Simple method for reducing the depolarization loss resulting from thermally induced birefringence in solid-state lasers

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A simple technique for reducing the loss that is due to depolarization resulting from thermally induced stress birefringence in solid-state lasers is reported. The technique uses a single intracavity quarter-wave plate with its fast or slow axis aligned parallel to the preferred plane of polarization, defined by an intracavity polarizer. This technique has been applied to a diode-bar-pumped Nd:YAG laser operating at 946 nm, resulting in a measured reduction in depolarization loss from ~1.7% to ~0.0006% and yielding a diffraction-limited, TEM_{00}, linearly polarized output power of 2.9 W for an incident pump power of 14.3 W. © 1999 Optical Society of America

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Stress-induced birefringence in solid-state laser materials, which is caused by thermal loading associated with the laser-pumping cycle, can be detrimental to the performance of both laser oscillators and amplifiers, particularly at high pump powers. Stress-induced birefringence manifests itself in two main ways: degradation in laser beam quality owing to the effect known as bifocusing and depolarization of a linearly polarized beam.[1] With the latter, if, as is commonly the case, one includes a polarizer in the amplifier–oscillator arrangement to select a linearly polarized output, then the effect of depolarization is apparent as a loss that increases with pump power, resulting in a serious reduction in efficiency. The above two effects of stress birefringence are a major factor limiting the beam brightness that is obtainable from a laser oscillator or amplifier. The problem of stress-induced birefringence is particularly severe in low-gain end-pumped solid-state lasers, in which thermal-loading densities are rather high owing to the high pump intensities that are required, and also because the performance of low-gain lasers is strongly affected by even a small increase in resonator loss.

A number of techniques to reduce the effects of stress-induced birefringence have been described. In one approach,[2] compensation of stress-induced birefringence is achieved by the use of two laser rods in tandem and an optical rotator located between the rods that rotates the direction of polarization by 90°. For full compensation of stress-induced birefringence with this approach it is necessary to have closely matching distributions of stress-induced birefringence in both laser rods. In addition, the rods should be positioned in close proximity, or alternatively, a suitable optical arrangement[3] must be used for imaging one rod onto the other rod. In practice, these conditions are difficult to achieve, especially in end-pumped laser oscillators and amplifiers that employ a small pump-beam size. An alternative approach that allows the use of a single laser rod[4] uses a Porro prism as the end reflector and an appropriate wave plate located between the Porro prism and the laser rod. The combined effect of the Porro prism and of double passing the wave plate is equivalent to that of a 90° optical rotator. For full birefringence compensation, the distribution of stress-induced birefringence must be symmetrical about the plane defined by the beam-propagation direction and the apex of the Porro prism. Losses and distortion in the vicinity of the apex can be a problem, particularly for the small beam sizes that are typical for diode-end-pumped lasers.

Here we report a simple alternative technique for reducing depolarization loss that is due to thermally induced stress birefringence. Only one extra component is inserted into the laser cavity, a quarter-wave ($\lambda/4$) plate located close to the laser rod and aligned with its fast (or slow) axis in the preferred polarization plane, as defined by a polarizer. This approach allows a single laser rod to be used and, owing to the low insertion loss of the $\lambda/4$ plate, is highly beneficial for use in the low-gain and quasi-three-level lasers. Although the compensation that this technique provides is not complete, even in principle, the technique can provide a major reduction in depolarization loss. The benefits are illustrated by experimental results for a diode-bar-pumped Nd:YAG laser at 946 nm that show a substantial reduction in depolarization loss with this approach and demonstrate efficient linearly polarized operation.

The principle of this technique can be explained with reference to Figs. 1 and 2, which show schematic views of the optical arrangement that forms part of a laser oscillator or amplifier and a cross section through the laser rod, respectively. A laser beam propagating in the z direction is incident upon the laser rod, the electric field of which is linearly polarized in the x direction, as defined by the polarizer. After it traverses the laser rod, different portions of the laser beam will, in general, experience a change in polarization state as a result of stress-induced birefringence that depends on their x, y coordinates. For a cylindrical laser rod the change in polarization state is generally largest for those portions of the laser beam that propagate along planes inclined at an angle of 45° to the x and y directions. This is because the radial and the tangential components of stress lead to birefringence in which the

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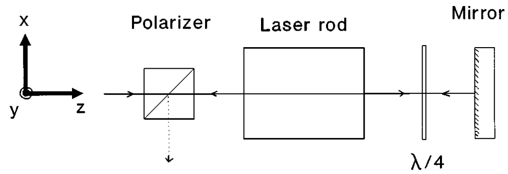

Fig. 1. Schematic diagram of the arrangement for reducing depolarization loss that is due to stress-induced birefringence.

