Phase conjugation of pico-second pulses by four wave mixing in a Nd:YVO$_4$ slab amplifier

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Abstract: We demonstrate 80 times phase conjugation by four-wave mixing of pico-second pulses in a diode-pumped Nd:YVO$_4$ amplifier. Slight pulse broadening as a result of four wave mixing processes was observed.

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OCIS codes: (190.5040) Phase conjugation; (320.5390) Picosecond phenomena; (140.3580) Lasers, solid-state; (140.3280) Laser amplifiers.

References and links

1. T. Omatsu, T. Imaizumi, M. Amano, Y. Ojima and K. Watanabe, “Multi-watt diffraction-limited picosecond pulses from a diode-pumped Nd:YVO$_4$ amplifier with a photorefractive phase conjugate mirror ,“ J. Opt. A **5** S467-S470 (2003).
2. T. Imaizumi, M. Goto, Y. Ojima and T.Omatsu, “Characterization of a pico-second phase conjugate Nd:YVO$_4$ laser system,” Japansese J. Appl. Phys.**43** 2515-2518 (2004).
3. A. Brignon, D. Geffroy, J. –P. Huignard, M. H. Garrett and I. Mnushkina, “Experimental investigations of the photorefractive properties of rhodium-doped BaTiO$_3$ at 1.06 µm,” Opt. Commun. **137** 311-316 (1997).
4. N. Hout, J. M. C. Jonathan, D. Rytz and G. Roosen, “Self-pumped phase conjugation in a ring cavity at 1.06 µm in cw and nanosecond regimes using photorefractive BaTiO$_3$:Rh,” Opt. Commun. **140** 296-298 (1997).
5. R. S. Cudney, M. Kaczmarek, “Light-induced removal of 180° ferroelectric domains in Rh:BaTiO$_3$,” Opt. Express **7** 323-328 (2000), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-7-9-323.
6. J. C. Diel, I. C. McMicheal and H. V. Vanherzeele, “Degenerate Four-Wave Mixing of Picosecond Pulses in a Saturable Amplification of a Dye laser,” IEEE J. Quantuum. Electron. **QE-20** 630-636 (1984).
7. K. Abe, M. Amano and T. Omatsu, “Efficient phase conjugation by pico-second four-wave-mixing in solid-dye amplifier,” Opt. Express **12** 1243-1248 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-7-1243.
8. A. W. Tucker, M. Birnbaum, C. L. Fincher and J. W. Erler, “Stimulated-emission cross section at 1064 and 1342 nm in Nd:YVO$_4$,” J. Appl. Phys. **48** 4907-4911 (1977).
9. R. A. Fields, M. Birnbaum and C. L. Fincher, “Highly efficient Nd:YVO$_4$ diode-laser end-pumped laser,” Appl. Phys. Lett. **51** 1885-1886 (1987).
10. D. Shen, A.Liu, J. Song and K. Ueda, “Efficient Operation of an Intracavity-Doubled Nd:YVO$_4$ KTP Laser End Pumped by a High-Brightness Laser Diode,” Appl. Opt. **37** 7785-7788 (1998).
11. J. E. Bernard and A J. Alcock, “High-efficiency diode-pumped Nd:YVO$_4$ slab laser,” Opt. Lett. **18** 968-970 (1993).
12. J. E. Bernard, E. McCullough and A J. Alcock, “High gain, diode-pumped Nd:YVO$_4$ slab amplifier ,” Opt. Commun. **109** 109-114 (1994).
13. S. Mailis, J. Hendrics, D. P. Shepherd, A. C. Tropper, N. Moore, R. W. Eason, G. J. Crofts, M. Trew and M. J.Damzen, “High-phase-conjugate ref lectivity (800%) obtained by degenerate four-wave mixing in a continuous-wave diode-side-pumped Nd:YVO$_4$ amplifier,” Opt. Lett. **24** 972-974 (1999).
14. T. Omatsu, Y.Ojima, B. A. Thompson, A. Minassian and M. J. Damzen, “150-times phase conjugation by degenerate four-wave mixing in a continuous-wave Nd:YVO$_4$ amplifier ,” Appl. Phys. B **75** 493-495 (2002).
15. A. Brignon, G. Feugnet, J. –P. Huignard, and J. -P. Pocholle, “Efficient degenerate four-wave mixing in a diode-pumped microchip Nd:YVO$_4$ amplifier,” Opt. Lett. **20** 548-550 (1995).
16. A. Brignon, G. Feugnet, J. –P. Huignard, and J. -P. Pocholle, “Multipass degenerate four-wave mixing in a diode-pumped Nd:YVO$_4$ saturable amplifier ,” J. Opt. Soc. Am. B **12** 1316-1325 (1995).
17. A. E. Siegman, *Lasers* (University Science Books, Mill Vally, 1986), Chap. 9.
18. M. J. Damzen, Y. Matsumoto, G. J. Crofts and R. P. M. Green, “Bragg-selectivity of a volume gain grating,” Opt. Commun. **123** 182-188 (1996).

