this particular operation corresponds to imposing phase information onto the probe in the orthogonal polarization by means of the cascaded nonlinearity, and is reminiscent of the phase locking obtainable using the nonlinear eigenmodes of the system [29], [30].

Finally, phase or amplitude modulation of the fundamental signal wave can be imparted to the orthogonally polarized *cw* fundamental pump. This is shown in Fig. 10, where the magnitude of the signal in phase with the pump is varied for two sets of nonlinear coefficients and wavevector-mismatches, $\kappa_1 L = 2\kappa_2 L = 2$ with $\Delta\beta_2 L = 10\Delta\beta_1 L = \pi$ and



(b)

Fig. 11. All-optical transistor operation. (a) Pump and (b) signal transmission versus initial phase of the weak input at ω. Here $\kappa_1 L = 1$, $\kappa_2 L = 2$, $\Delta\beta_1 L = \pi$, $\Delta\beta_2 L = 0.1\pi$, $|a_1(0)|^2 = 50$ and $|a_2(0)|^2 = 0.1$.

$\kappa_2 L = 2\kappa_1 L = 2$ with $\Delta\beta_1 L = 10\Delta\beta_2 L = \pi$, respectively. It is important to emphasize the degree of pump-AM achieved in Fig. 10(b), along with regions of good linearity for "small signal" operation. Transistor action is obtained at the same optical carrier frequencies in input and output for signals dc-biased about either zero (dashed line, Fig. 10(b)) or finite input powers (i.e., ac modulated with an average value well above zero, 0.3 for the solid line curve in Fig. 10(b)). Actual energy transfer towards the weak input is accomplished as well, as can be seen in Fig. 10(a). By keeping the relative intensities (powers) fixed, substantial AM can be imposed on the pump by simply varying the initial phase of the probe, as plotted in Fig. 11(b) for $\kappa_2 L = 2\kappa_1 L = 2$ and $\Delta\beta_1 L = 10\Delta\beta_2 L = \pi$. Even in this case the signal undergoes substantial amplification (Fig. 11(a)).

In conclusion, we have indicated a number of possibilities offered by coherent effects in cascaded second-order interactions involving up- and down-conversion of an input wave to and from its second harmonic. Although the number of parameters involved makes a comprehensive description of these phenomena, difficult specific, all-optical operations can be accomplished by carefully choosing relative field-crystal orientations and initial excitation conditions. Phase and amplitude control and switching can be obtained by seeding the interaction at the input with a weak signal at 2ω, and true transistor operation by employing orthogonal waves at the same frequency and coupling them via a cascaded interaction with the same second harmonic wave.

References

[1] H. Gibbs, *Optical Bistability: Controlling Light with Light.* Orlando, FL: Academic, 1985.

[2] G. I. Stegeman and E. M. Wright, "All-optical waveguide switching," *Opt. Quantum Electron.*, vol. 22, pp. 95–122, 1990.

[3] G. Assanto, "Third-order nonlinear integrated devices," in *Guided Wave Nonlinear Optics*, D. B. Ostrowsky and R. Reinisch, Eds. The Netherlands: Kluwer Academic (NATO Advance Study Institute), 1992, pp. 257–284.

[4] J.-M. R. Thomas and J.-P. E. Taran, "Pulse distortions in mismatched second-harmonic generation," *Opt. Commun.*, vol. 4, pp. 329–334, 1972.

[5] E. Yablonovitch, C. Flytzanis, and N. Bloembergen, "Anisotropic interference of three-wave and double two-wave frequency mixing in GaAs," *Phys. Rev. Lett.*, vol. 29, pp. 865–868, 1972.

[6] D. N. Klyshko and B. F. Polkovnihov, "Phase modulation and self-modulation of light in three-photon processes," *Sov. J. Quantum Electron.*, vol. 3, pp. 324–326, 1972.

[7] N. R. Belashenkov, S. V. Gagarskii, and M. V. Inochkin, "Nonlinear refraction of light on second-harmonic generation," *Opt. Spectrosc.*, vol. 66, pp. 806–808, 1989.

[8] H. J. Bakker, P. C. M. Planken, L. Kuipers, and A. Lagendijk, "Phase modulation in second-order nonlinear-optical processes," *Phys. Rev. A*, vol. 42, pp. 4085–4100, 1990.

[9] G. R. Meredith, "Second-order cascading in third-order nonlinear optical processes," *J. Chem. Phys.*, vol. 77, pp. 5863–5871, 1982.

[10] Chr. Flytzanis and N. Bloembergen, "Infrared dispersion of third-order susceptibilities in dielectrics: retardation effects," *Quantum Electron.*, vol. QE-4, pp. 271–300, 1976.

[11] G. Assanto, G. I. Stegeman, M. Sheik-Bahae, and E. Van Stryland, "A novel approach to all-optical switching based on second-order nonlinearities," in *Proc. Nonlinear Optics: Materials, Fundamentals, and Applications*, Lahaina, Maui, HI, paper PD11, Aug. 1992, pp. 1–4.

