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Temperature-stable pumping realization through the optimization the pump-laser spectral distribution in optical amplifiers

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ABSTRACT

A new approach to stabilizing the temperature of laser diode arrays for pumping is proposed and experimentally demonstrated. Experimental results show that when the pump center wavelengths of the two optical amplifiers are set to 804.0 nm and 810.5 nm, stable pumping laser operation over a temperature range exceeding 15 °C can be achieved. The concept of the effective, rather than actual, absorption spectrum is introduced for the first time, in order to better analyze the laser diode pump spectral characteristics of the Nd:YAG material of the optical amplifier. The effective absorption spectrum for a typical LD spectrum shape is evaluated, and experiments demonstrate that the fluctuation of the center wavelength of the pump affects the pumping energy distribution. A proof-of-concept 1064 nm laser system is especially developed, demonstrating the generation of 3.36J laser pulses of pulsewidth 4.58 ns and beam quality 2.12 times of diffraction limit, at a frequency of 100 Hz.

1. Introduction

The use of laser diodes to pump solid-state lasers has accelerated the development high-power lasers [1]. Because the spectrum of a laser-diode (LD) depends on the temperature of the heat-sink, LD wavelength stabilization has attracted great attention [2], using both external stabilization configurations (e.g., an external cavity incorporating a Fabry–Perot filter [3,4] or a Littrow grating reflector [5]), and internal stabilization configurations (e.g., a distributed Bragg reflector (DBR) [6,7] and a distributed-feedback(DFB) cavity [8]). Recently, volume Bragg gratings (VBG) have been used to narrow the LD's emission band, hence increasing the efficiency of the laser system and locking the wavelength of LDs or LD bars at the same time [9–11]. However, the application of VBGs is difficult in laser-diode arrays. Here, we propose a new approach to achieving stable wavelength control based on optimizing the LD spectral distribution. Compared with the result achieved using wavelength-locked diode lasers for pumping, this simple economical approach is well suited for laser-diode arrays involving many bars.

The LD Spectrum is an important feature that must be considered in the context of LD pumping. In most cases, only the central wavelength of a LD is tuned to compensate for temperature changes by reaching a compromise between the absorption coefficient in the crystal and the energy efficiency [12,13]. On the other hand, although cooling water can be used to control working temperature, a lot of factors (such as working current changes and environmental temperature of the laser system) can fluctuate the working temperature of the laser diode, thus affecting the pump uniformity and inducing changes to the gain characteristics, which degrade the stability of laser system, making them impractical for field operations. Limited attention has been paid to the optimization of the pump spectral distribution of the two laser amplifiers of pulsed laser systems for stabilizing the pumping uniformity and gain characteristics over a large operating temperature range.

The present study first discusses the concept of the effective absorption spectrum (EAS), which depends on the laser system structure and the pumping LD spectral distribution. The effective absorption spectrum enables the influences of the pump spectral bandwidth and spectral distribution to be analyzed. For a typical pump spectral distribution of full width at half maximum (FWHM) of 6.3 nm, we found the optimal central pump wavelength to be 807.5 nm, which clearly deviates from the Nd:YAG absorption peak (808.6 nm). We discuss a new approach

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to controlling the pump spectral distribution in stabilize the pumping uniformity when temperature changes fluctuate the center of the pump wavelength. We conclude that the pumping efficacy is governed by the trade-off between the plateau region of the optimized effective absorption spectrum and the pump efficiency resulting from the pump spectral bandwidth. If the pump spectral bandwidth is too narrow, the flat region of the effective absorption spectrum decreases, resulting in a poor adaptability to the ambient temperature. On the other hand, a broad pump spectral bandwidth reduces the pumping efficiency. Finally, an experimental setup for optimizing the pump spectral distribution is proposed, and results show that if the center wavelengths of the pump LDs of the two optical amplifier are 804.0 and 810.5 nm, a 15 mm-diameter side-pumped temperature-stabilized Nd:YAG amplifier structure can be developed, capable of realizing a 1064 nm laser system generating 3.36 J laser pulses of pulsewidth 4.58 ns and beam quality 2.12 times of diffraction limit, at a frequency of 100 Hz.

2. Effective absorption spectrum

It is known that atoms excited from the ground state $4I_{9/2}$ to state $4F_{5/2}$ induce a series of absorption peaks. The peak at 808.6 nm is always taken as the central wavelength for pumping. However, the spectrum width and the other absorption peaks (e.g., at 804.5 or 813.0 nm) also affect the absorption efficiency. The spectral FWHM bandwidth of a high-power laser-diode array is typically 3–5 nm, which significantly affects the absorption. For example, when the central wavelength is 808.5 nm and the pumping spectrum width is 3 nm, the wavelength range covered is from 807.0 to 810.0 nm. As shown in Fig. 1, each wavelength in this effective region makes a different contribution to the overall absorption spectrum. We define the effective absorption spectrum (EAS) as the overlap integral of the absorption spectrum and the LD pumping spectrum, which can be expressed as:

$$\alpha_{\mathrm{eff}}(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} f(x-\lambda)\,\alpha(x)\,dx}{\int_{\lambda_1}^{\lambda_2} f(x)\,dx} \tag{1}$$