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1. Introduction

Phase conjugation of ultrafast laser pulses has received a lot of attention, because it can be used in high average power master-oscillator and power-amplifier (MOPA) systems and for pulse synthesis in a pico- or femto-second regime [1].

Omatsu *et al*. have demonstrated 7.5W high quality, pico-second output from a phase conjugate MOPA using a photorefractive Rh-doped $BaTiO_3$ crystal [2]. The use of a photorefractive phase conjugate mirror can allow for a self-pumping geometry as well as a relatively high reflectivity [3,4], and thus, it simplifies the system. However, depoling effects observed when using 1μm laser radiation limits frequently power scaling of the system [5].

An alternative solution for obtaining efficient phase conjugation of ultrafast lasers is four-wave mixing (FWM) based on gain-gratings formed in a laser amplifier. Pico-second phase conjugation by FWM in a jet dye amplifier [6], and a solid-dye amplifier [7] have been demonstrated in the visible region. However, there are few reports concerning pico-second phase conjugation in the infrared region, in which practical solid-state lasers lase.

Phase conjugation based on the formation of gain-gratings by pico-second pulses requires a high small-signal gain as well as a broad emission band to the laser amplifier. A Nd:YVO_4 crystal having a large stimulated emission cross-section ($\sim 2\text{x}10^{-18}\text{cm}^2$) as well as a relatively broad emission-band (~1nm) compared with conventional Nd:YAG crystal, is a promising candidate for using as a phase conjugate mirror for pico-second pulses [8-10].

In this Letter, we demonstrate 80-times phase conjugation of pico-second pulses by four-wave-mixing in a diode-pumped Nd:YVO_4 slab amplifier. The reflectivity obtained is the highest, to the best of our knowledge, obtained by phase conjugation in the pico-second regime. We have also investigated the diffraction efficiency and wavelength selectivity of the gain-gratings in the Nd:YVO_4 amplifier. The maximum experimental diffraction efficiency achieved was 20-times.

2. Experiments

2.1 Phase conjugation

Figure 1 is a schematic diagram of the experimental setup. A a-cut Nd:YVO_4 slab with 1.0at.% Nd^{3+} ions doping was used for as an amplifier having a bounce geometry [11,12]. Its dimensions were 20mm x 5mm x 2mm. The pump surface was anti-reflection coated for 808nm. The end surfaces of the crystal were anti-reflection coated for 1064nm, and they were cut at 2^o relative to the normal of the pump face to suppress self-lasing within the crystal. The crystal, wrapped in indium foils, was sandwiched between two aluminum blocks whose temperature was maintained at $\sim 10^o$C by a water re-circulating chiller. The diode used was a 50W CW single-bar diode array and its output was focused to a line with dimensions 0.3mm x 10mm onto the crystal. The diode polarization was parallel to the c-axis of the crystal, thereby yielding maximum pump absorption.

