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All-optical modulation via nonlinear cascading in type II second-harmonic generation

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Utilizing a type II interaction for second-harmonic generation in a crystal of potassium titanyl phosphate, we experimentally demonstrate the all-optical action of a light modulator with both signal and output at the same optical wavelength. This modulator is controlled by the intensity of the injected signal, a characteristic that makes it a suitable candidate for all-optical transistor action and ultrafast analog processing in transparent networks for telecommunications.

All-optical effects constitute an active area of interest which is beginning to expand into the research and development community. Transparent networks and all-optical real-time reconfigurable systems have become common concepts in those areas of investigation dealing with ultrafast telecommunications.[1] Recently, a new spur of activities in nonlinear optics for all-optical applications has been promoted by the novel, although physically well understood, concept of large phase shifts via cascading of second-order nonlinear effects,[2,3] partly because of the mature technology available in second-order materials in comparison to third-order systems. The cascading nonlinearity, however, is not only being investigated as a potentially more suitable mechanism for producing phase shifts in all those configurations for which the optical Kerr effect used to be considered the optimum candidate,[4,5] but it is revealing its peculiar potentials in other areas, such as new solitarylike solutions in space and time[6–8] and analog processing. For the latter, various all-optical modulator schemes have been proposed which rely on the coherent nature of cascading nonlinear interactions.[9–12] One of them, utilizing a weak phase-modulated second-harmonic seed signal to produce large throughput changes in the fundamental frequency pump in a potassium titanyl phosphate (KTP) crystal, has been recently reported by us.[13]

In this letter we report, to the best of our knowledge, the first experimental demonstration of a KTP all-optical transistor which, in contrast to the schemes previously investigated, does not rely on a specific phase relationship between signal and pump and, moreover, is capable of producing an amplified signal at the same optical frequency as the input.

The present scheme for all-optical modulation if based on type II second-harmonic generation (SHG), in the case of unbalanced input components along the spatial directions corresponding to the allowed propagation eigensolutions in an anisotropic crystal.[12] The equations governing the three-wave interaction for type II SHG are the classical set describing parametric generation:

$$i\frac{dA_j(\omega,\xi)}{d\xi}=A^*_{3-j}(\omega,\xi),B(2\omega,\xi)+k_jA_j(\omega,\xi),$$
$$i\frac{dB(2\omega,\xi)}{d\xi}=A_1(\omega,\xi)A_2(\omega,\xi)+k_BB(2\omega,\xi), \quad (1)$$
$$j=1,2,$$

with A_j and B slowly varying field amplitudes (in $W^{1/2}\ m^{-1}$), $k_j=\beta_j(\omega)/\chi\sqrt{P}$, $k_B=\beta_B(2\omega)/\chi\sqrt{P}$, $\xi=z\chi\sqrt{P}$, P the total input power, and $\chi\approx 4\pi/\lambda d^{(2)}_{\mathrm{eff}}\sqrt{1/2c\epsilon_0 n^3}$ the effective nonlinear coefficient.

These equations, however, encompass a richer phenomenology when the initial conditions on the fundamental frequency (FF) waves are nonidentical, i.e., when one of the input components is larger (weaker) than the other one.[12,14] Under these circumstances, the well-known $\mathrm{sech}^2(\chi z)$ solution for the transmission of the FF wave is replaced by a solution where energy is periodically exchanged between FF and second harmonic (SH). This is illustrated in Fig. 1, where a small imbalance between the FF inputs results in-

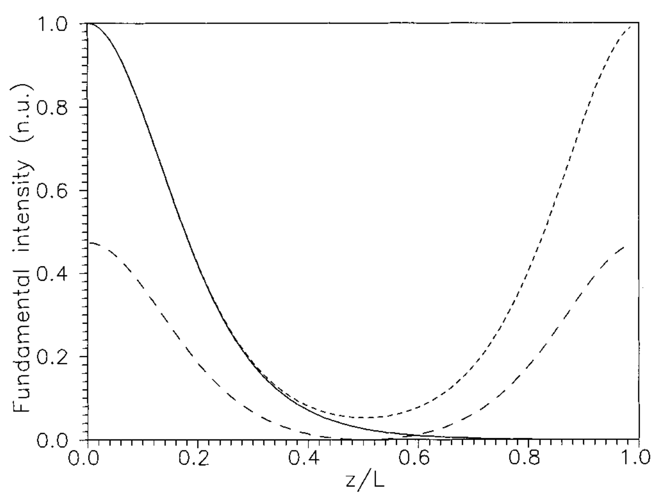

FIG. 1. Total normalized fundamental intensity $\eta(z)=(|A_1(z)|^2+|A_2(z)|^2)/(|A_1(0)|^2+|A_2(0)|^2)$ vs distance *z/L* at phase matching for $r=|A_2(0)|^2/|A_1(0)|^2=1$ (solid line) and r=0.9 (short dashed). In the latter case the long-dashed line represents the weaker $(|A_2(z)|^2)$ component. Total input excitation was $L^2\chi^2P=25$ at ω, and the calculation was carried out using plane waves and cw fields.

