# Simple method for reducing the depolarisation loss due to thermally-induced birefringence in solid-state lasers

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## Abstract

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

Stress-induced birefringence in solid-state laser materials, 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 due to the effect known as bifocussing and depolarisation of a linearly-polarised beam[1]. With the latter, if, as is commonly the case, a polariser is included in the amplifier/oscillator arrangement to select a linearly-polarised output, then the effect of depolarisation is apparent as a loss which 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 obtainable from a laser oscillator or amplifier. The problem of stress-induced birefringence is particularly severe in low gain, end-pumped solid-state lasers where thermal loading densities are rather high owing to high pump intensities 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 using two laser rods in tandem and an optical rotator, located between the rods, which rotates the direction of polarisation by 90°. To obtain full compensation of stress-induced birefringence via 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 employing a small pump beam size. An alternative approach which allows the use of a single laser rod[4] uses a Porro prism as the end reflector and an appropriate wave plate located between Porro prism and laser rod. The combined effect of the Porro prism and double passing the wave plate is equivalent to a 90° optical rotator. To obtain 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 typical for diode-end-pumped lasers.

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

The principle this technique can be explained with reference to Figs. 1 and 2, which show respectively; a schematic view of the optical arrangement, which forms part of a laser oscillator or amplifier, and a schematic view of a cross-section through the laser rod. A laser beam propagating in the z-direction is incident on the laser rod with its electric field linearly-polarised in the x-direction as defined the polariser. After traversing the laser rod, different portions of the laser beam will, in general, experience a change in polarisation state resulting from stress-induced birefringence, which depends on their x,y coordinates. For a cylindrical laser rod the change in polarisation state is generally largest for those portions of the laser beam which propagate along planes inclined at an angle of 45° to the x and y directions. This is because the radial and tangential components of stress lead to a birefringence in which the principal axes are radial and tangential, with corresponding refractive indices, $n_r$ and $n_\phi$ respectively, and are thus inclined at 45° to the polarisation direction of the incident laser beam (as shown in Fig.2). In general, it is these portions of the laser beam which, in the absence of compensation suffer, the largest depolarisation loss at the polariser. The portions of the laser beam propagating along the x-z and y-z planes experience essentially no change in polarisation state, since the radial and tangential components of stress are parallel or perpendicular to the plane of polarisation of the incident beam. These portions of the laser beam suffer negligible depolarisation loss, and so do not require compensation.

After emerging from the laser rod, the laser beam is incident on a λ/4-plate aligned with its fast and slow axes parallel to the x and y directions. After a double-pass of the λ/4-plate the laser beam emerges with different portions having experienced changes in polarisation state which again depend on their x and y coordinates. Those portions propagating in, or close to, the x-z and y-z planes have essentially no change in polarisation state since they have electric fields linearly polarised in the x-direction, i.e. parallel to the fast or slow axis of the λ/4-plate. Thus, these portions emerge, after a second transit of the laser rod, linearly-polarised in the x-direction and hence experience negligible loss at the polariser. The portions which propagate along planes with other orientations have, prior to entering the wave plate, different polarisation states to that of laser beam incident on the laser rod, due to stress-induced birefringence, and hence have polarisation components in both the x and y directions. Thus, in double-passing the λ/4-plate, these portions of the laser beam experience a further change of polarisation state due to the additional phase shift of $\pi$ radians between x and y components. Portions of the laser beam which propagate along planes at 45° to the x-z and y-z planes, due to the effect of the wave plate, return to the laser rod with radial and tangential components of polarisation simply rotated by 90°. Hence, after traversing the laser rod for the second time, these portions emerge with electric field linearly polarised in the x-direction, and consequently now also suffer negligible loss at the polariser. Portions of the laser beam propagating in other sectors have their radial and tangential components of polarisation rotated by differing amounts by the quarter-wave plate depending on the angle of inclination of their plane of propagation to the x-z plane. In general, the radial and tangential components of polarisation will be rotated by an angle $2\phi$ or $(180-2\phi)$, where $\phi$ is the angle between the plane of propagation and the x-z plane (as shown in Fig.2). After traversing the laser rod for the second time, these portions of the laser beam emerge with a polarisation state which is not purely linearly polarised in the x-direction, due to the effect of stress-induced birefringence. However, it can be shown that the unwanted component of polarisation in the y-direction is significantly smaller than would be the case without the wave plate, and particularly so for portions propagating along planes inclined at an angle $\phi$ close to 45°. Since these portions would normally provide (with the absence of the λ/4-plate) the most significant contribution to the y-component of polarisation, and hence suffer the greatest the loss at the polariser, then the overall result of the λ/4-plate is a very large reduction in depolarisation loss.