A diode-pumped CW mode-locked Nd:YVO_4 laser was used as a probe, forward-pump and backward-pump beams for FWM in the amplifier. Its pulse repetition frequency and pulse duration were 100MHz and 7ps, respectively. An optical isolator was placed between the laser and the amplifier to prevent phase conjugate feedback to the laser. The probe and forward pump beams formed a transmission grating in the amplifier. A prism was used for optimizing the temporal overlapping between probe and forward-pump pulses. A backward-pump beam was deflected by the grating, and produced the phase conjugate beam. To prevent the formation of a reflection grating, we made the optical path difference between the forward- and backward-pump beams considerably longer than the coherence length. All beams (probe, forward-pump, and backward-pump beams) were focused inside the amplifier to be a ϕ0.2mm spot, thereby yielding good spatial overlapping among all beams. Their polarization was parallel to the c-axis of the crystal, thereby maximizing the amplification.

The external grazing angle of the probe beam to the pump surface was 6^o, and the external angle between probe and forward pump beams was 4^o (the corresponding internal angle between probe and forward pump beams was $\sim 2^o$). Under these conditions, the experimental

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single-pass gain of the probe beam was approximately 9,000. The power ratio of the probe, forward pump and backward-pump beams was 0.1:1:0.83.

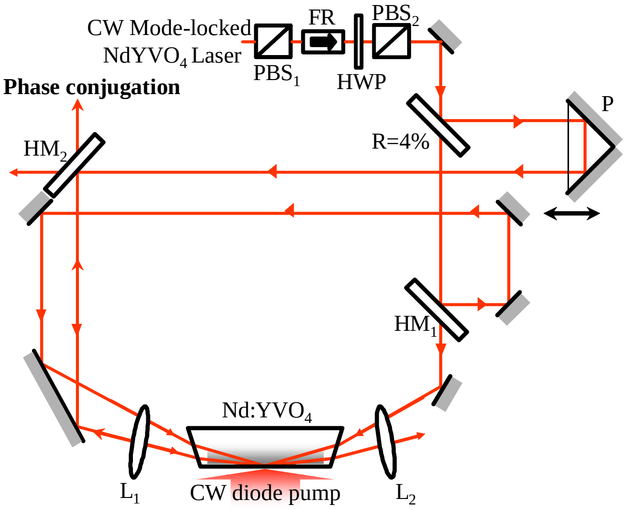

Fig. 1. Schematic diagram of experimental setup for phase conjugation. L$_1$, L$_2$,spherical lenses (focal length 100mm); HM$_1$, HM$_2$, half mirrors; PBS$_1$, PBS$_2$, polarizing beam splitters; FR, faraday rotator; HWP, half wave plate, P, prisms.

The experimental phase conjugate reflectivity as a function of forward-pump average intensity normalized to saturation intensity I_s for two gain levels is shown in Fig. 2. The reflectivity is defined as the phase conjugate power divided by the probe beam power. A maximum reflectivity of 80 was obtained, and then the average power of phase conjugation was ~40mW. The peak reflectivity occurred at a forward pump average intensity of $0.009I_s$(~5mW). When the single-pass gain decreased, the maximum phase conjugate reflectivity also decreased. In this case, the forward pump average intensity required for maximum reflectivity increased. These results are consistent with those reported earlier for phase conjugation based on gain-grating in CW and nano-second regimes [13-16].

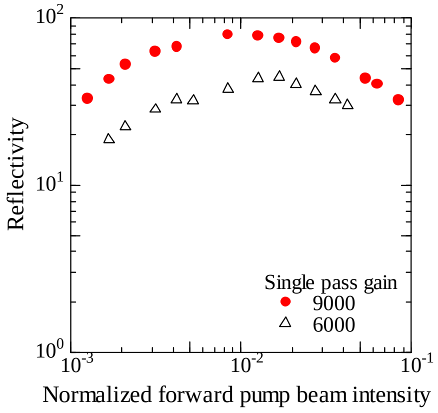

Fig. 2. Experimental phase conjugate reflectivity as a function of normalized forward pump beam intensity.

Experimental far-field patterns of the phase conjugation are shown in Fig. 3(c). Though the phase conjugation exhibited a slight ellipsoidal spot in the far field, it exhibited a beam propagation factor M^2 of < 1.2. To investigate the potential of phase correction in our system, we placed an aberrating plate along the optical path of the probe beam. As shown in Fig. 3(d), the phase conjugation was not affected at all. This shows that the phase conjugate mirror is capable of compensating for phase aberration.