[12] G. I. Stegeman, M. Sheik-Bahae, E. Van Stryland, and G. Assanto, "Large nonlinear phase-shifts in second-order nonlinear-optical processes," *Opt. Lett.*, vol. 18, pp. 13–15, 1993.

[13] G. Assanto, G. I. Stegeman, M. Sheik-Bahae, and E. Van Stryland, "All-optical switching devices based on large nonlinear phase shifts from second harmonic generation," *Appl. Phys. Lett.*, vol. 62, pp. 1323–1325, 1993.

[14] R. Schiek, "All-optical switching in the directional coupler caused by nonlinear refraction due to cascaded second-order nonlinearity," *Opt. Quantum Electron.*, vol. 26, pp. 415–431, 1994.

[15] G. Assanto, A. Laureti-Palma, C. Sibilia, and M. Bertolotti, "All-optical switch based on second harmonic generation in a nonlinearly asymmetric directional coupler," *Opt. Commun.*, vol. 110, pp. 599–603, 1994.

[16] R. Schiek, "Nonlinear refraction caused by cascaded second-order nonlinearity in optical waveguide structures," *J. Opt. Soc. Am.*, vol. B 10, pp. 1848–1854, 1993.

[17] R. DeSalvo, D. J. Hagan, M. Sheik-Bahae, G. Stegeman, and E. W. Van Stryland, "Self-focusing and self-defocusing by cascaded second-order effects in KTP," *Opt. Lett.*, vol. 17, pp. 28–30, 1992.

[18] M. I. Sundheimer, Ch. Bosshard, E. W. Van Stryland, G. I. Stegeman, and J. D. Bierlein, "Large nonlinear phase modulation in Quasi-phasematched KTP waveguides due to cascaded second-order processes," *Opt. Lett.*, vol. 18, pp. 1397–1399, 1993.

[19] D. Y. Kim, W. E. Torruellas, J. Kang, C. Bosshard, G. I. Stegeman, P. Vidakovic, J. Zyss, W. E. Moerner, R. Twieg, and G. Bjorklund, "Second-order cascading as the origin of large third-order effects in organic single-crystal-core fibers," *Opt. Lett.*, vol. 19, pp. 868–870, 1994.

[20] D. Hutchings, J. S. Aitchison, and C. N. Ironside, "All-optical switching based on nondegenerate phase shifts from a cascaded second-order nonlinearity," *Opt. Lett.*, vol. 18, pp. 793–795, 1993.

[21] S. Nitti, H. M. Tan, G. P. Banfi, and V. Degiorgio, "Induced 'third-order' nonlinearity via cascaded second-order effects in organic crystals of MBA-NP," *Optics Commun.*, vol. 106, pp. 263–268, 1994.

[22] H. Tan, G. P. Banfi, and A. Tomaselli, "Optical frequency mixing through cascaded second-order processes in β-barium borate," *Appl. Phys. Lett.*, vol. 63, pp. 2472–2474, 1993.

[23] A. L. Belostotsky, A. S. Leonov, and A. V. Meleshko, "Nonlinear phase change in type II second-harmonic generation under exact phase-matched conditions," *Opt. Lett.*, vol. 19, pp. 856–868, 1994.

[24] J. A. Armstrong, N. Bloembergen, J. Ducuing, and P. S. Pershan, "Interaction between light waves in a nonlinear dielectric," *Phys. Rev.*, vol. 127, pp. 1918–1939, 1962.

[25] P. St. J. Russell, "All-optical high gain transistor action using second-order nonlinearities," *Electron. Lett.*, vol. 29, pp. 1228–1229, 1993.

[26] P. St. J. Russell, "Theoretical study of parametric frequency and wave-front conversion in nonlinear holograms," *IEEE J. Quantum Electron.*, vol. 27, pp. 830–835, 1991.

[27] R. A. Baumgartner and R. L. Byer, "Optical parametric amplification," *IEEE J. Quantum Electron.*, vol. QE-15, pp. 432–444, 1979.

[28] D. J. Hagan, M. Sheik-Bahae, Z. Wang, G. Stegeman, E. W. Van Stryland, and G. Assanto, "Phase controlled transistor action by cascading of second-order nonlinearities in KTP," *Opt. Lett.*, vol. 19, 1305–1307, 1994.

[29] S. Trillo, S. Wabnitz, R. Chisari, and G. Cappellini, "Two-wave mixing in a quadratic nonlinear medium: bifurcations, spatial instabilities, and chaos," *Opt. Lett.*, vol. 17, pp. 637–639, 1992.

[30] A. E. Kaplan, "Eigenmodes of $\chi^{(2)}$ wave mixings: Cross-induced second-order nonlinear refraction," *Opt. Lett.*, vol. 18, pp. 1223–1225, 1993.

[31] S. Trillo and G. Assanto, "Polarization spatial chaos in second harmonic generation," *Opt. Lett.*, vol. 19, pp. 1825–1827, 1994.

[32] G. Assanto, I. Torelli, and S. Trillo, "All-optical processing by means of vectorial interactions in second-order cascading: Novel approaches," *Opt. Lett.*, vol. 19, pp. 1720–1722, 1994.

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