Femtosecond nonlinear polarization evolution based on cascade quadratic nonlinearities

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We experimentally demonstrate that one can exploit nonlinear phase shifts produced in type I phase-mismatched second-harmonic generation to produce intensity-dependent polarization evolution with 100-fs pulses. An amplitude modulator based on nonlinear polarization rotation provides passive amplitude-modulation depth of up to ~50%. Applications of the amplitude and phase modulations to mode locking of femtosecond bulk and fiber lasers are promising and are discussed. © 2000 Optical Society of America

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Techniques that provide intensity-dependent transmittance or reflection of light beams are essential for many applications, such as all-optical switching and amplitude modulation. Nonlinear polarization evolution (NPE) is one such technique and is based on the difference in intensity-dependent phase shifts accumulated by two orthogonally polarized electric field components. Polarizers convert the polarization rotation to amplitude modulation. Intensity discrimination based on self-phase modulation and cross-phase modulation with cubic nonlinearities was first demonstrated in birefringent fiber by Stolen *et al.*, [1] and amplitude modulation arising from NPE is now commonly employed in mode-locked fiber lasers.[2,3]

It is also possible to implement NPE by use of phase shifts produced by quadratic nonlinear interactions. Nonlinear phase shifts ($\Delta\Phi^{NL}$) produced in quadratic interactions[4–6] can potentially be larger than those produced by the electronic Kerr nonlinearity, so NPE based on quadratic media will generally require lower power and (or) shorter interaction lengths for a given rotation of the polarization. Lefort and Barthelemy demonstrated that the phase retardation that underlies polarization rotation can be generated in quadratic nonlinear media.[7] In close analogy to the way that NPE is implemented in fibers with low birefringence, these workers employed phase-matched type II second-harmonic generation (SHG) with unequal input components to rotate the polarization. However, the pulse duration will be limited by the intrinsic group-velocity mismatch (GVM) between the orthogonally polarized [ordinary (*o*) and extraordinary (*e*)] input pulses, to applications involving pulses $\gtrsim$1 ps in duration. NPE based on type II interaction has been successfully applied to mode locking of a Nd:YVO_4 laser[8] to produce 2.8-ps pulses. Buchvarov *et al.* showed theoretically that phase-mismatched type II interactions can also be exploited for NPE.[9]

Here we address the issues associated with exploiting NPE in quadratic media on the 100-fs time scale. The use of a phase-mismatched type I interaction eliminates the GVM between the input pulses, which is one of the impediments to application of quadratic NPE with 100-fs pulses. GVM reduces the nonlinear phase shifts that can be generated in quadratic processes and can also seriously distort the temporal evolution of $\Delta\Phi^{NL}(t)$ across the pulse. The basic concept underlying our approach was proposed theoretically by Saltiel *et al.* [10] but without any consideration of the effects of GVM. In previous work on mode locking,[11] pulse compression,[12] and soliton formation[13] by use of quadratic nonlinearities it was established that one can adjust the phase mismatch to manage the effects of GVM between fundamental and harmonic pulses. Based on this approach, we experimentally demonstrate NPE in type I phase-mismatched SHG. Intensity-dependent transmittance changes as large as 50% are observed in 80-fs pulses. The design of femtosecond lasers based on type I NPE is discussed.

The principle of an amplitude modulator or optical switch based on quadratic NPE is illustrated by the schematic of the experimental setup shown in Fig. 1. A vertically polarized input pulse is reflected from the polarizing beam splitter and is incident upon the SHG crystal at an angle α with respect to the normal to the principal plane (which is defined by the incident wave vector and the optic axis). Under phase-mismatched conditions, the *o* component of the fundamental frequency accumulates a nonlinear phase shift. The combination of a 45° Faraday rotator and a mirror rotates the polarizations of the original *o* and *e* components, and the new *o* component accumulates another nonlinear phase shift on the return through the SHG crystal. If the SHG crystal is excited with unequal *o* and *e* components, a net nonlinear phase delay $\Delta\Phi^{NL}$ between the two components is produced after two passes of the SHG crystal. This arrangement fully compensates for the linear phase delay and the

