Novel pulse-delayed scheme for degenerate optical parametric amplification in $\chi^{(3)}$ waveguides

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We describe a novel pulse-delayed scheme to realize degenerate optical parametric amplification in $\chi^{(3)}$ planar waveguides. The scheme utilizes two identical birefringent plates placed before and after a $\chi^{(3)}$ planar waveguide to implement a single-arm, pulse-multiplexed nonlinear Mach–Zehnder interferometer. Using this scheme, we demonstrate ultrafast degenerate optical parametric amplification in AlGaAs waveguides.

Planar waveguide optical parametric amplifiers (OPA's) are potentially attractive for realizing compact phase-sensitive optical amplifiers. Nondegenerate OPA's have been demonstrated in $\chi^{(2)}$ Ti-difussed $LiNbO_3$ waveguides,[1,2] for which phase matching of the pump and the signal is achieved by temperature tuning. Degenerate OPA's (DOPA's) utilizing the $\chi^{(3)}$ nonlinearity can be more desirable, as in this case the phase-matching condition is automatically satisfied because the pump and the signal are at the same wavelength. The main obstacle in realizing DOPA's in $\chi^{(3)}$ planar waveguides has been the difficulty in separating the pump beam from the signal beam at the waveguide output because both beams have the same polarization.

Recently Shirasaki and Haus[3] proposed a nonlinear Mach–Zehnder interferometer (NMZI) DOPA scheme in which an identical $\chi^{(3)}$ waveguide is placed in each arm of the interferometer, as shown in Fig. 1. In this scheme pump P and signal S enter the interferometer from opposite sides of an input 50/50 beam splitter. After the signal is amplified by the pump by a parametric process in the nonlinear waveguides, the pump is separated from the amplified signal at the output 50/50 beam splitter. The NMZI DOPA scheme was demonstrated in optical fibers with a nonlinear loop mirror configuration.[4,5] In principle, this scheme can also be realized with two identical $\chi^{(3)}$ planar waveguides and active stabilization of the interferometer. However, the difficulty in fabricating two identical waveguides and the complexity of active stabilization make this scheme less attractive for future device realization.

In this Letter we describe a novel pulse-delayed scheme for realizing DOPA's in $\chi^{(3)}$ planar waveguides. The scheme utilizes two identical birefringent plates, one placed before and one after a $\chi^{(3)}$ planar waveguide, to implement a single-arm, pulse-delayed NMZI.[6] The key element in the scheme is the birefringent plates that are used as polarization-sensitive optical pulse delay lines. Our scheme is equivalent to the two-arm NMZI DOPA scheme but differs in that it replaces the spatial separation of pulses in the two arms with a time separation in a single arm.

Figure 2 is a schematic diagram of our DOPA scheme; the polarizations of the pulses at positions A–E are shown in the inset. A linearly polarized pump pulse P and an orthogonally polarized signal pulse S are combined at polarization beam splitter cube PBS2. Their polarizations at position A are shown in the inset where the signal is polarized along the y axis and the pump is polarized along the x axis. Using half-wave plate HP3, we rotate the polarization of both the pump and the signal pulses by 45°. The pump and the signal pulses are then sent through birefringent plate BP1, which has its fast and slow axes aligned with the x and the y axes, respectively, as shown in the inset at B. The pump and the signal pulses interfere at BP1, resulting in a P + S pulse polarized along the slow axis (y axis) and in a P − S pulse polarized along the fast axis (x axis), as shown in the inset at C. Because of the difference in propagation velocities between the fast and slow axes of BP1, the P + S pulse becomes delayed in time by an amount T with respect to the P − S pulse at the output of BP1. This time delay is given by $T = d\Delta n/c$, where d is the thickness of the plate, Δn is the refractive-index difference between the fast and the slow axes, and c is the speed of light in vacuum. The time delay T must be such that the leading P − S pulse and the trailing P + S pulse are completely separated in time. Otherwise, an elliptically polarized component will be generated that will degrade the performance of the DOPA.

