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Phase conjugation in a continuous-wave diode-pumped Nd:YVO_4 laser

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Abstract. We demonstrate phase conjugation and dynamic holography by degenerate four-wave mixing in a continuous-wave diode-pumped Nd:YVO_4 laser for the first time. A phase-conjugate reflectivity of 1.4% is obtained with a 12 W diode power. The experimental results and the optimizing parameters, such as the cavity mirror reflectivities, are compared with results from a steady-state theoretical analysis.

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In recent years, phase conjugation by degenerate four-wave mixing (DFWM) in saturable gain media has been the subject of intense investigation for applications to dynamic holography [1] and laser architectures with intracavity phase distorsion compensation [2, 3]. The use of laser amplifiers for such operations presents very attractive features, including the automatic matching of the nonlinearity with the laser wavelength, a fast response time and a high efficiency of the nonlinear process due to the laser amplification of all interacting beams. Saturable-gain DFWM has been demonstrated in solid-state laser media such as flash-lamp-pumped Nd:YAG [4–8], diode-pumped Nd:YVO_4 [9] and laser-pumped Ti:sapphire [10]. Most of these experiments have been performed in the transient regime, i.e., with pulses much shorter than the population relaxation time. Continuous-wave (cw) operation of DFWM in a solid-state laser amplifier has also been reported in a Nd:YVO_4 amplifier pumped by a cw Ti:sapphire (Ti:S) laser [11]. However, the use of a Ti:S laser as the pumping source is a limitation for practical application. The aim of this article is to demonstrate, for the first time, to our knowledge, cw DFWM and dynamic holography in a compact, easy-to-handle diode-pumped Nd:YVO_4 gain medium.

The scheme that we used (see Fig. 1) is similar to the one described by Fisher and Feldman, who used a CO_2 laser [12], or by Tomita, who used a flash-lamp-pumped Nd:YAG laser [4]. In this scheme, the laser itself is used as a phase-conjugate mirror, so that only one gain medium is required. The medium, of length L, is placed in a linear cavity formed by two mirrors M_1 and M_2 with reflectivities R_1 and R_2, respectively. We assume that M_2 is the output mirror of the laser. A portion of the laser output is used as a signal beam and is injected back into the gain medium at an angle θ with respect to the laser axis. Since two intracavity counterpropagating beams already exist in the laser, the interaction between these beams and the injected signal produces the conjugate beam propagating backwards along the same path as the signal. To enhance the efficiency of the DFWM process, a two-pass DFWM geometry can be used in which the signal beam is directed back into the laser medium after reflection from some properly placed mirrors (not shown in Fig. 1). In the plane-wave approximation, and with the assumption of weak signal and conjugate fields, the following coupled-wave equations can be derived [11, 13]:

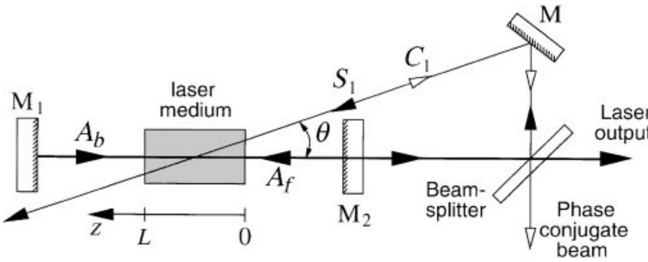

Fig. 1. Schematic of DFWM in the laser itself

$$\frac{dA_f}{dz} = \left(\gamma_0 - \gamma_1 \frac{|A_b|}{|A_f|}\right) A_f \,, \tag{1a}$$

$$-\frac{dA_b}{dz} = \left(\gamma_0 - \gamma_1 \frac{|A_f|}{|A_b|}\right) A_b \,, \tag{1b}$$