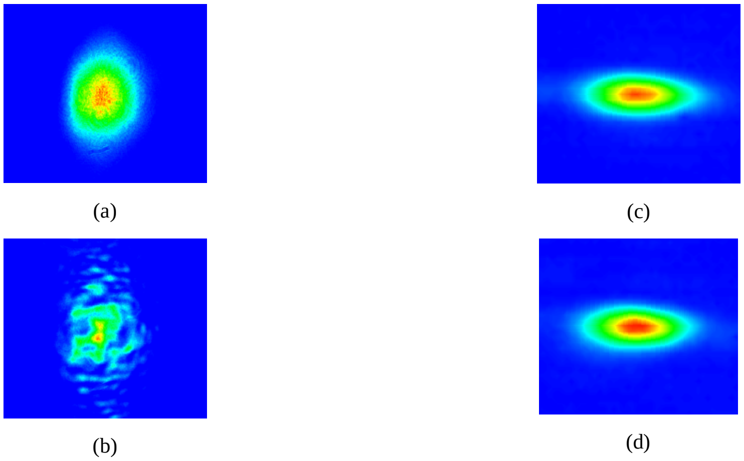

Fig. 3. Experimental far field spatial forms of (a) the probe beam, (b) the probe beam with the phase aberrating plate, (c) the phase conjugation and (d) the phase conjugation with the phase aberrating plate.

2.2 Diffraction efficiency

We also investigated the diffraction efficiency of the gain-grating formed in the amplifier. The experimental setup is almost the same as that for phase conjugation except for the power ratio of the probe, forward pump and backward pump beams. The power ratio of the probe, forward pump and backward-pump beams was 1.3:1.0:0.11. Figure 4 shows experimental plots of diffraction efficiency as a function of the forward pump average intensity normalized to saturation intensity I_s. The diffraction efficiency is defined as the diffraction power divided by the backward-pump power. A maximum diffraction efficiency of 20 times was obtained. Experimental peak diffraction appeared around the pump average intensity of approximately $0.003I_s$.

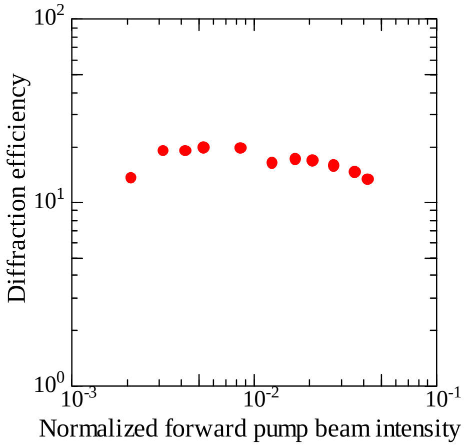

Fig. 4. Experimental diffraction efficiency as a function of normalized forward pump beam intensity.

2.3 Temporal evolution of phase conjugation

The experimental intensity autocorrelation trace of the phase conjugation, obtained by second harmonic generation in a 5mm KTP crystal, is shown in Fig. 5. The phase conjugate pulse exhibited a FWHM of 13ps, which corresponds to a pulse width of 9.2ps for a Gaussian-shaped pulse. Slight pulse broadening was observed.

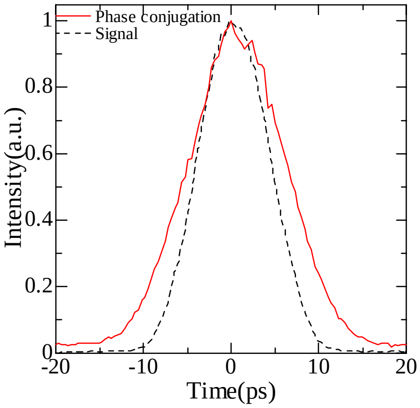

Fig. 5. Intensity autocorrelation traces of the signal pulse (dashed line) and the phase conjugation (solid line).

