Phase-insensitive, single wavelength, all-optical transistor based on second order nonlinearities

Z. Wang, D.J. Hagan, E.W. Van Stryland and G. Assanto

Indexing term: Nonlinear optics

The authors describe how the phase-sensitivity problem of optical transistors based on second order nonlinearities may be avoided using two type-II SHG crystals. The first crystal couples the mutually incoherent signal and pump, and the second crystal amplifies this signal. All inputs and outputs may be at the same wavelength.

Nonlinearities produced by the cascading of second order nonlinear ($\chi^{(2)}$) materials, have been known for many years [1, 2]. However, advances in nonlinear materials have spurred a resurgence of interest in such phenomena [3, 4]. In particular, several schemes for applying cascading in second harmonic generating (SHG) crystals to optical transistor-like devices have been proposed [5, 6] and demonstrated [7 – 9]. Such devices allow a weak signal beam to impose a large amplitude modulation on a strong 'pump' beam, through wave mixing in a $\chi^{(2)}$ crystal. To our knowledge, all the devices reported to date required the pump and signal beams to be temporally coherent, as the process is strongly dependent on the phase between these two beams. Although this may be exploited to advantage in some circumstances [7], it may be impractical, as it requires interferometric stability between input beams, and consequently between interacting switching devices. A device of this nature is also very limited in applications, as the pump and signal must be derived from the same source. There have been some suggestions [8, 9] that type II phasematched SHG may remove phase sensitivity, but the devices proposed still require the signal to be in phase with one of the two perpendicularly polarised pump beams. We describe how we may properly exploit type II phase matching to produce a truly phase-insensitive all optical transistor (AOT) with equal input and output wavelengths, based on second order nonlinearities.

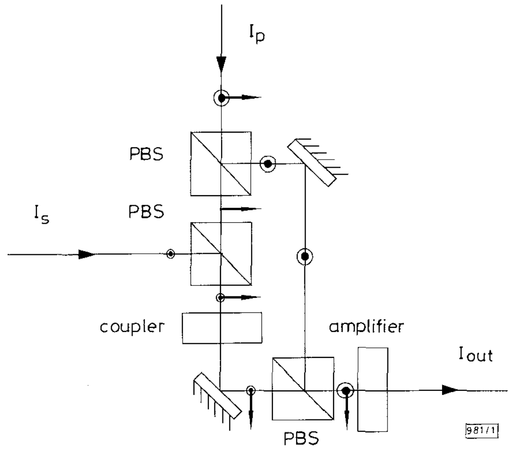

Fig. 1 *Schematic diagram of phase-insensitive AOT*

The configuration of the proposed phase-insensitive AOT is shown schematically in Fig. 1. In a single device, two type II phase-matched second order nonlinear crystals are used. The pump beam irradiance I_p is split into two approximately equal, orthogonally polarised components, irradiances I_1 and I_2. One of these I_1 passes through the first nonlinear crystal (the 'coupler'), where it is modulated by the weak, perpendicular-polarised incoherent signal, IS, with a coupling effeciency of less than unity. This modulated pump is recombined with the other component of the pump and incident on the second crystal, (the 'amplifier'), where the modulation is strongly amplified.

The principle of the amplifier has been described in [9]. Here we give only a brief description. Two orthogonally polarised input waves to the amplifier have irradiances I_1, the modulated pump; and I_2, the fixed pump. For perfect phasematching and $I_1 = I_2$, the total fundamental transmittance will follow a sech² dependence on input field amplitude or crystal thickness L_2 and will monotonically approach zero along the propagation distance. By introducing a small imbalance between I_1 and I_2, the transmittance becomes periodic in field amplitude or propagation distance and hence will start to increase after propagating through the point of largest depletion. Hence, if there is a small modulation δ on I_1, the modulation of total transmitted fundamental irradiance may greatly exceed δ. This is seen in Fig. 2, where we plot the transmittance of the total fundamental irradiance I_T through the amplifier against normalised input 'bias' in terms of incident irradiances I_1 and I_2, as $(I_2-I_1)/(I_2+I_1)$. For small δ, the modulation of the transmitted irradiance is directly proportional to δ. It is shown below that the small signal gain of the amplifier is also exponentially dependent on L_2 and I_2.