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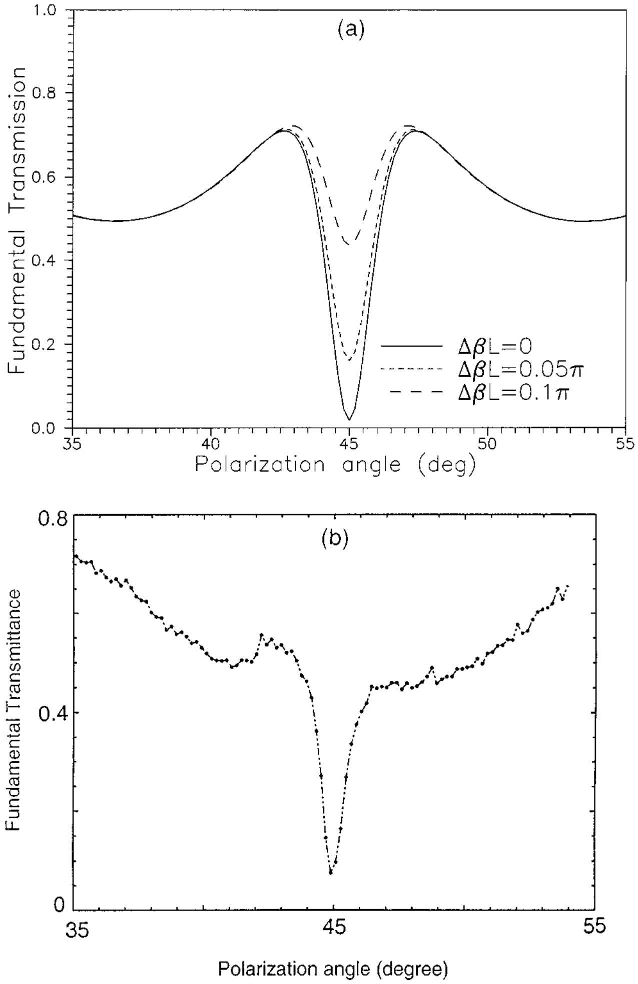

FIG. 2. Fundamental throughput $\eta=(|A_1(L)|^2+|A_2(L)|^2)/(|A_1(0)|^2+|A_2(0)|^2)$ vs angle of polarization at the entrance facet of the crystal. 45° corresponds to balanced excitation, i.e., standard type II SHG. (a) Numerical calculation including time averaging over a Gaussian pulse and for various wave vector mismatches; (b) experimental results with 26 ps pulses.

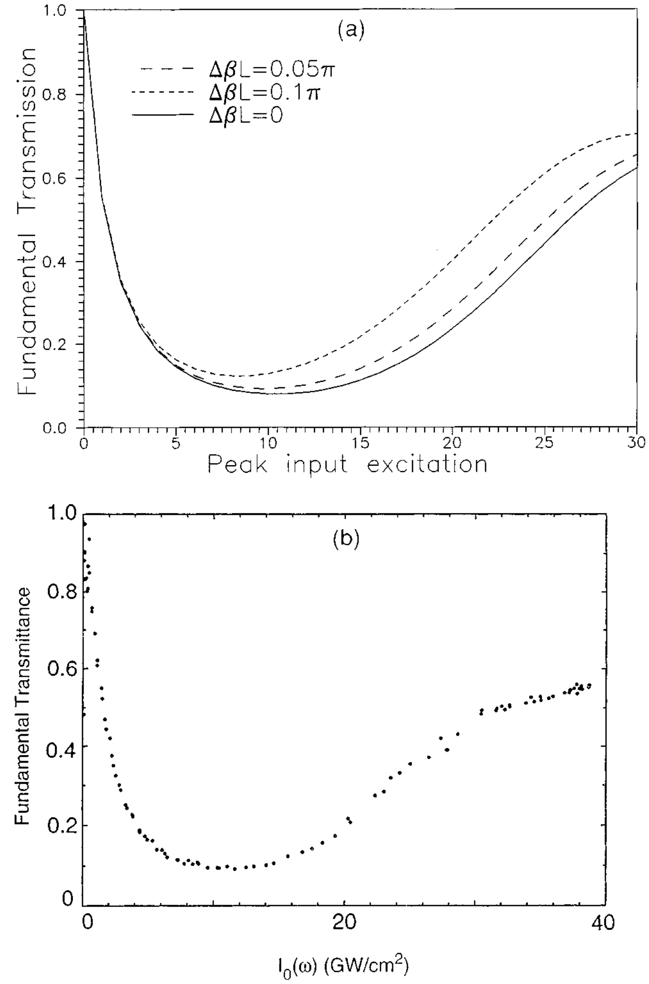

FIG. 3. Fundamental throughput η vs total FF input fluence for a fixed ratio $r\cong 0.98$ between the FF components in $z=0$. (a)Numerical simulation for $\Delta\beta L=0,\ 0.05\pi,\ 0.1\pi$, and time integration; (b) experimental results. A normalized excitation $L^2\chi^2 P=30$ corresponds to an intensity of 32 GW/cm^2.