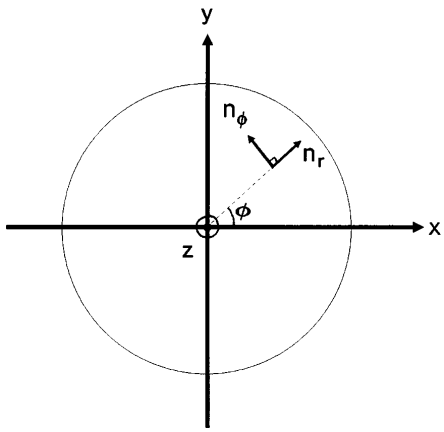

Fig. 2. Cross section of the laser rod. The beam that is incident upon the laser rod is linearly polarized in the x direction.

principal axes are radial and tangential, with corresponding refractive indices n_r and n_ϕ, respectively, and are thus inclined at 45° to the polarization direction of the incident beam (as shown in Fig. 2). In general, it is these portions of the laser beam that, in the absence of compensation, suffer the largest depolarization loss at the polarizer. The portions of the beam that are propagating along the $x-z$ and the $y-z$ planes experience no change in polarization state, since the radial and the tangential components of stress are either parallel or perpendicular to the plane of polarization of the incident beam. These portions of the laser beam suffer negligible depolarization loss, and so they do not require compensation.

After it emerges from the laser rod, the laser beam is incident upon on a $\lambda/4$ plate aligned with its fast and slow axes parallel to the x and y directions. After a double pass through the $\lambda/4$ plate, the beam emerges with different portions' having experienced changes in polarization state that again depend on their x and y positions. Those portions propagating in, or close to, the $x-z$ and the $y-z$ planes have essentially no change in polarization state since they have electric fields that are linearly polarized in the x direction, i.e., parallel to the fast or the slow axis of the $\lambda/4$ plate. Thus after a second transit of the laser rod these portions emerge linearly polarized in the x direction and hence experience negligible loss at the polarizer. The portions that propagate along planes with other orientations, before they enter the wave plate, have different polarization states from that of the beam that is incident upon the laser rod, owing to stress-induced birefringence, and hence have polarization components in both the x and the y directions. Thus, in double passing the $\lambda/4$ plate, these portions of the laser beam experience a further change of polarization state that is due to an additional phase shift of π rad between the x and the y components. Because of the effect of the wave plate, portions of the beam that propagate along planes at 45° to the $x-z$ and $y-z$ planes return to the laser rod with the radial and the tangential components of polarization simply rotated by 90°. Hence, after the beam traverses the laser rod for the second time, these portions emerge with their electric fields linearly polarized in the x direction, and consequently they now also suffer negligible loss at the polarizer. Portions of the laser beam that are propagating in other sectors have their radial and tangential components of polarization rotated by differing amounts by the $\lambda/4$ plate, depending on the angle of inclination of their plane of propagation to the $x-z$ plane. In general, the radial and the tangential components of polarization will be rotated by an angle 2ϕ or $(180 - 2\phi)$, where ϕ is the angle between the plane of propagation and the $x-z$ plane (Fig. 2). After they traverse the laser rod for the second time, these portions of the laser beam emerge with a polarization state that is not purely linearly polarized in the x direction, owing to the effect of stress-induced birefringence. However, it can be shown that the unwanted component of polarization in the y direction is significantly smaller than would be the case without the wave plate, particularly for portions that are propagating along planes inclined at an angle ϕ close to 45°. Since these portions would normally provide (without the $\lambda/4$ plate) the largest contribution to the y component of polarization, and hence suffer the greatest loss at the polarizer, the overall result of using the $\lambda/4$ plate is a large reduction in depolarization loss.