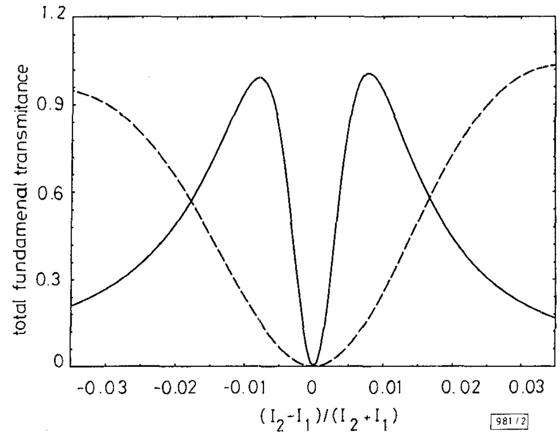

Fig. 2 *Amplifier transmittance against input bias*

——— I_t = 1.0GW/cm²
- - - - I_t = 0.6GW/cm²

The key feature of the device proposed here is the method of imposing a modulation on I_1 from a weak signal I_s that is temporally incoherent. This is achieved by coupling I_s to I_1 in another type-II phasematched SHG crystal, labelled as the coupler in Fig. 1. This is inserted into the path of I_1 before it is incident on the amplifier crystal. The polarisation of the signal field is perpendicular to that of I_1. For a weak signal $I_s \ll I_1$, the transmitted pump irradiance will be linearly modulated by the signal and is given by

$$I_1(L_1) = I_1(0) - I_S(0)\sin^2(\gamma_1 L_1) \qquad (1)$$

where $I_1(0)$ and $I_s(0)$ are the incident irradiances of I_1 and I_s, respectively, $\gamma_1^2 = 4\omega^2 d_1^2 I_1(0)/n_\omega^2 n_{2\omega}\varepsilon_0 c^3$, d_1 is the effective doubling coefficient for the coupler crystal and L_1 is its thickness.

Eqn. 1 is just the well known result for sum-frequency generation [1]. Indeed, both the device principle and analysis given in this Letter may be applied to sum or difference-frequency generation as well as type II SHG. The reason SHG is chosen, however, is that all input and output beams are at the same wavelength. As seen from eqn. 1, the maximum modulation efficiency is unity, which may be achieved for finite values of the fundamental intensity. We find that the maximum coupling will occur at $\gamma_1 L_1 = (2q+1)\pi/2$, where $q = 0, 1, 2, 3...$. This gives the following design criterion for the most efficient coupling:

$$I_1(0) = (2q+1)^2 \frac{\pi^2 n_\omega^2 n_{2\omega}\varepsilon_0 c^3}{16\omega^2 d_1^2 L_1^2} \quad q = 0, 1, 2, 3, ... \qquad (2)$$

The modulation imposed on I_1 in the coupler is then amplified in the amplifier crystal. The presence of the signal causes a modulation of I_1, which in turn produces an imbalance of $\delta = \sin^2(\gamma_1 L_1) I_s(0)$ between I_1 and I_2 incident on the amplifying crystal. As described above and in [9] the interaction between these two fundamental waves in the amplifier results in amplification of this imbalance. It can be shown that the gain of the amplifier is given by

$$G \propto \sin^2(\gamma_1 L_1) e^{\gamma_2 L_2} \qquad (3)$$

where $\gamma_2^2 = 4\omega^2 d_2^2 I_2(0)/n_\omega^2 n_{2\omega} \varepsilon_0 c^3$, d_2 is the effective doubling coefficient for the amplifier crystal and L_2 is its thickness. The constant of proportionality is a function of bias, itself proportional to the slope of the appropriate curve in Fig. 2.

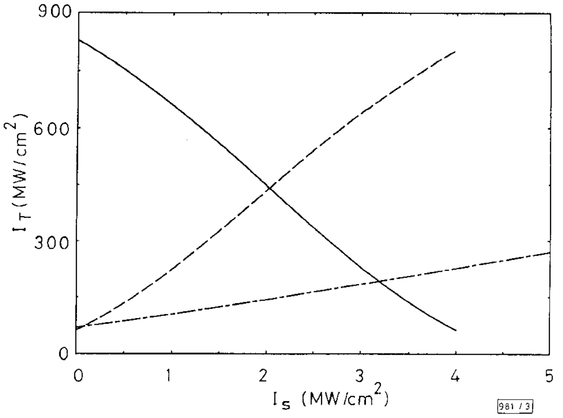

Fig. 3 *Transistor output against input signal for 1cm KTP amplifier*

·········· I_t = 1.0GW/cm^2, bias = 1MW/cm^2
——— I_t = 1.0GW/cm^2, bias = –5MW/cm^2
–·–·–·– I_t = 0.6GW/cm^2, bias = 4MW/cm^2