$$(-1)^{j+1} \frac{dS_j}{dz} = \alpha S_j - \kappa C_j^* \,, \tag{1c}$$

$$(-1)^{j} \frac{dC_j}{dz} = \alpha C_j - \kappa S_j^* \,. \tag{1d}$$

For $j = 1$, the four coupled-wave equations describe the conventional DFWM, in which the signal experiences a single pass in the gain medium, whereas for $j = 1$ and 2, the six equations describe the two-pass geometry. A_f and A_b denotes the amplitudes of the forward and backward pump beams, respectively. The nonlinear gain coefficients γ_0 and α and the coupling coefficients γ_1 and κ are spatially averaged over a grating period; their expressions can be found in [11]. The C_j and S_j $(j = 1, 2)$ are the amplitudes of the phase-conjugate and signal beams, respectively. Equation (1) can be solved numerically with the following boundary conditions: $A_f(0) = R_2^{1/2} A_b(0)$, $A_b(L) = R_1^{1/2} A_f(L)$, where $S_1(0)$ is the input signal, $C_1(L) = 0$ for $j = 1$, and $S_2(L) = R_1^{1/2} S_1(L)$, $C_2(0) = 0$, $C_1(L) = R_1^{1/2} C_2(L)$ for $j = 2$. This yields the phase-conjugate reflectivity $R_c = |C_1(0)/S_1(0)|^2$. The phase-conjugate reflectivity is plotted in Fig. 2 as a function of the output-mirror reflectivity R_2. For these calculations, a small-intensity gain-length product $\alpha_0 L$ of 4 has been chosen. For a conventional linear cavity with $R_1 = 100\%$, a maximum phase-conjugate reflectivity $R_c = 20\%$ is reached for an output coupler reflectivity of $R_2 \simeq 1\%$. Since the value of R_2 controls the degree of saturation of the gain medium, it can be seen that R_c is low for small values of R_2 (small degree of saturation), i.e., near the threshold of the laser, and for large values of R_2 (high degree of saturation). It is worth noting that R_c can be optimized by reducing R_1. Indeed, R_1 allows the ratio between the backward pump beam and the forward pump beam to be controlled. A maximum phase-conjugate reflectivity of about 100% can be obtained for equal pump beam ($R_1 \simeq R_2 \simeq 5\%$ in our example), which is consistent with previous analyses of DFWM in laser amplifiers [13].

The experimental setup of cw DFWM with a diode-pumped Nd:YVO_4 laser is shown in Fig. 3. The water-cooled a-cut 1-at. % doped Nd:YVO_4 crystal has a cross-sectional area of 5 mm × 5 mm and a thickness of $L = 5$ mm. The right-hand face of the crystal is antireflection-coated (AR-coated) at 1064 nm, whereas the left-hand face, which serves as the rear mirror M_1 of the laser resonator, is AR-coated at 808 nm and high-reflection-coated at 1064 nm. The crystal is longitudinally pumped by a diode laser bar coupled through a 600-μm-core fiber with a numerical aperture of 0.22 and an output power of 12 W. The fiber output is placed close to the crystal end without any intermediate optics. The cw gain of the inverted Nd:YVO_4 crystal is measured with a probe beam of a few milliwatts at 1064 nm, provided by a cw diode-pumped Nd:YAG laser. The diameter of the probe beam is adjusted to 600 μm to match the gain region in the crystal. By taking into account the slight detuning between the Nd:YAG and Nd:YVO_4 resonance frequencies, an unsaturated two-pass amplification factor of 7.5 was measured at the Nd:YVO_4 resonance frequency, giving a single-pass small-intensity gain-length product $\alpha_0 L = 1$. An interesting feature of such an amplifier is its large angular bandwidth of ±30° (FWHM). Also note that the amplification factor remains unchanged for incident angles θ less than 10°.

