

Continuous-wave diode-pumped Nd:YVO₄ holographic laser oscillator

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We present the use of the gain grating technique in the construction of a continuous-wave diode-pumped Nd:YVO₄ holographic laser oscillator. The oscillator was able to produce a small signal gain of $\approx 7 \times 10^7$ and a relatively circular TEM₀₀ spatial mode with an output power of ≈ 5.7 W.

Keywords: Nd:YVO₄; diode-pumped lasers; adaptive oscillators; optical phase conjugation

Presentamos la aplicación de la técnica de rejillas de ganancia en la construcción de un oscilador láser holográfico de Nd:YVO₄ de onda continua bombeado por diodos. El oscilador fue capaz de producir una ganancia de pequeña señal de $\approx 7 \times 10^7$ y un modo espacial TEM₀₀ relativamente circular con ≈ 5.7 W de salida.

Descriptores: Nd:YVO₄; láseres bombeados por diodos; osciladores adaptivos; conjugación de fase óptica

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1. Introduction

Nowadays good spatial quality and high-power beams are needed for laser systems to fulfill the requirements of many applications; however the main problem of the high-power laser systems is the heating of its active medium caused by the high pumping powers used. In the high-power solid-state laser systems this heating causes phase distortions as well as depolarization [1]. As a solution to this problem, the optical phase conjugation technique (OPC) [2] has been used in order to correct for intracavity phase distortions by means of the generation of dynamic gain gratings in the active medium [3]. This nonlinear technique has been applied in the construction of several self-adaptive pulsed solid-state laser systems like flash-lamp pumped Nd:YAG lasers [4], diode-pumped Neodymium: Yttrium Orthovanadate (Nd:YVO₄) lasers [5], and lasers-pumped Ti:sapphire lasers [6].

The self-adaptive lasers are constructed by using the four-wave mixing OPC technique in order to induce the formation of a gain grating in an active medium. The gain grating is produced by the gain saturation in the amplifier laser medium obtained through the interference of two coherent intersecting beams. In this way, the self-adaptive laser is created via the diffraction produced by the gain grating when the amplifier medium is located in a self-intersecting geometry, see Fig. 1. This gain grating is a volume hologram that codifies the distortions from the oscillator loop, including those caused by the amplifier medium itself, and in this way allows the correction of the phase distortions. Because in the self-adaptive laser systems the formation of the loop oscillator is achieved by the creation of a volume hologram resulting from the induced gain grating, those lasers have been referred to as holographic laser oscillators (HLO) [7].

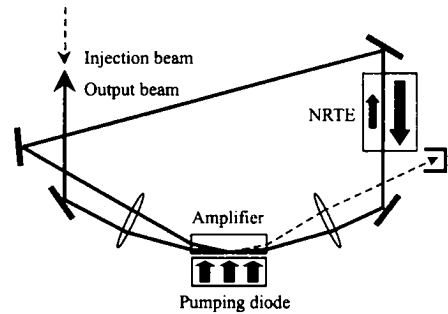


FIGURE 1. Schematic diagram of the diode-pumped Nd:YVO₄ HLO.

Although the high-gain requirements of this technique made its implementation to continuous-wave lasers to be more difficult to achieve, recently it has been shown that it is possible to obtain an efficient OPC in a continuous-wave side-pumped laser amplifier used in a four-wave mixing configuration [8]. Here we report on the application of the gain grating technique to the construction of a continuous-wave diode-pumped Nd:YVO₄ HLO.

2. The experimental holographic laser oscillator

In the self-intersecting configuration shown in Fig. 1 an injected beam propagating in the anti-clockwise direction passes through the amplifier and is redirected to self-intersect in the amplifier again. The interference pattern generated by this self-intersection of the injected beam in the amplifier pro-

duces the modulation of the population inversion inside the active medium. This modulation forms a volume gain grating which keeps information of any phase distortion suffered by the injected beam along its whole propagation in the closed loop oscillator, which is formed by the Bragg-matched diffraction of the gain grating light. This allows the oscillation of the light in the opposite direction to the injected beam, the clockwise direction in Fig. 1, when the loop gain reaches its threshold level.