After going through BP1, the P − S and the P + S pulses are coupled into the $\chi^{(3)}$ waveguide, exciting a TE and a TM mode, respectively. In the $\chi^{(3)}$ waveguide the signal components of P − S and P + S pulses are either amplified or deamplified (depending on the signal–pump phase mismatch) by their respective pump components by means of the parameteric process. Because the parametric gain as a func-

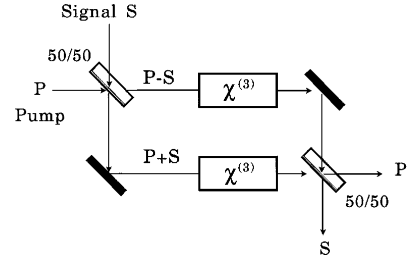

Fig. 1. NMZI scheme for a $\chi^{(3)}$-based degenerate OPA.

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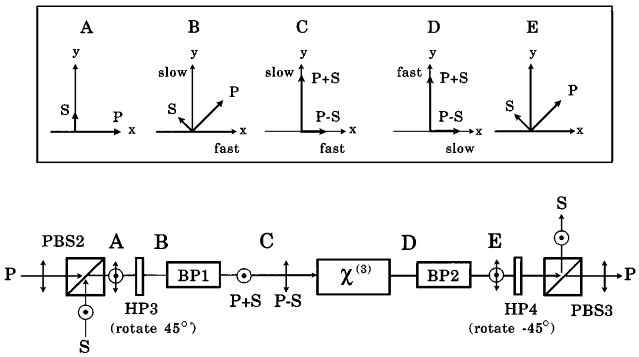

Fig. 2. Novel pulse-delayed DOPA scheme.

tion of the signal–pump phase mismatch has a π periodicity, both signal components are amplified or deamplified simultaneously. We can see this by noting that, if the pump and the signal fields in the P + S pulse are in phase, then the pump and the signal fields in the P − S pulse will be out of phase by π. The amplification of the signal pulse will be maximum when the signal–pump phase mismatch is either 0 or π. After going through the waveguide, the leading P − S pulse and the trailing P + S pulse pass through a second birefringent plate, BP2, which is identical to BP1 but with its slow and fast axes rotated by 90°, as shown in the inset at D. At BP2 the trailing P + S pulse overlaps the leading P + S pulse in time, and the two interfere, resulting in a pump pulse P orthogonally polarized to an amplified signal pulse S, as shown in the inset at E. We spatially separate the pump pulse from the amplified signal pulse by rotating the polarization of both the pump and the signal by −45°, using half-wave plate HP4, and passing the beams through a polarization beam splitter cube (PBS3). Two important requirements must be satisfied to ensure maximum DOPA gain and minimum pump leakage into the amplified signal at the output of the DOPA: (a) the waveguide material must be isotropic so the signal components in P + S and P − S experience the same gain and (b) the two birefringent plates must be identical to allow the P + S and P − S pulses to overlap completely in time and to interfere at the second birefringent plate.