The overall performance of the proposed AOT may be modelled by numerical simulation of the coupled equations governing the SHG process in both crystals [1, 9]. The results are shown in Fig. 3, where we plot the total transmitted fundamental irradiance I_T against the input signal irradiance for different pump irradiances and biases. The slopes of curves in the figure represent the gain of the transistor. Fig. 3 shows that both inverting and noninverting amplifiers can be realised by choosing proper biases. We find that the gain of the AOT can be linear over a wide range of pump irradiance and bias. The exponential nature of the gain makes the material choice extremely important, e.g., an overall gain of 40dB requires a total input irradiance of 2.5GW/cm^2 in a 1cm KTP amplifier, while for a 1cm NPP crystal, with a d_{eff} of 85pm/V [8], 40dB of gain is achievable with an irradiance of 3.6MW/cm^2. If a waveguide geometry were used, with an effective mode area of 25µm^2, the corresponding peak power would be <1W for a length of 1cm. In each case an optimised coupler length is assumed. In practical devices, averaging over spatial mode and temporal pulse shape will raise the required peak irradiance and will reduce overall gain.

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Synchronous pumping of a periodically poled LiNbO$_3$ optical parametric oscillator

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Indexing terms: Lithium niobate, Nonlinear optics, Optical parametric amplifiers

The authors have demonstrated synchronous pumping of a quasi-phasematched optical parametric oscillator using periodically poled LiNbO$_3$ as the nonlinear medium. Depletion efficiencies up to 83% were observed.

We demonstrate synchronous pumping of a quasi-phasematched (QPM) optical parametric oscillator (OPO) using periodically poled LiNbO$_3$ (PPLN) as the nonlinear medium. Synchronous pumping permits the production of very short pulses of tunable light by using short-pulse mode-locked lasers as OPO pump sources [1]. The pulses may be produced either as a CW train or as a burst controlled by a *Q*-switch. For applications that do not require short mode-locked pulses, the *Q*-switch burst mimics the corresponding long-pulse *Q*-switch lasers while providing higher peak power and OPO efficiency.

Recent material development has made QPM nonlinear optics, offering a significant improvement over traditional birefringent phasematching, practical [2 – 7]. Quasi-phasematching allows the device designer to non-critically phasematch any nonlinear interaction while taking advantage of the largest nonlinear coefficients of the material. The result is a large effective nonlinear interaction strength and greatly enhanced singlepass gain. This has enabled the fabrication of low-peak-power, long-pulse OPO devices [8] that were previously impractical because of the smaller nonlinearities of conventional materials. Synchronous pumping of a QPM device adds additional capability by using high peak power mode-locked pulses to obtain more efficient conversion while providing pulse profiles similar to long-pulse OPOs.

Synchronous pumping is also advantageous for use with materials with limited apertures, such as PPLN. The electric-field poling technique for fabricating PPLN has been demonstrated on crystals with a thickness of 0.5mm or less. This necessitates tight focusing of the pump beam, a large energy flux, and the risk of crystal damage from only modest peak energies. Synchronous pumping, however, uses a train of high peak power but low energy pulses, avoiding the damage threshold and making high average powers and high efficiencies readily attainable. When using a *Q*-switched mode-locked pump laser, it is possible to average over the *Q*-switch envelope to obtain high effective peak energies and still avoid the damage threshold.

The PPLN crystal for this device was fabricated from a 0.5mm thick z-cut lithium niobate wafer, cut to a length of 15mm. The polished end faces were AR coated with a total transmission of 98, 96, and 97% for the pump, signal, and idler, respectively. The QPM structure was fabricated using a standard field-poling technique [3]. The 29.75µm grating period was designed for first order quasi-phasematching with all fields *e*-polarised: a pump wavelength of 1.064µm; and room temperature signal and idler wavelengths of 1.51 and 3.59µm, respectively.

The cavity layout for the OPO is shown in Fig. 1. The pump is an Nd:YAG mode-locked *Q*-switched laser operating at 1.064µm. The mode-locked pulses are 100ps long, separated by 13.2ns. The pulses propagate in a burst determined by the *Q*-switch envelope,