Phase-controlled transistor action by cascading of second-order nonlinearities in KTP

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Received March 21, 1994

We demonstrate a 4.6-to-1 modulation depth imposed on the fluence of an intense 1.06-μm picosecond pulse by varying the relative phase of a weak second-harmonic control pulse under near phase-matched conditions. This transistorlike action is based on quadratic nonlinearities in KTP.

One of the key features of electronics is that complex amplitude, including phase, can be preserved, modulated, amplified, and recovered during signal processing. Since the first research on optical bistability, the nonlinear-optics community has been trying to develop such transistor operation for optical beams by using an intensity-dependent refractive index.[1] This search has placed emphasis on using intensity as a control variable, omitting the opportunity for utilizing the optical phase. A totally different approach is to use second-order nonlinear processes such as second-harmonic generation (SHG) or parametric generation. These interactions are coherent; therefore both amplitude and phase of the fundamental and the second harmonic (when the SHG process is seeded) determine the output signal. As an initial step, nonlinear phase shifts (both + and −) in the fundamental beam were recently demonstrated by use of the Z scan in bulk second-harmonic-active media[2] and by self-phase modulation[3] in quasi-phase-matched waveguide media, all in agreement with theoretical predictions. It has also been pointed out theoretically that all-optical self-switching is possible by use of SHG.[4,5] Furthermore, numerical studies show that if a weak second-harmonic (SH) beam is also input, both the amplitude and the phase of the fundamental output can be controlled with the phase and/or amplitude of the seed, leading to new applications to switching devices,[4] including small-signal gain and transistor action.[6,7]

In this Letter we report what is to our knowledge the first experimental demonstration of the modulation of the fundamental beam achieved by varying the phase of a weak SH beam relative to the phase of the fundamental, another step toward developing an all-optical transistor. Specifically, using KTP crystal as the nonlinear medium, we achieve a 4.6-to-1 switching ratio for a 1.06-μm fundamental by modulating the relative input phase of the 0.53-μm control beam having 1.2% of the fundamental energy (3.4% of the fundamental peak irradiance).

The equations that describe the above effects are the same as those for SHG:

$$\frac{dE_2}{dz} = -\frac{i2\omega}{4cn_{2\omega}}\chi^{(2)}(2\omega;\omega,\omega)E_1{}^2\exp(i\Delta kz), \tag{1}$$

$$\frac{dE_1}{dz} = -\frac{i\omega}{4cn_{\omega}}\chi^{(2)}(\omega;2\omega,\omega)E_2E_1^*\exp(-\Delta kz), \tag{2}$$

where E_1 and E_2 are the complex field amplitudes of the fundamental and the SH, respectively, which can be expressed in terms of slowly varying amplitude and phase as $E_j = A_j\exp(i\phi_j)$. Δk is the wave vector mismatch, n_ω and $n_{2\omega}$ are the index of refraction at the fundamental and the SH, respectively, c is the speed of light, and z is the depth of propagation through the nonlinear material. MKS units are used throughout. From the Manley–Rowe equations, $\chi^{(2)}(\omega;2\omega,-\omega) = 2\chi^{(2)}(2\omega;\omega,\omega)$.[8] For simplicity, we define the relative phase of the SH and fundamental waves as $\Delta\phi = \phi_{2\omega} - 2\phi_\omega$. Hence we define the SH seed wave in terms of the initial relative phase, $\Delta\phi_0$, and its irradiance (usually expressed as a fraction of the input fundamental irradiance).

In the absence of a seed and for $\Delta k = 0$, the emerging SH wave propagates with a constant relative phase of $\Delta\phi = \pi/2$. Therefore injection of a weak seed with $\Delta\phi_0 = \pi/2$ will cause a minimal change in the conversion efficiency. For other values of $\Delta\phi_0$ the initial phase of the seed mimics a phase mismatch, and solutions to Eqs. (1) and (2) reveal that large changes in the output conversion efficiency can be induced by the seed.[9] This is illustrated in Fig. 1, which shows the calculated depletion of the fundamental for high conversion efficiency as a function of phase mismatch in the presence of a seed

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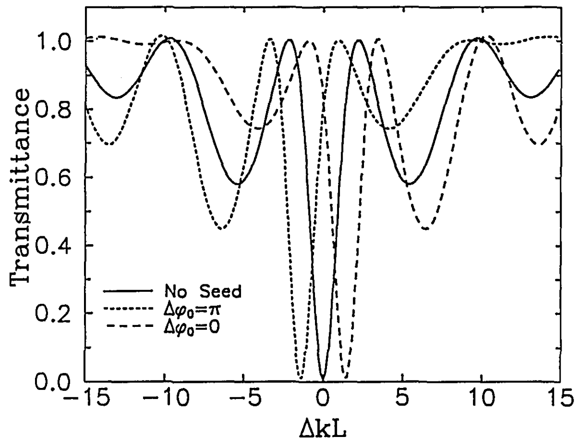