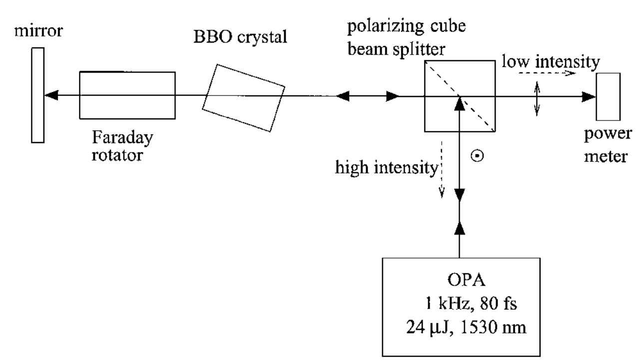

Fig. 1. Schematic of the experimental setup. OPA, optical parametric amplifier.

group-velocity delay between the o and the e waves, which is essential for NPE with ultrashort pulses.[14]

Neglecting linear losses, we can write the transmittance of light through the polarizing beam splitter as

$$T = 1 - \sin^2(2\alpha)\sin^2(\Delta\Phi^{\mathrm{NL}}/2). \tag{1}$$

To a first approximation,[6]

$$\Delta\Phi^{\mathrm{NL}} \approx -(\Gamma^2 L^2/\Delta kL)(\Delta I/I), \tag{2}$$

where $\Gamma = \omega d_{\mathrm{eff}}|E_o|/c(n_{2\omega}n_\omega)^{1/2}$, $\Delta k = k_{2\omega} - 2k_\omega$ is the phase mismatch, L is the crystal length, I is the total incident intensity, and ΔI is the intensity difference between the o and the e components. For most applications (e.g., mode locking of a laser), the maximum $|\mathrm{d}(1-T)/\mathrm{d}I|$ at a given intensity is desired, which corresponds to $\alpha \approx 28°$.[2] Hence we set $\alpha = 28°$ in the experiments.

Transform-limited 80-fs laser pulses of up to 24-μJ pulse energy at 1.53 μm were produced by an optical parametric amplifier pumped by a femtosecond Ti:sapphire regenerative amplifier. The input beam was collimated to a diameter of 2.1 mm before it entered the NPE setup. The quadratic medium was a 17-mm-long barium metaborate (BBO) crystal cut for type I SHG at ~1.55 μm.

The deleterious effects of GVM can be suppressed by use of adequate phase mismatch ΔkL, at the expense of the magnitude of $\Delta\Phi_{\mathrm{NL}}$; this is illustrated in Ref. 11, and a criterion for the required value of ΔkL is given in Ref. 12. For SHG of 80-fs pulses at 1.55 μm in BBO, the GVM length $L_{\mathrm{GVM}} = \tau/\Delta\nu_g{}^{-1} \approx 7$ mm (the difference of the inverse group velocities $\Delta\nu_g{}^{-1} \approx 12$ fs/mm), which requires that $|\Delta kL| \gtrsim 10\pi$. A separate advantage of working at large phase mismatch is the reduction of the energy loss that is due to SHG. The group-velocity dispersion of BBO at 1.55 μm is 24 fs^2/mm and anomalous, which implies single-pass pulse broadening of <2%.

Figure 2 shows the measured nonlinear transmittance along with transmittance values [expression (2)] based on nonlinear phase shifts given by approximate analytic calculations with Eq. (1) and one-dimensional numerical solutions of the coupled wave equations that take into account the effects of GVM and group-velocity dispersion. The experimental results for phase mismatches ΔkL of -14π, -20π, -30π, and -120π agree overall with the results of calculations. The measurement at -120π can be viewed as a control experiment, since the cascade phase shift is negligible. With $\Delta kL = -14\pi$ there is a significant discrepancy between the measured and the calculated trends. The origin of this disagreement is not understood. However, for $\Delta kL \approx -14\pi$ and closer to zero, we observe continuum generation that indicates that spatial effects owing to phase distortion may be important. For $\Delta kL = -14\pi$ and $I = 7$ GW/cm^2, the maximum observed SHG efficiency is ~8%.