The non-reciprocal transmission element (NRTE), formed by a half-wave plate and a Faraday rotator located between a pair of polarizers, increases the operation efficiency since it maximizes the gain grating modulation and allows the unidirectional oscillation in the clockwise direction due to its different transmissions for the anti-clockwise and clockwise directions [9]. The laser radiation propagating in the clockwise direction can form a self-consistent spatial mode which is the spatial phase conjugate of the injected beam [10]. This conjugated beam effectively corrects for the aberrations inside the loop oscillator and maintains the high spatial quality of the output beam [7].

In the experimental HLO shown in Fig. 1; the used amplifier was a Nd:YVO₄ crystal at 1.1 atm % with dimensions of (20 mm × 5 mm × 1 mm). The (5 mm × 1 mm) surfaces were anti-reflection coated for the lasing wavelength, 1064 nm; and the pump surface, the (20 mm × 1 mm) surface, was anti-reflection coated for the pumping wavelength, 808 nm. The self-lasing inside the crystal was highly suppressed by cutting the (5 mm × 1 mm) surfaces of the crystal at an angle of $\approx 2^\circ$ with respect to the normal of the pumped surface.

The pumping source was a 25 W continuous-wave fast-diverging axis collimated diode bar, which was focused in the Nd:YVO₄ crystal by a cylinder lens with focal length of 12.7 mm. Due to the birefringence of the Nd:YVO₄, the polarization of the light emitted by the pumping diode had to be rotated by means of a half-wave plate to be parallel to the *c*-axis of the crystal in order to access its high absorption cross section for the pumping wavelength [11].

When the Nd:YVO₄ amplifier is pumped, the non-uniform exponential decay of the gain region in function of the deep inside the crystal can be highly compensated by angling the beam being amplified. The inclined incidence on the amplifier allows the beam being amplified to experience a total internal reflection in the pumped surface of the crystal. This total internal reflection allows the averaging of the transverse gain variation along the spatial profile of the beam being amplified. Such a configuration, known as bouncing geometry, provides with the high gain needed to obtain an efficient operation of the HLO [11]; and it has been shown that the observed small signal gain is a function of the total internal reflection angle of the beam being amplified [12]. Because the gain region is narrow in the transverse plane, in order to access it, it was necessary to use 10 cm focal length spherical focusing and recollimating lenses at each side of the amplifier.

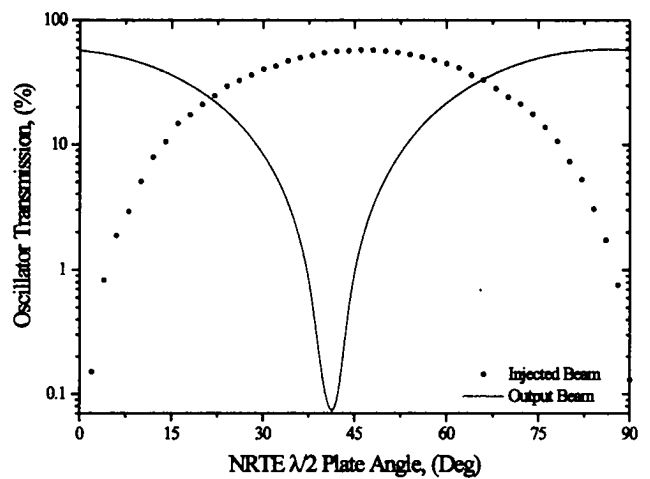


FIGURE 2. Transmission of the HLO as a function of the NRTE wave-plate angle.

The right orientation of the NRTE half-wave plate allows the reduction of its transmission in the anti-clockwise direction (injected beam) in order to optimize the gain grating formation, while this transmission for the clockwise direction (output beam) is increased in order to produce an efficient laser oscillation. The HLO anti-clockwise transmission, T_+ , was directly measured by varying the NRTE half-wave plate angle, θ ; then by adjusting this angle to allow the maximum anti-clockwise transmission ($\theta = 45^\circ$) it was possible to determine $T_0 = 56.8\%$ in

$$T_+ = T_0 \sin^2 2\theta, \quad (1)$$

therefore the HLO clockwise transmission, T_- , could be calculated using

$$T_- = T_0 \cos^2 2\theta, \quad (2)$$

and is shown together with the HLO anti-clockwise transmission in Fig. 2 as a function of the NRTE half-wave plate angle.