Fig. 1. Calculated fundamental irradiance transmittance versus ΔkL for SHG with high input irradiance and a 5% seed, for several values of $\Delta\phi_0$.

with input irradiance 5% of the input fundamental. The dashed curve shows $\Delta\phi_0 = \pi$, the dotted curve shows $\Delta\phi_0 = 0$, and the solid curve is calculated for zero seed. The effect of the seed is to cause the depletion curve to become asymmetric, and it produces a shift of the maximum depletion point along ΔkL. Here L is the sample length. The phase of the seed, $\Delta\phi_0$, dictates the direction of the shift, which is toward $+\Delta kL$ for $\Delta\phi_0 = 0$ and toward $-\Delta kL$ for $\Delta\phi_0 = \pi$. For $\Delta\phi_0 = \pm\pi/2$ the curve is unshifted and nearly identical to that in the zero-seed case. Holding ΔkL fixed and varying the phase or amplitude of the seed will modulate the fundamental. For example, from Fig. 1 we see that setting $\Delta\phi_0 = 0$ and varying the amplitude of the seed can result in almost 100% modulation of the fundamental. In addition, the analysis shows that the transmitted fundamental wave also experiences phase modulation.[6] It is found numerically that the smaller the seed amplitude, the smaller the shift along ΔkL. For small seed fractions, the shift becomes approximately proportional to the amplitude of the seed electric field, and for large depletion it becomes independent of the fundamental irradiance. It can be shown theoretically, by use of an approximate solution to Eqs. (1) and (2), that the apparent shift in ΔkL is proportional to $E_{20}\cos(\Delta\phi_0)$ (approximate for $|\Delta kL| > 2$), where E_{20} is the SH field amplitude at $z = 0$ (the seed field amplitude).[4] The small-signal gain may be expected to be largest where SHG conversion efficiency is most strongly dependent on ΔkL (i.e., where the slope of the curve in Fig. 1 is largest). The above analysis is valid only for plane waves or for laser pulses of spatially and temporally uniform irradiance. In practice, spatial and temporal averaging will reduce the modulation depth.

We experimentally demonstrate modulation of the fundamental by a weak seed, using a 1-mm-thick sample of KTP. The sample is oriented for type II phase matching for SHG at a fundamental wavelength of $\lambda = 1.06\ \mu$m. The KTP is mounted in a computer-controlled, three-axis goniometric stage to permit precise angle tuning of the phase-matching conditions. The laser source is a Q-switched and mode-locked Nd:YAG laser, producing single 20-ps FWHM pulses at a 10-Hz repetition rate. To produce the coherent and collinear SH seed, a type I phase-matched KDP crystal is placed in the beam, as shown in Fig. 2. This method of sharing a common path between seed and fundamental removes the need for interferometric stability in the experiment but makes independent modulation of the seed difficult without modulation of the fundamental. Hence our experimental demonstration concentrates on modulation of $\Delta\phi_0$. We accomplish control of $\Delta\phi_0$ by passing the collinear seed and unconverted 1.06-μm pulses through a cell containing nitrogen gas. By varying the pressure, we exploit the dispersion of the refractive index of the gas to produce a precise variation of $\Delta\phi_0$. The collinear and phase-shifted beams are then both focused onto the KTP sample by a 500-mm focal-length lens to beam waists with measured $1/e^2$ irradiance radii of 85 μm for the fundamental and 60 μm for the seed.

The detection system is configured to measure either total transmitted energy or on-axis fluence (energy per unit area) of the fundamental. To measure the energy, we place a large area photodiode immediately after the filters. To measure the on-axis fluence and to eliminate spatial averaging effects, we use a 100-mm focal-length lens to image the irradiance distribution at the exit surface of the KTP with 3× magnification onto a 100-μm-diameter pinhole. This arrangement eliminates damage to the pinhole. Rejection filters are used to ensure that only the fundamental is detected.

Empirically, we obtained the largest modulation of the fundamental by varying the phase of the SH seed at $\Delta kL \simeq 1.3$ with $I_1 = 20$ GW/cm^2 and a SH seed energy 1.2% of the input fundamental energy (3.4% of the irradiance). In our experimental configuration the SH is polarized at 45° with respect to the fundamental, and only the component polarized perpendicular to the fundamental (1.2% by energy) is responsible for the observed modulation. This results in a 1.8-to-1 energy modulation of the transmitted fundamental as the seed phase is varied, with the energy transmittance changing from 57% to 31%. The imaging lens and aperture are used to remove spatial averaging; this modulation increases to 4.6-to-1, corresponding to a variation of the transmitted fluence from 83% to 18%, as shown in Fig. 3.