where $\alpha_{\mathrm{eff}}(\lambda)$ is the effective absorption coefficient, $f(x)$ the shape of the LD pumping spectrum, and $\alpha(x)$ the shape of the Nd:YAG absorption spectrum. The integration range of the pumping spectrum is assumed to be bounded by the wavelengths λ_1 and λ_2, and λ is the central pumping wavelength. To calculate the EAS, $f(x)$ and $\alpha(x)$ must be fitted numerically from measurements. In the present study, the wavelength interval used between each measurement was $\alpha_0 = 0.5$ nm, which was set by the spectrum analyzer. Each point on the LD spectrum contributed to the effective absorption coefficient. Taking the contribution of the central wavelength as a normalization factor, the individual contributions of all the other points and the total EAC can be expressed as

$$\alpha_{\mathrm{eff}}(\lambda) = \sum \frac{c_i}{\sum c_i}\alpha_i(\lambda_i) \tag{2}$$

where c_i is the contribution to the absorption coefficient by the pumping wavelength λ_i.

$$\alpha = -\frac{1}{L}\ln\left\{\frac{I}{I_0}\left[1-\left(\frac{n_1-n_0}{n_1+n_0}\right)^2\right]^{-2}\right\} \tag{3}$$

where I_0 and I are the incident and transmitted light intensities, L is the slice thickness, and n_0 and n_1 are the refractive indices of air and of the Nd:YAG slice, respectively. The measured index of the Nd:YAG slice was $n_1 = 1.822$, and the Fresnel loss on the refractive surface was 8.49%. The experimental measured absorption coefficient was shown in Table 1.

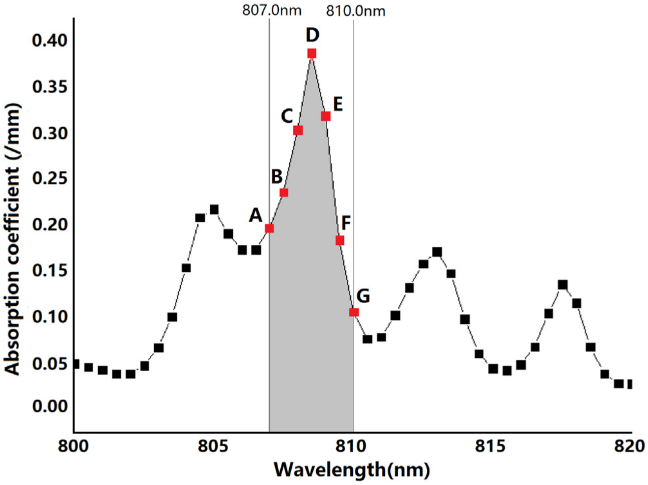

Fig. 1. Measured absorption coefficient of the Nd:YAG rod.

3. Pump spectrum optimization

The experimental setup for measuring the pumping distribution involved three components, namely, the side-pumped amplifier, the focusing lens, and the spectrometer. The focal length of the lens was 150 mm, and its diameter was 25.4 mm. The distance between the amplifier and the focusing lens was 910 mm. The photodetector of the spectrometer AVaSpec-3648 (Avantes Co., Ltd) was placed at the lens focus. An optical filter of center wavelength 1064 nm and absorption band 20 nm, which was used to absorb the amplified spontaneous emission (ASE) at 808 nm, was placed in front of the spectrometer receiver. The side-pumping amplifier was built in-house, with 7 laser-diodes arrays placed in a circle uniform around the working material, and each laser-diodes stacks had 24 bars, and rated power of each bar of 200 W. The fast axis was parallel to the rod. The length of the Nd:YAG rod was 160 mm, and its diameter was 15 mm. The doping concentration of the Nd:YAG rod was 0.6%.

The measured spectrum of the LD pump is shown in Fig. 2, which is a typical pump spectrum with a FWHM of 6.3 nm. With manufacturers specifications and our experimental results, threshold current of LD arrays is 22 A, working voltage is 1.91 V/bar, when the temperature of cooling water increases from 21 °C to 30 °C, with the working current of 100 A, output average power decreases from 477.2 to 464.3 W, is about 2.7%. The EAC was calculated at different wavelengths from Eq. (2), where we assumed that the pump spectral distribution does not change when the center wavelength of LD arrays fluctuates from 780 to 830 nm. The relation between the EAC and the pump center wavelength is also plotted in Fig. 2, which shows that a peak value of 0.2028 mm^{-1} at the center wavelength 807.5 nm. The 80% bandwidth about the peak is 5.5 nm (i.e., from 806.0 to 811.5 nm), and the 90% bandwidth is 3.5 nm (from 806.5 to 810.0 nm). Table 2 lists the EAC calculated using the measured LD pump spectrum, of FWHM = 6.3 nm. The EAS in Fig. 2 reveals the influence of temperature on the LD-pumped laser system. When the center wavelength of LD changes, the EAC changes, inducing fluctuation in the pump energy distribution in the rod, which deteriorates the stability of the laser system.

To achieve a plateau region in the EAS, the corrected coefficient can be calculated from the data in Table 1. If the minimum of the EAC in the designed region is $\min(\alpha_{\mathrm{eff}})$, a correction factor

$$\beta = \frac{\min(\alpha_{\mathrm{eff}})}{\alpha_{\mathrm{eff}}} \tag{4}$$

is applied to the EAC to realize a plateau region. This simple pump-spectrum optimization is carried out using a single correction factor. By