As a demonstration of the effectiveness of this technique we applied it to a diode-bar-pumped Nd:YAG laser operating at 946 nm to achieve efficient linearly polarized operation. This transition has attracted much interest for frequency doubling to the blue, at 473 nm.[5,6] However, scaling linearly polarized 946-nm Nd:YAG lasers to the high average powers required for frequency doubling while maintaining high efficiency has proved rather difficult since, because of the low-gain cross section and the quasi-three-level nature of this transition, the laser performance is adversely affected by even a small increase in loss as a result of thermally induced birefringence. Our resonator design (Fig. 3) was a simple folded cavity consisting of a plane mirror with high reflectivity (>99.8%) at 946 nm and high transmission (~96%) at the diode-pump wavelength of 808 nm, a 25-mm radius-of-curvature mirror with high reflectivity at

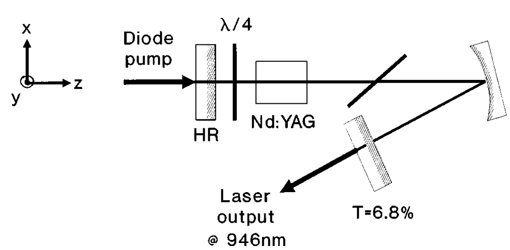

Fig. 3. Diode-pumped Nd:YAG laser at 946 nm with a $\lambda/4$ plate for reducing the depolarization loss that is due to stress-induced birefringence. HR, high reflector.

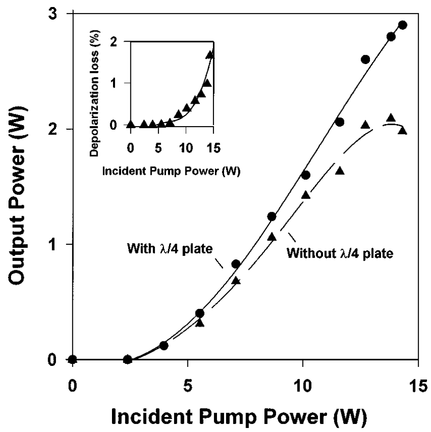

Fig. 4. Laser output power versus incident pump power. Inset: Depolarization loss versus incident pump power without the $\lambda/4$ plate present in the cavity.

946 nm, and a plane output coupler coated for 6.8% transmission at 946 nm. The curved mirror and output mirror coatings also had high transmission (>90%) at 1.06 μm, which prevented lasing on the higher-gain laser transitions at wavelengths near 1.06 μm. A Nd:YAG laser rod of length 3 mm was mounted in a water-cooled copper heat sink, and both end faces of the rod were antireflection coated at both the lasing and the pump wavelengths. We also included a Brewster-angled fused-silica plate in the cavity to select linearly polarized operation. The $\lambda/4$ plate compensator was inserted between the pump input mirror and the laser rod and aligned with its fast or slow axis perpendicular to the plane of incidence of the Brewster-angled plate. Both faces of the $\lambda/4$ plate were antireflection coated at both the pump and the lasing wavelengths. The pump source (not shown) was a 20-W diode bar (Opto Power Corporation, Model OPC-AO20-mmm-CS) that we reformatted by use of a two-mirror beam shaper[7] to equalize the M^2 beam-propagation factors in the orthogonal planes and focused with an arrangement of crossed cylindrical lenses to a nearly circular beam of radius 142 μm $\times$ 131 μm. The maximum pump power that was incident upon the laser was 14.3 W, with ~67% absorbed into the Nd:YAG rod. Without the $\lambda/4$ plate, the maximum linearly polarized output power that was attainable was 2.1 W for 13.8 W of incident pump power. For a further increase in pump power the laser power was found to actually decrease (Fig. 4). The additional contribution to the cavity loss owing to thermally induced depolarization was determined by measurement of the power that was reflected from the faces of the Brewster-angled plate and was found to increase rapidly with increasing pump power (Fig. 4), reaching a value of 1.7% at the maximum available pump power. Thus the laser power for this resonator configuration is limited by thermally induced depolarization rather than by the available pump power. With the $\lambda/4$ plate in place, the measured depolarization loss was dramatically reduced at 0.0006%, and the maximum linearly polarized laser output power was 2.9 W in a TEM_{00} beam with beam-propagation factors $M_x{}^2 \approx 1.2$ and $M_y{}^2 \approx 1.1$. As can be seen from Fig. 4, the output power from the compensated resonator is now limited by the available pump power rather than by depolarization loss, suggesting that it should be possible to scale polarized operation to significantly higher powers simply by increasing the pump power.

In summary, we have described a simple, low-cost technique for reducing the depolarization loss that is due to thermally induced birefringence in solid-state lasers that is particularly well suited to low-gain and quasi-three-level end-pumped lasers that employ a single laser rod. Despite the fact that compensation is not, in principle, total, the residual losses can be very low, as suggested by detailed calculations. The large reduction in depolarization loss that is achievable with this approach suggests that there is considerable scope for further efficient power scaling of various linearly polarized lasers.

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