The nonlinear transmittance versus phase mismatch at fixed intensity (7 GW/cm^2) is shown in Fig. 3. The experimental data closely follow the simple calculations with Eq. (1) and expression (2) and the results of numerical solutions, especially in the range of this experiment ($\Delta kL < -10\pi$).

The nonlinear phase shifts that we infer from the measured transmittance agree well with calculations (the Kerr effect produces approximately 5–10% of the total nonlinear phase shift). At $I = 7$ GW/cm^2, we expect a total nonlinear phase shift $\Delta\Phi_{\mathrm{NL}} \approx 0.7\pi$. From Eq. (1), we get $T \approx 0.44$, in agreement with the measured transmittance of 0.45. The nonlinear phase shift naturally influences the pulse spectrum. Curve (b) of Fig. 4 shows the output spectrum at low power, where the nonlinear phase shifts are negligible.

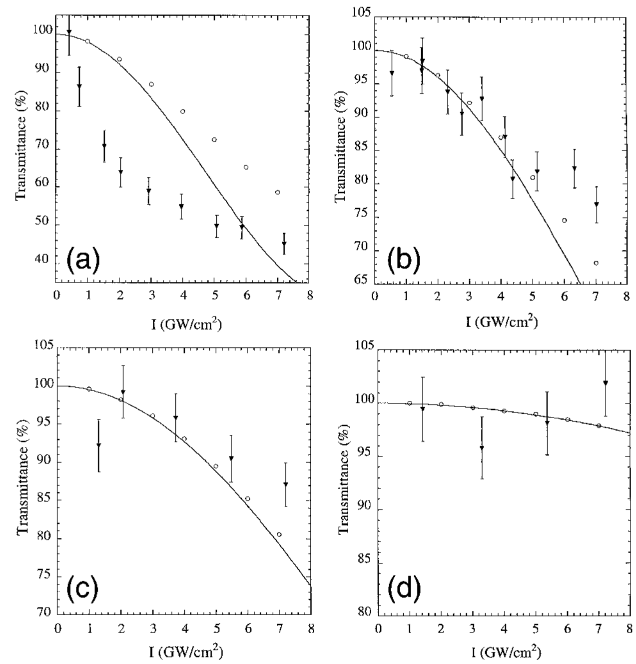

Fig. 2. Experimental (triangles with error bars) and calculated intensity-dependent transmittance obtained with an analytic expression (curves) and numerical simulations (circles) at phase mismatches of (a) -14π, (b) -20π, (c) -30π, and (d) -120π. As expected, the results of the numerical simulations and the analytic expression diverge with increasing nonlinearity. Note that the transmittance scale changes between plots.

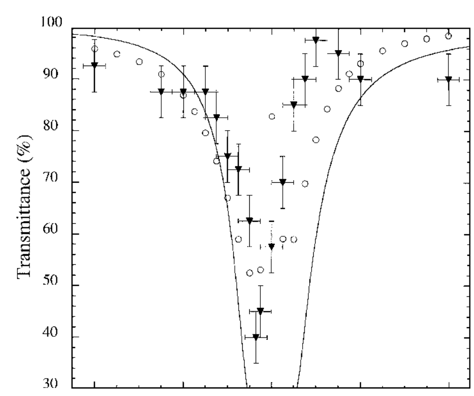

Fig. 3. Experimental (triangles with error bars) and calculated transmittance based on analytic expression (curves) and numerical simulations (circles) versus phase mismatch at $I = 7$ GW/cm^2.