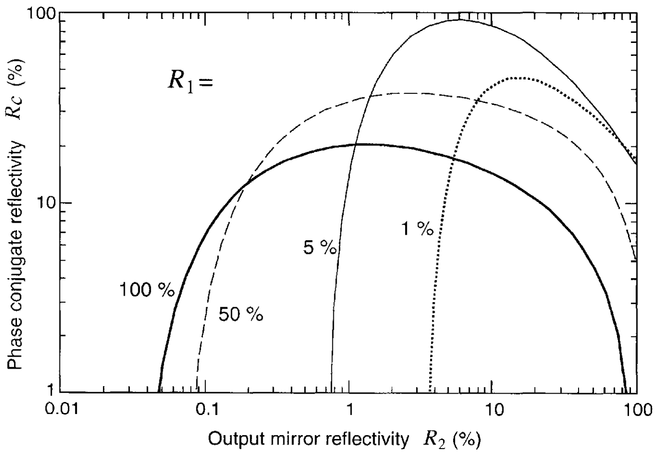

Fig. 2. Theoretical curves of the phase-conjugate reflectivity as a function of the ouput mirror reflectivity R_2 for various values of the rear mirror reflectivity R_1. The single-passs geometry and a small-imtensity gain-length product $\alpha_0 L = 4$ have been assumed

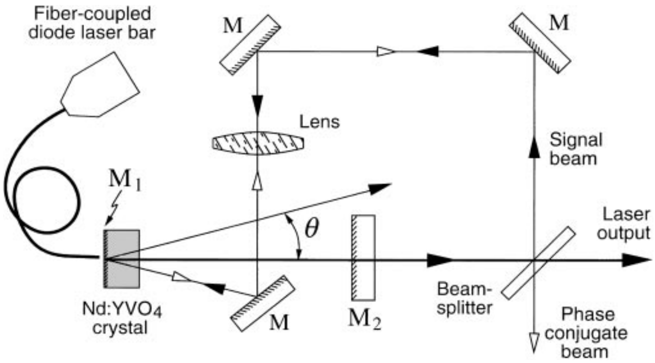

Fig. 3. Experimental setup of cw DFWM in a diode-pumped Nd:YVO_4 laser. M, high-reflectivity flat mirrors

As shown in Fig. 3, the laser cavity is closed by a flat output coupler M_2 at a distance of about 10 cm from the Nd:YVO_4 crystal. The strong thermal lensing effect in the gain medium means that such a cavity is stable and equivalent to a plano-concave resonator. An output power up to 4 W is obtained in the TEM_{00} mode with an $R_2 = 87\%$ output coupler, giving an optical-to-optical efficiency of 33%. The experimental output power of the laser at 1064 nm versus R_2 is plotted in Fig. 4. These results are in good qualitative agreement with the theoretical normalized outpout power η given by

$$\eta = \frac{(1 - R_2)\,|A_b(0)|^2}{\alpha_0 L\, I_{sat}}\,, \tag{2}$$

and calculated by solving (1a)–(1b) with $R_1 = 99\%$. In (2), I_{sat} denotes the saturation intensity. Contrary to the coventional Rigrod analysis [14, 15], our calculation takes into account the spatial hole-burning effect or induced-grating coupling effects caused by the interference between the forward- and backward-traveling waves inside the laser cavity.

DFWM in the Nd:YVO_4 laser was performed by directing a small portion of the laser output back into the gain medium. As shown in Fig. 3, a focusing lens was used to focus the signal beam into the crystal to a 200-μm-diameter spot so that it could spatially overlap the gain region and the counterpropagating DFWM pump beams. In all experiments, the incident signal beam angle was $\theta = 10°$. Owing to the low coherence length of the laser, the path length of the signal was carefully adjusted to be a multiple of the cavity length to make all the beams interfer. The measured phase-conjugate reflectivity is plotted in Fig. 5 as a function of the output coupler reflectivity. In this experiment,