A schematic of the experimental setup to demonstrate our DOPA scheme is shown in Fig. 3, where the DOPA section is denoted by the dashed box. The laser source was an additive-pulse mode-locked color-center laser (NaCl:OH), generating 220-fs pulses at a 82-MHz repetition rate. We obtained a strong pump beam and a weak orthogonally polarized signal beam by splitting the output of the laser using half-wave plate HP1 and polarization beam splitter PBS1. We varied the pump beam intensity by using a combination of half-wave plate HP2 and polarizer P1. The pump and the signal beams were combined at polarization beam splitter PBS2 (i.e., the pulses spatially and temporally overlap but are still orthogonally polarized) and passed through half-wave plate HP3 and 4-mm-thick calcite birefringent plate BP1, generating the P + S and P − S pulses separated in time by ~2 ps. The optical phase of the signal pulses with respect to the pump pulses was adjusted with a piezoelectric transducer. The P − S and P + S pulses were end-fire coupled into a 2.2-cm-long strip-loaded AlGaAs waveguide by 40× microscope objective lens. The AlGaAs waveguide comprised a 1.0-μm-wide by 1.5-μm-thick $Al_{0.27}Ga_{0.73}As$ stripe, a 1.5-μm-thick $Al_{0.23}Ga_{0.77}As$ guiding layer, and a 3.5-μm-thick $Al_{0.27}Ga_{0.73}As$ lower cladding layer, all grown on top of a semi-insulating GaAs substrate. The waveguide had an estimated mode cross-sectional area of 5 μm^2. After going through the waveguide, the pulses were recollimated and passed through a second 4-mm-thick calcite plate (BP2), where the P − S and P + S pulses overlapped in time and interfered to yield orthogonally polarized pump and amplified signal pulses. The separation of the pump from the signal was accomplished by the combination of half-wave plate HP4 and polarizing beam splitter cube PBS3. The amplified signal was detected by photodiode PD1.

Figure 4 shows typical data traces obtained in our experiments. Figure 4(a) shows the output signal for the cases when the pump is on and off as a function of the signal–pump phase mismatch, normalized to the output signal level when the pump is off. We varied the signal–pump phase mismatch by varying the phase of the input signal at 100 Hz with a piezoelectric transducer. As can be seen from Fig. 4(a), when the pump is on the signal experiences both parametric amplification and parametric deamplification as the phase of the input signal is varied. A maximum signal parametric gain of 3.3 was obtained when the signal–pump phase mismatch was 0 or π, whereas the maximum parametric deamplification was ~0.5 when the signal–pump phase mismatch was $\pi/2$ or $3\pi/2$. Note that adjacent deamplification maxima have unequal magnitude; we attribute the fact to the expansion (less than a full wavelength) of the piezoelectric transducer. For this case the pump and the signal intensities inside the waveguide were estimated to be 1.16 and 0.35 GW/cm^2, respectively. Figure 4(b) shows the interference between the pump and the signal pulses that we obtained by splitting off a small percentage of the beam after PBS2. A comparison between Figs. 4(a) and 4(b) shows that the amplification maxima of the signal have a period that is twice that

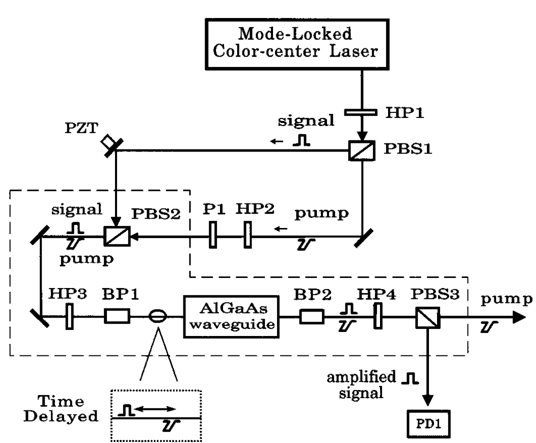

Fig. 3. Experimental setup to demonstrate the pulse-delayed DOPA, using AlGaAs waveguides.

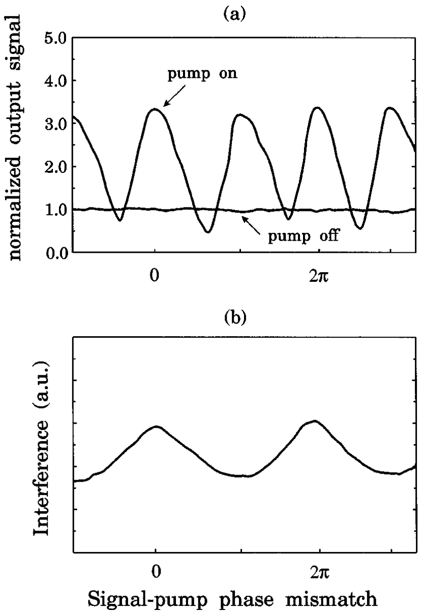

Fig. 4. (a) Normalized output signal for the cases when the pump is on and off: $I_p = 1.16\ \mathrm{GW/cm^2}$ and $I_s = 0.35\ \mathrm{GW/cm^2}$; (b) interference between pump and signal as a function of the pump–signal phase mismatch.