The injection source for the HLO was an external continuous-wave Nd:YVO₄ laser which spectral characteristics of single-mode and frequency were inherited to the HLO output beam. This injection laser was also used to measure the single pass gain of the amplifier.

3. Results and discussion

The highest output power obtained for the experimental HLO was ≈ 5.7 W with an internal incidence angle of $\approx 2^\circ$ with respect to the pumped surface; a separation angle between the self-intersected beams of $\approx 1^\circ$; and an injection power of ≈ 25.5 mW. Figure 3 shows the output TEM₀₀ spatial mode for the maximum obtained output power; which is elliptical due to the asymmetry of the gain region. This output beam was extracted from the HLO by means of an optical isolator located between the HLO and the injection laser. The self-

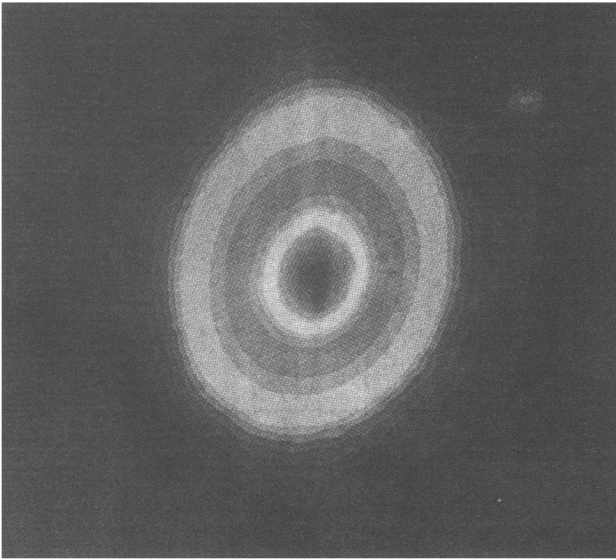


FIGURE 3. Output beam TEM₀₀ apatial mode.

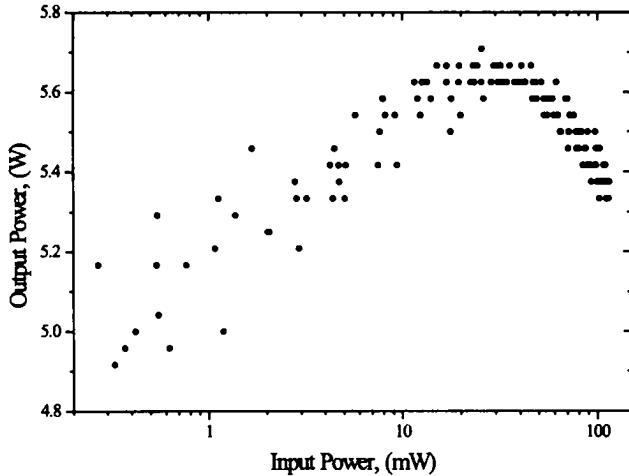


FIGURE 4. Output power of the HLO as a function of the injection beam input power.

adaptive capability of the oscillator became evident since the HLO was able to produce such an spatial high quality mode like the one shown in Fig. 3.

In Fig. 4, we show the experimental measurements of the output power of the HLO as a function of the injection beam input power, for an anti-clockwise NRTE transmission of $\approx 1.5\%$. In this Fig. 4 it is possible to observe that there exists an optimum injection beam power for a given small signal gain of the amplifier.

Measurements of the oscillating beam in the plane of the first focusing lens, the left-hand side lens in Fig. 1, showed spot sizes of $w_{x_f} = 35 \mu\text{m}$ and $w_{y_f} = 30 \mu\text{m}$ for the horizontal and the vertical axes, respectively. With those spot sizes measurements at the focusing lens plane, it was possible to estimate the focused beam spot sizes the oscillating beam will have at some point near the centre of the amplifier,