complete switching of energy from SH to FF waves. While the case $r=1$ (balanced FF inputs) corresponds to the standard type II SHG case (the standard configuration employed in KTP frequency doublers), a large transmission change is introduced for r close (but not equal) to 1. Such occurrence is more rapid with r and with better high/low contrast the smaller the wave vector mismatch $\Delta\beta=\beta_B(2\omega)-\beta_1(\omega)-\beta_2(\omega)$ characterizing the interaction.[12] Moreover, this throughput variation, as also indicated by Hutchings *et al.*[15] in the framework of frequency nondegenerate interactions, is insensitive to the phase offset of either FF input components, lending itself to all-optical transistor action with true (relative) intensity control.

For the experimental demonstration of this all-optical modulation scheme, we utilized a 2-mm-thick flux-grown KTP crystal. The crystal was mounted in an three-axis goniometric stage and placed at the waist of a focused Gaussian beam from a 1.064 μm Q-switch mode-locked Nd:YAG laser producing single, switched-out 26 ps pulses (FWHM) at a rep-rate of 10 Hz. The laser beam was linearly polarized and a λ/2 waveplate allowed the angular shift of the FF input field at the entrance of the crystal, so as to control the projection of the input onto the two orthogonal polarization directions involved in a type II interaction. First, the crystal and the electric field were aligned in order to maximize SHG, with an angle of 45° at the input facet. This resulted in a substantial depletion of the fundamental. We verified that a waveplate rotation of ±22.5° about this position resulted in a negligible amount of second harmonic, even at the largest power available from the laser source. Then, after placing an imaging system (5×) and a 100 μm pinhole at the output of the crystal in order to reduce (or eliminate) the effects of spatial averaging, we measured the total throughput versus waveplate rotation. Such rotation corresponds to a variation in the ratio between the FF inputs. Figures 2(a) and 2(b) show the predicted and experimental results, for an input beam waist ($1/e^2$) of 80 μm and an estimated FF intensity of 32 GW/cm^2. The effective nonlinearity was taken $d_{\rm eff}^{(2)}=3.1$ pm/V,[16] and for the simulation we assumed that a certain phase mismatch was achieved over a pulse Gaussian in time but planar in space. The latter assumption is acceptable in view of the imaging geometry adopted for the measurement. The FF transmittance was normalized to its linear value, and no corrections were introduced for angular or temporal walk-off due to crystal birefringence. The results exhibit an abrupt switching feature about 45°, with a transmission contrast of almost 7:1 for a $-1°$ change in input angle (0.5° waveplate rotation), i.e., a 1.7% variation in the size of each FF input component. This corresponds to a throughput modulation $\Delta\eta \cong (0.5\text{–}0.075)$ over 1° rotation (≅42.5%/degree) or an equivalent (small signal) amplification $\Delta(|A_1(z=L)|^2+|A_2(z=L)|^2)/2\Delta(|A_2(0)|^2)\equiv 14$ dB. The slight asymmetry visible in Fig. 2(b) is attributable to the alignment, but the overall comparison between our simple model and the experimental results is quite satisfactory for a mismatch $\Delta\beta L$ between 0.05 and 0.1π. Similar results are obtained using two separate input beams.[17] The measurement of an actual small signal amplification, distinguishing the ''pump'' from the ''signal'' input, is under way and will be presented elsewhere.

In order to verify the validity of the model, a different set of data was collected varying the input excitation to the crystal, setting the FF component ratio (or, equivalently, the waveplate angle) to a value corresponding to a transmittance of ≈0.3 in Fig. 2(b). Figures 3(a) and 3(b) show the numerical and experimental results which, also in this case, are in good agreement in the same estimated range of wave vector mismatches.

In summary, we have experimentally demonstrated a frequency-degenerate second-order nonlinear all-optical transistor, based on a type II SHG interaction in a KTP crystal. This result, not yet optimized, is particularly relevant in the framework of all-optical analog signal processes where an FF signal coherent with the pump may not be available, and indicates the feasibility of other schemes based on an inherently ultrafast cascaded nonlinearity. Even though the intensities employed were relatively high, a substantially lower power budget will be required when employing materials with higher ''$d^{(2)}$,'' such as the organic crystal MMONS,[18] and/or guided-wave geometries.[4,5] An order of magnitude increase in nonlinearity and/or interaction length would indeed allow for two/four orders of magnitude reduction in power, with further reductions possible when using smaller cross sections and/or shorter pulses.

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