Frequency narrowing due to the finite wavelength selectivity of the gratings formed in the phase conjugate mirror frequently makes the phase conjugate pulse broader [17]. To confirm the mechanism of pulse broadening, we simulated numerically the wavelength selectivity of the phase conjugate mirror using the coupled mode equations including the phase-mismatching factor due to the wavelength detuning [18]. The relatively short coherence length (~3mm) of the pico-second pulses can prevent the formation of the reflection and 2k gratings in the Nd:YVO$_4$ amplifier. To simplify the numerical model (Fig. 6), we assumed that the formation of the reflection and 2k gratings were negligible and that all beams overlap completely in the gain length. In this case, the coupled mode equations can be written as follows,

$$\frac{dA_1}{dz} = \gamma A_1 - \kappa A_3 \tag{1}$$

$$\frac{dA_2}{dz} = -\gamma A_2 + \kappa A_4 \tag{2}$$

$$\frac{dA_3}{dz} = \gamma A_3 - \kappa A_1 \tag{3}$$

$$\frac{dA_4}{dz} = -\gamma A_4 + \kappa A_2 \tag{4}$$

$$\gamma = g(\Delta\omega)(S^2 - C^2)^{-1/2} + j\eta(\Delta\omega) \tag{5}$$

$$\kappa = g(\Delta\omega)C[1 - S(S^2 - C^2)^{-1/2}] \tag{6}$$

$$g(\Delta\omega) = g_0 \exp\left(-\ln 2\left(\frac{\Delta\omega}{\Delta\omega_0}\right)^2\right) \tag{7}$$

$$\eta(\Delta\omega) = \frac{\pi\Delta\omega}{n_0 \Lambda^2 \cos\theta} \tag{8}$$

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$$S = 1 + \sum_{j=1}^{4} A_1{}^2 / I_S \tag{9}$$

$$C = 2(A_1 A_3 + A_2 A_4) / I_S \tag{10}$$

, where A_1, A_2, A_3, and A_4 are the amplitudes of the forward pump, backward pump, probe, and phase conjugation respectively, γ is the gain term, κ is the transmission grating coupling term, $\Delta\omega$ is the detuning frequency from the center of lasing spectrum, g_0 is the signal gain of amplifier, $\Delta\omega_0$ is the gain-band for amplifier, n_0 is the refractive index of amplifier, Λ is the grating period, θ is Bragg's angle of the gain grating, and I_s is the saturation intensity, respectively.

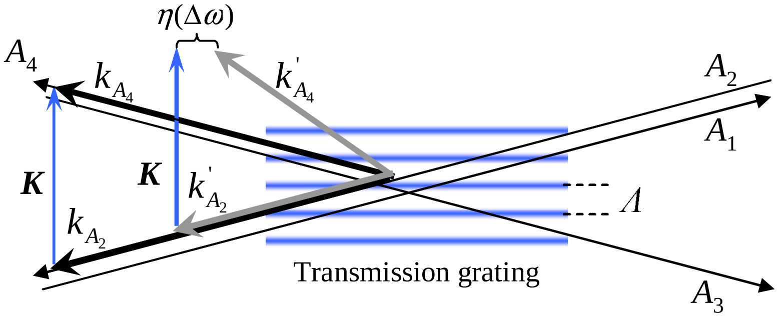

Fig. 6. Schematic diagram of numerically simulated model. K is wave number vector of the grating. k_{A_2} and k_{A_4} are wave number vectors of backward pump beam and phase conjugation at $\omega=\omega_0$. k'_{A_2} and k'_{A_4} represent wave number vectors at $\omega=\omega_0+\Delta\omega$ ($\Delta\omega>0$). $\eta(\Delta\omega)$ is the phase mismatching.

Substituting the parameters (λ=1064nm, and $\theta = 2^o$) into Eqs. (1)-(10), the diffraction efficiency as a function of detuning frequency at different forward pump levels was simulated. The small signal gain was fixed to be 9,000. The simulated results are shown in Fig. 7. At a detuning frequency of 0, a diffraction efficiency was as high as ~4,000% is predicted at a forward pump intensity of $0.025 I_S$. The wavelength selectivity $\Delta\lambda_{pcm}$ of the phase conjugate mirror, defined as a FWHM of the diffraction efficiency, was mainly limited by the finite gain-band of the amplifier itself, and, it was estimated to be 0.7nm. This wavelength selectivity $\Delta\lambda_{pcm}$ is comparable with the spectrum bandwidth of a pico-second laser used in our experiments (0.35nm).