As a demonstration of the effectiveness of this technique we have applied it to a diode-bar-pumped Nd:YAG laser operating at 946nm to achieve efficient linearly-polarised operation. This transition has attracted much interest for frequency-doubling to the blue, at 473nm[5,6]. However, scaling linearly-polarised 946nm Nd:YAG lasers to the high average powers required, whilst maintaining high efficiency, has proved rather difficult, since, due to the low gain cross-section and quasi-three-level nature of this transition, the laser performance is adversely affected by even a small increase in loss due to thermally-induced birefringence. Our resonator design (shown in Fig.3) was a simple folded cavity consisting of plane mirror with high reflectivity ($>99.8\%$) at 946nm and high transmission ($\sim 96\%$) at the diode pump wavelength of 808nm, a 25mm radius of curvature mirror with high reflectivity at 946nm, and a plane output coupler coated for 6.8% transmission at 946nm. To prevent lasing on the higher gain laser transitions at wavelengths around 1.06$\mu$m, the curved mirror and output mirror coatings were also specified to have high transmission ($>90\%$) at 1.06$\mu$m. The Nd:YAG laser rod of length 3mm was mounted in a water-cooled copper heat-sink, and both end faces of rod were antireflection coated at the lasing and pump wavelengths. A Brewster-angled fused silica plate was also included in the cavity to select linearly-polarised 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 plane of incidence of the Brewster-angled plate. Both faces of the $\lambda/4$-plate were antireflection coated at the pump and lasing wavelengths. The pump source (not shown) was a 20W diode-bar (Opto Power Corporation, Model OPC-AO20-mmm-CS), which was reformatted by a two-mirror beam shaper[7] to equalise the $M^2$ beam propagation factors in orthogonal planes and focussed, with an arrangement of crossed cylindrical lenses, to a nearly circular beam, of radii 142$\mu$m × 131$\mu$m. With this arrangement the maximum pump power incident on the laser was 14.3W, with $\sim 67\%$ absorbed in the Nd:YAG rod. Without the $\lambda/4$-plate, the maximum linearly-polarised output power attainable was 2.1W for 13.8W of incident pump power. For further increase in pump power the laser power was found to actually decrease, as shown in Fig.4). The additional contribution to cavity loss due to thermally-induced depolarisation was determined by measuring the power reflected from the faces of the Brewster-angled plate and was found to increase rapidly with increasing pump power (as shown in 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 depolarisation, rather than by the available pump power. With the $\lambda/4$-plate in place, the measured depolarisation loss was dramatically reduced at 0.0006%, and the maximum linearly-polarised laser output power was 2.9W in a $TEM_{00}$ beam with a 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 depolarisation loss, suggesting that it should be possible to scale polarised operation to significantly higher powers simply by increasing the pump power.

In summary, we have described a very simple, low-cost technique for reducing the depolarisation loss due thermally-induced birefringence in solid-state lasers, which is particularly well-suited to low gain and quasi-three-level end-pumped lasers employing 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 depolarisation loss achievable via this approach suggests that there is considerable scope for further efficient power-scaling of various linearly-polarised lasers.