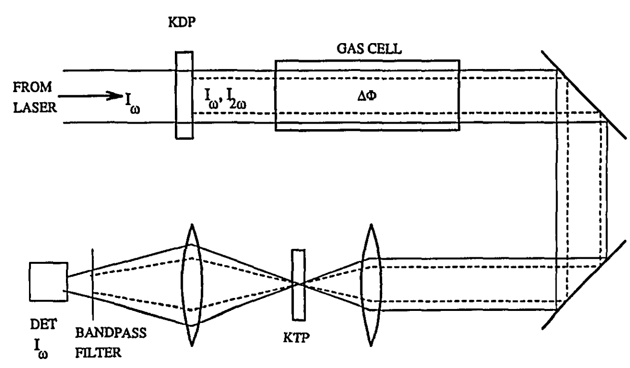

Fig. 2. Experimental apparatus for demonstration of all-optical transistor action, as described in the text. DET, photodiode detector.

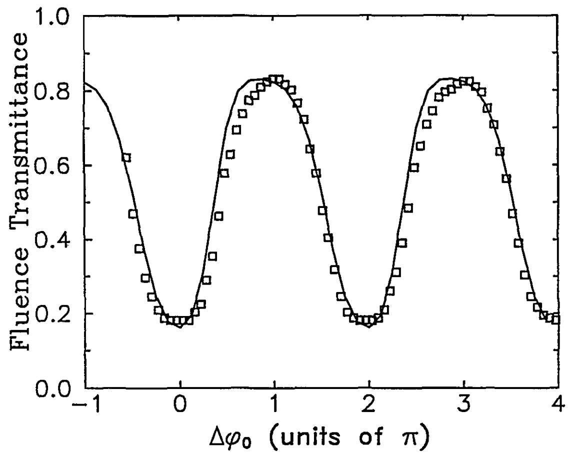

Fig. 3. Transmission of the fundamental fluence as a function of $\Delta\phi_0$. The peak input fundamental irradiance is 20 GW/cm^2, and the seed irradiance fraction is 3.4% (1.2% by energy). The solid curve is a fit performed by integrating Eqs. (1) and (2).

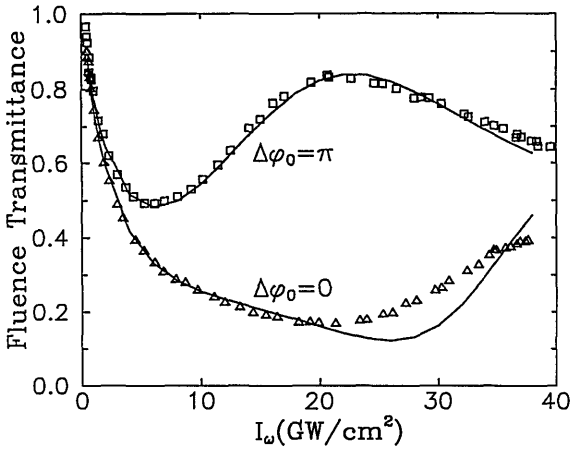

Fig. 4. Fundamental normalized fluence transmission as a function of input irradiance for $\Delta kL = 1.3$ and $\Delta\phi_0 = 0$ (triangles) or $\Delta\phi_0 = \pi$ (squares). The seed fraction varies because of changing irradiance (see text), but for $I_\omega = 20$ GW/cm^2 the seed fraction is $\simeq 3.4\%$, as in Fig. 3. Solid curves are fits to data using Eqs. (1) and (2).

Figure 4 shows the transmitted fundamental fluence as a function of input irradiance for $\Delta\phi_0 = 0$ and π. Because the seed beam is generated by SHG crystal placed after the attenuator, the ratio of seed to fundamental is continuously varying as the input irradiance is increased. The solid curves are numerical fits based on Eqs. (1) and (2) including temporal integration with $d_{eff} = 3.1$ pm/V,[2,10,11] where $d_{eff} = |\chi^{(2)}(2\omega; \omega, \omega)|/2$.

Having measured the values of the bound electronic nonlinear refractive index, n_2, at both ω and 2ω as well as the value of the two-photon absorption coefficient, β, at 2ω, where it is energetically allowed,[12,13] we investigated their effects on these measurements. We found numerically that the combination of n_2 and β changes the transmittance in Figs. 3 and 4 by less than 5%, even at the highest irradiance used in Fig. 4.

In summary, the results presented here demonstrate the potential of all-optical switching by use of $\chi^{(2)}$ nonlinearities. These results may not be optimal because of the large number of parameters that may be varied, and it may be possible to obtain better performance from KTP. Moreover, the switching irradiance scales as $(Ld_{eff})^{-2}$,[2] so new organic crystals with $\chi^{(2)}$ more than ten times that of KTP will significantly reduce switching irradiances. For example, in the organic crystal NPP, $d_{eff} = 70$ pm/V,[14] so the switching irradiances ought to be smaller than in KTP by approximately a factor of 10^3. Because of the L^{-2} dependence, waveguide geometries will lead to further reductions in the switching power. For a 1-cm-long NPP waveguide we may expect a switching irradiance 10^5 times smaller than for KTP or 400 kW/cm^2. For 1-psec pulses in a 3 μm × 3 μm guide, this corresponds to a switching energy of approximately 40 fJ, or a peak power of 40 mW.

We gratefully acknowledge the support of National Science Foundation grant ECS#9120590 and NATO grant CRG931142.

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