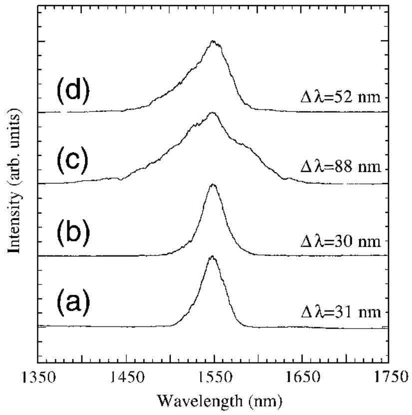

Fig. 4. (a) Input pulse spectrum and transmitted pulse spectra at (b) $I = 0.7$ GW/cm^2, $\Delta kL = -20\pi$, (c) $I = 7$ GW/cm^2, $\Delta kL = -14\pi$, and (d) $I = 7$ GW/cm^2, $\Delta kL = -120\pi$. Spectral widths Δ are shown.

The spectral bandwidth is ~26 nm, almost identical to the 25-nm input spectral bandwidth [curve (a)]. Considering the contribution from the Kerr effect of the polarizing cube (which does not contribute to the NPE action), a maximum total phase shift of $\sim 0.9\pi$ is estimated, which corresponds to a maximum spectrum broadening[15] by a factor of ~3.4, in good agreement with the experimental spectrum for $I = 7$ GW/cm^2 and $\Delta kL = -14\pi$ [curve (c)]. At $\Delta kL = -120\pi$, the estimated phase shift is $\sim 0.23\pi$, corresponding to spectrum broadening by a factor of ~1.6, again in good agreement with the experimental spectrum shown in curve (d).

To reduce the intensity required for generation of a given polarization rotation one can employ a configuration with two crystals oriented such that they have opposite signs of ΔkL and their o axes are rotated 90° with respect to each other.[10] This configuration will be ideal for implementation of the NPE scheme in a ring cavity laser to provide the needed amplitude and (or) frequency modulations for mode locking. However, one has to take special care to ensure the exact cancellation of linear phase delays by suitably matching the two crystal lengths.

To assess the practical feasibility of type I NPE we consider a periodically poled lithium niobate waveguide for implementing the NPE scheme in mode-locked lasers. Using a 20-mm-long periodically poled lithium niobate waveguide with a 50-μm^2 guiding area, we estimate the pulse energy necessary for $\Delta\Phi_{NL} = \pi$ with 200-fs pulses at 1.55 μm to be $\lesssim$100 pJ, assuming $d_{eff} = 15$ pm/V and GVM of 320 fs/mm. Such energies are readily obtained. Furthermore, possible beam distortions arising from the large $\Delta\Phi_{NL}$ are avoided in the guided-wave geometry. In addition to the amplitude or phase modulations, it will be possible to use the positive (negative) nonlinear phase shifts for solitonlike pulse shaping with anomalous (normal) GVD.

In conclusion, we have demonstrated strong intensity-dependent transmittance of femtosecond pulses by the use of NPE based on type I phase-mismatched SHG. This approach offers several advantages over related techniques. Compared with NPE in cubic media, type I NPE will require lower power and (or) shorter interaction lengths to achieve a given rotation of the polarization. Quadratic NPE also produces less background nonlinear phase shift than does cubic NPE, in which SPM produces most of the nonlinear phase shift. In a sense, NPE in cubic nonlinear media is inefficient. Owing to the relative strengths of cross-phase and self-phase modulation in birefringent cubic nonlinear media, a minimum peak phase shift of $\sim 5\pi$ is needed for generation of a π phase difference[1]; this introduces excessive spectral broadening that is undesirable in some applications. Furthermore, there is the advantage of working with 100-fs pulses with respect to type II NPE for ultrafast applications. We anticipate that using linearly polarized light in type I NPE will be advantageous for mode locking of polarization-maintaining fibers. Additionally, generation of negative nonlinear phase shifts can be used to compensate some of the Kerr phase shift that is accumulated by a pulse in a fiber laser. Apart from mode locking of lasers, possible applications include all-optical switching and modulation, optical limiting, and pulse shaping.

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