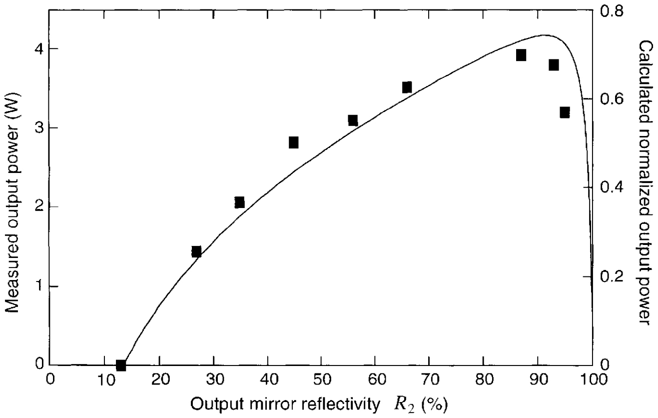

Fig. 4. Experimental data and theoretical curve of the laser output power as a function of the output mirror reflectivity

the pump-to-signal beam intensity ratio β was 5. A maximum phase-conjugate reflectivity of 0.55% was obtained for $R_2 = 45\%$. It can be seen that the output coupler reflectivity that optimizes the phase conjugate reflectivity is smaller than the one that optimizes the laser output power. This observed behavior is in reasonably good agreement with the theoretical curve calculated by solving (1) in the two-pass DFWM case ($j = 1$ and 2). However, the measured reflectivities are less than the predicted ones, which can be explained by the limited temporal coherence of the laser and the plane wave and weak signal approximations used to calculate the curve. With the optimized output coupler ($R_2 = 45\%$), a phase-conjugate reflectivity of 1.4% was obtained for a weaker signal ($\beta = 30$), which is closer to the theoretical prediction ($R \simeq 9\%$). It is also expected that a more sophisticated laser design with a spectral filtering device would lead to even higher experimental reflectivities. It is interesting to note that the phase-conjugate beam power was rather stable, with peak-to-peak fluctuations less than 2%. In a method similar to the experiment by Tomita [4], the phase conjugate nature of the return beam was confirmed by inserting a phase plate aberrator whose distorsions were compensated after a double pass.

Cw dynamic holography was also performed in the Nd:YVO_4 laser. After the beamsplitter shown in Fig. 3, the

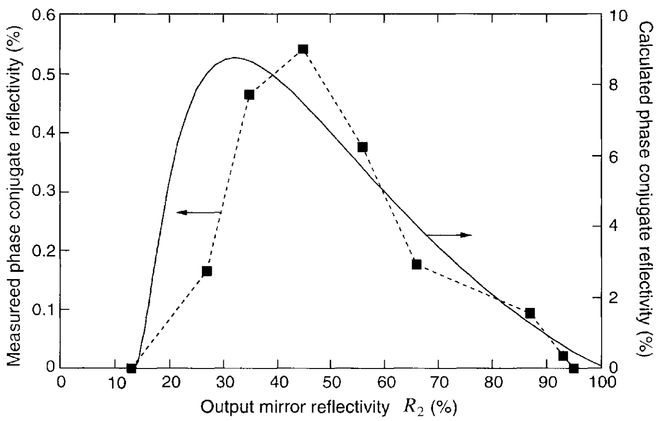

Fig. 5. Experimental data (*points* and *dashed line*) and theoretical curve (*solid line*) of the phase conjugate reflectivity versus the output mirror reflectivity