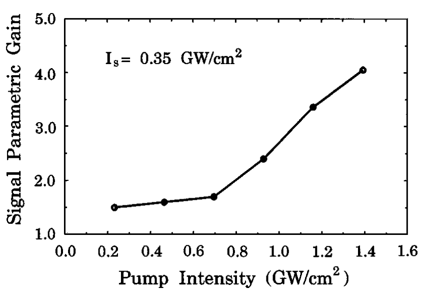

Fig. 5. Normalized degenerate OPA gain of the input signal as a function of pump intensity inside the AlGaAs waveguide.

of the interference maxima, which confirms that the signal amplification results from a parametric process. As mentioned above, it is important to minimize the amount of pump leakage into the amplified signal. In the experiments the amount of pump leakage was found to be ~5% of the input pump, and we determined it by blocking the input signal beam. In all the parametric gain measurements the pump leakage was subtracted from the amplified signal trace.

Figure 5 shows the normalized DOPA gain of the signal as a function of pump intensity in the AlGaAs waveguide for the case when the signal intensity was $I_s = 0.35\ \mathrm{GW/cm^2}$ and the signal–pump phase mismatch was zero. As the figure shows, when the pump intensity I_p was low, in the range 0.2–0.7 $\mathrm{GW/cm^2}$, there was a modest signal parametric gain. However, as the pump intensity was increased to the maximum available level of $\sim 1.4\ \mathrm{GW/cm^2}$, the parametric gain increased substantially. The behavior of the parametric gain can be understood from the equation[4] $I_s^{\mathrm{norm}} = (I_p/I_s)\sin^2(\phi_{\mathrm{nl}}) + \cos^2(\phi_{\mathrm{nl}})$, where $\phi_{\mathrm{nl}} = (2\pi/\lambda)n^{(2)}L\sqrt{I_p I_s}$ is the nonlinear phase shift. Here I_s^{norm} is the amplified signal normalized by the input signal, λ is the wavelength of light in free space, $n^{(2)} = 3.2 \times 10^{-14}\mathrm{cm^2/W}$ is the intensity-dependent refractive index of AlGaAs,[7] L is the waveguide length, I_p is the pump intensity, and I_s is the signal intensity. In the low pump intensity regime, ϕ_{nl} is less than 0.5 π, which from the above equation shows that the gain is proportional to $I_s^{\mathrm{norm}} = (I_p/I_s)\sin(\phi_{\mathrm{nl}})^2$. Because the pump intensity is approximately twice the signal intensity, the maximum normalized gain will be limited to less than 2. As the pump intensity increases, the normalized signal gain is proportional to $I_s^{\mathrm{norm}} = I_p/I_s$, because the sinusoidal component $\sin(\phi_{\mathrm{nl}})^2 \sim 1$. For the maximum available pump intensity of $I_p = 1.4\ \mathrm{GW/cm^2}$ the normalized gain is ~4, in agreement with the experimental data. In general, the gain of the DOPA is limited by the ratio of the pump-to-signal intensity. In our experiments, the gain was limited to ~4 (6 dB) because of the 5% pump leakage, which sets the lower limit on the input signal intensity.

In summary, we have presented a novel pulse-delay scheme to realize degenerate optical parametric amplification in $\chi^{(3)}$ waveguides. The scheme consist of a single-arm, pulse multiplexed interferometer that uses two identical birefringent plates, one placed before and one after a $\chi^{(3)}$ waveguide. We demonstrated the scheme by using a 2.2-cm long strip-loaded AlGaAs waveguide and obtained a maximum parametric gain of ~4 (6 dB) for 220-fs pulses at ~1.6 μm.

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