The internal angle between probe and forward pump beams is ~2°, and thus, the actual FWM region is approximately 60% of the gain-length seen by probe beam. In the case of partial overlap of the beams in the gain-length, the pump intensity required for gain-grating formation is one- or two-orders of magnitude higher than that in the case of complete overlap of the beams [13, 14]. And thus, it is expected that the actual wavelength selectivity is slightly broader than $\Delta\lambda_{pcm}$.

According to a numerical estimation ($1/\Delta\lambda_{pc}=1/\Delta\lambda_{pcm}+1/\Delta\lambda_{probe}$) based on a conventional convolution integral, the spectrum bandwidth of phase conjugation was estimated to be 0.23nm. The experimental spectrum bandwidth of phase conjugation was measured to be 0.19nm as shown in Fig. 8, and it was consistent with the simulated value. The corresponding Fourier-transform-limit is 8.8ps. These show that the frequency narrowing due to the finite wavelength selectivity of the gain-grating formed in the amplifier is the main cause of pulse broading. We also simulated the wavelength selectivity as a function of the forward pump fluence as shown in Fig. 7(b).

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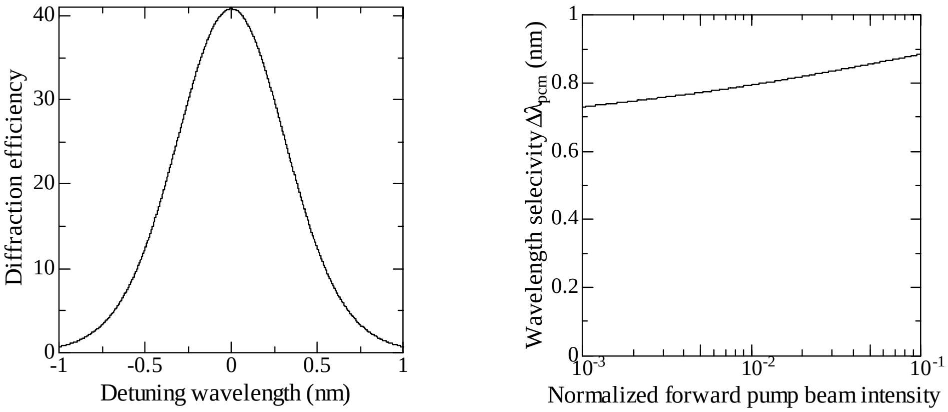

(a) (b)

Fig. 7. (a) Numerically simulated diffraction efficiency at the forward pump of 0.025 I_s as a function of detuning frequency. (b) Numerically simulated wavelength selectivity as a function of normalized forward pump beam intensity

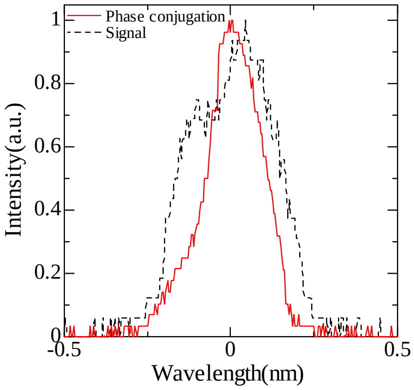

Fig. 8. Experimental frequency spectra of the signal pulse (dashed line) and the phase coinjugation (solid line). Origin is 1064.5nm.

3. Conclusion

In conclusion, we have demonstrated efficient phase conjugation of pico-second pulses by four-wave-mixing based on gain-gratings formed in the diode-pumped Nd:YVO_4 amplifier. A maximum reflectivity of 80 was obtained. The pulse duration of phase conjugation was 9.2ps. Pulse broadening effects observed was due to the finite wavelength selectivity of the gain-grating.

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