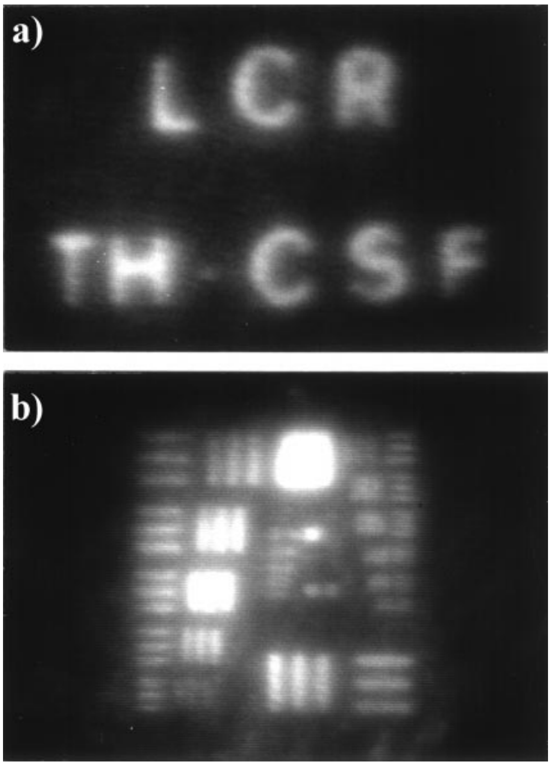

Fig. 6a,b. Phase conjugate images obtained in a cw dynamic holography experiment at 1064 nm in the diode-pumped Nd:YVO_4 laser. **a** Slide with 1.7-mm-high letters. **b** Resolution target

signal was expanded to illuminate a slide or a resolution target. The signal was then refocused into the Nd:YVO_4 crystal to spatially overlap the counterpropagating pump beams. The gain hologram written in the inverted Nd:YVO_4 crystal is simultaneously read out as the generated conjugate image is monitored by a CCD camera. The resulting phase-conjugate images are shown in Fig. 6. In the case of the target (Fig. 6b), the power of the signal beam at the crystal was 300 mW and the beam intensity ratio $\beta = 1$. Under these conditions, the power of the phase conjugate beam was 300 μW ($R_c = 0.1\%$).

In conclusion, we have demonstrated degenerate four-wave mixing in a continuous-wave diode-pumped Nd:YVO_4 laser. Since the laser itself is used as the phase-conjugate mirror, no additional nonlinear material is needed and the counterpropagating pump beams are automatically provided by laser oscillation. By adjusting the reflectivities of the cavity mirrors, it has been theoretically shown that DFWM in the laser itself can be as efficient as DFWM in a separate laser amplifier. Such a technique holds promise for applications in dynamic holography, signal processing and phase conjugation.

References

1. A. Brignon, J.-P. Huignard: J. Imag. Sci. Technol. **41**, 474 (1997)
2. M.J. Damzen, R.P.M. Green, K.S. Syed: Opt. Lett. **20**, 1704 (1995)
3. P. Sillard, A. Brignon, J.-P. Huignard: IEEE J. Quantum Electron. **QE-34**, 465 (1998)
4. A. Tomita: Appl. Phys. Lett. **34**, 463 (1979)
5. G.J. Crofts, R.P.M. Green, M.J. Damzen: Opt. Lett. **17**, 920 (1992)

6. A. Brignon, J.-P. Huignard: IEEE J. Quantum Electron. **QE-30**, 2203 (1994)
7. A. Brignon, J. Raffy, J.-P. Huignard: Opt. Lett. **19**, 865 (1994)
8. R.P.M. Green, G.J. Crofts, M.J. Damzen: Opt. Lett. **19**, 393 (1994)
9. A. Brignon, G. Feugnet, J.-P. Huignard, J.-P. Pocholle: Opt. Lett. **20**, 548 (1995)
10. G.J. Crofts, X. Banti, M.J. Damzen: Opt. Lett. **20**, 1634 (1995)
11. A. Brignon, J.-P. Huignard: Opt. Lett. **20**, 2096 (1995)
12. R.A. Fisher, B.J. Feldman: Opt. Lett. **4**, 140 (1979)
13. J. Reintjes, B.L. Wexler, N. Djeu, J.L. Walsh: J. Phys. (Paris) **44**, C2-27 (1983)
14. W.W. Rigrod: J. Appl. Phys. **36**, 2487 (1965)
15. A.E. Siegman: *Lasers* (University Science Books, Mill Valley, CA 1986) pp. 485–489