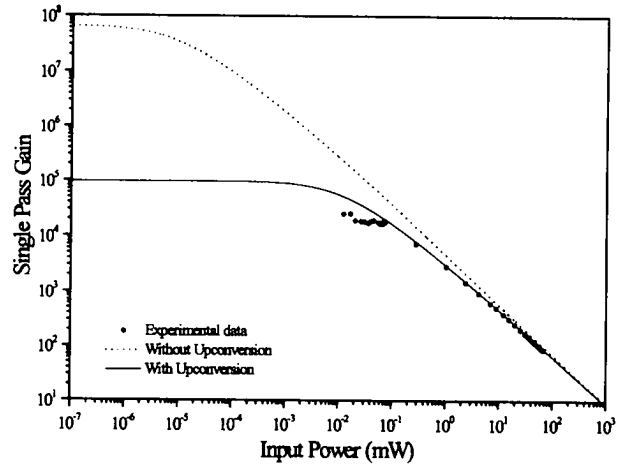


FIGURE 5. Single pass gain for the HLO.

w_{x_0} and w_{y_0} , using [13]

$$w_{x_0, y_0} \approx \frac{f\lambda}{\pi w_{x_f, y_f}}, \quad (3)$$

where $f = 10 \text{ cm}$ is the focal length of the focusing lens and $\lambda = 1.064 \times 10^{-4} \text{ cm}$ is the oscillating beam wavelength. Therefore, the focused beam horizontal and vertical spot sizes resulted to be $w_{x_0} \approx 93 \mu\text{m}$ and $w_{y_0} \approx 108 \mu\text{m}$, and those calculations allowed us to approximate the focused beam transverse area as $A = \pi w_{x_0} w_{y_0} \approx 3.15 \times 10^{-4} \text{ cm}^2$.

This estimation of the focused beam transverse area was used together with the maximum measured output power, $P_{\text{out}} \approx 5.7 \text{ W}$, in equation

$$I_{\text{st}} = \frac{P_{\text{out}}}{A}, \quad (4)$$

in order to calculate the stored intensity as $I_{\text{st}} \approx 18 \text{ kW/cm}^2$; which then could be used to obtain the value of the Nd:YVO₄ absorption coefficient-length product, $\alpha_0 L$, from relation

$$I_{\text{st}} \approx 2\alpha_0 L I_{\text{sat}}, \quad (5)$$

where $I_{\text{sat}} \approx 1 \text{ kW/cm}^2$ is the saturation intensity of the Nd:YVO₄.

Finally, this value of $\alpha_0 L$ was used in order to estimate a small signal gain coefficient from

$$G_0 = \exp(2\alpha_0 L), \quad (6)$$

which resulted to be $G_0 \approx \exp(18) = 7 \times 10^7$; being consistent with our experimental measurements for the single pass gain and the phase-conjugate reflectivity shown in Figs. 5 and 6, respectively, after considering that some recombination processes take place in the Nd:YVO₄ amplifier. Perhaps the most important of those being the Auger upconversion recombination process [14]. A simple theoretical model was used to show the Auger upconversion recombination process effect in the small signal gain of the oscillator and the results are also shown in Fig. 5.

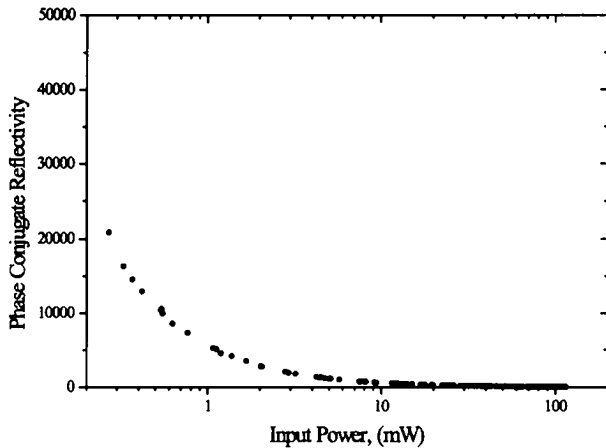


FIGURE 6. Phase-conjugate reflectivity for the HLO.

4. Conclusions

As a conclusion, we have applied the gain grating technique to the construction of a continuous-wave diode-pumped injected holographic laser oscillator. The system provided an output power of up to ≈ 5.7 W in a single longitudinal mode with the same frequency as that from the injected beam. The self-adaptive capability of the oscillator became evident since it was able to correct for the heat induced phase distortions in the amplifier and produce a high spatial quality TEM₀₀ output mode.

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