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Fig. 1

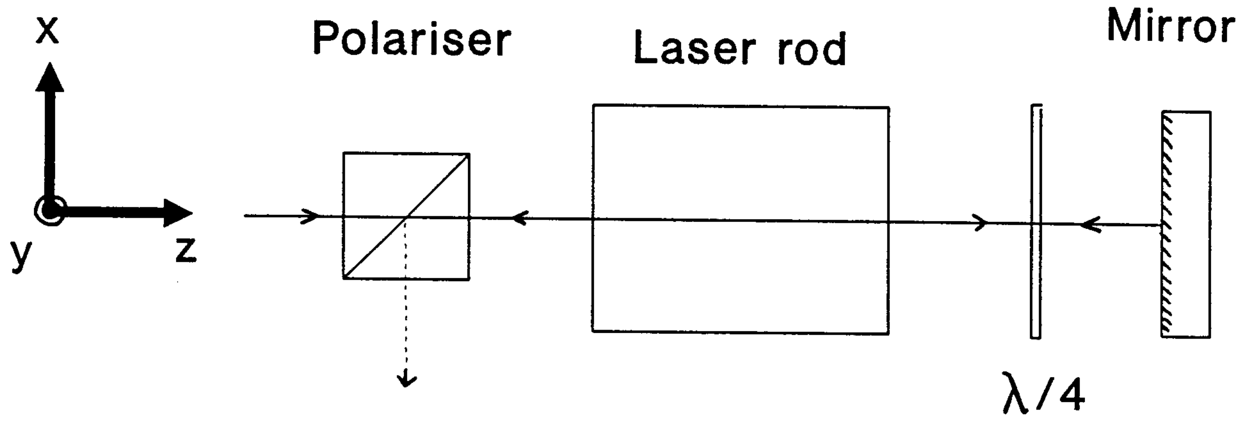

Fig. 1 Schematic diagram of arrangement for reducing the depolarisation loss due to stress-induced birefringence.

Fig. 2

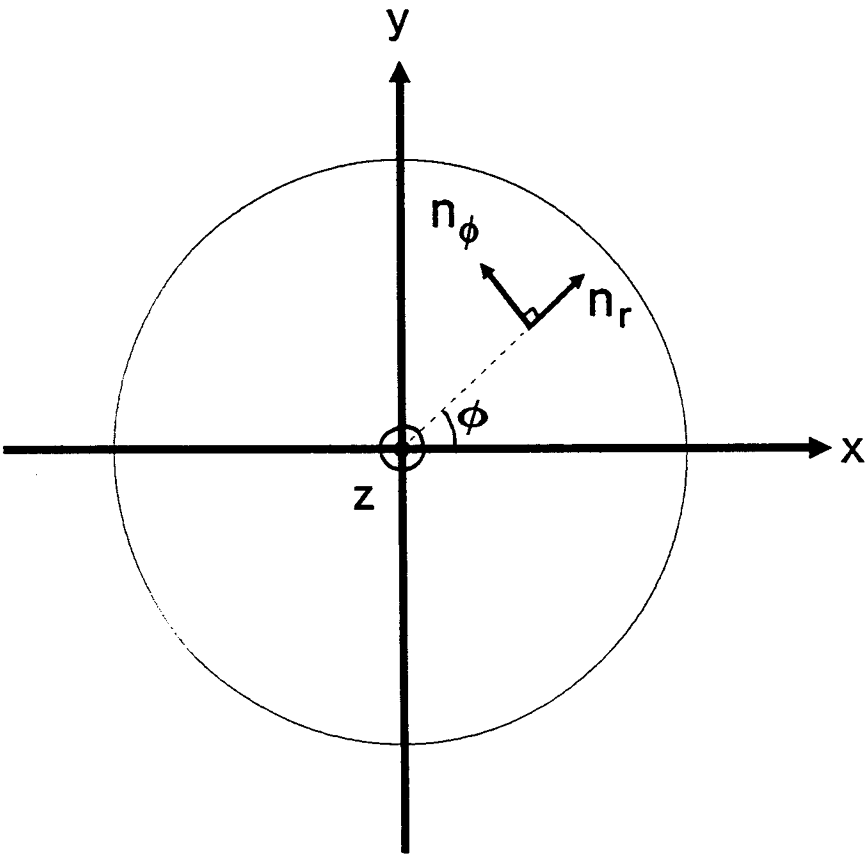

Fig.2 View of a cross-section through the laser rod. The beam incident on the laser rod is linearly-polarised in the x-direction.

Fig. 3

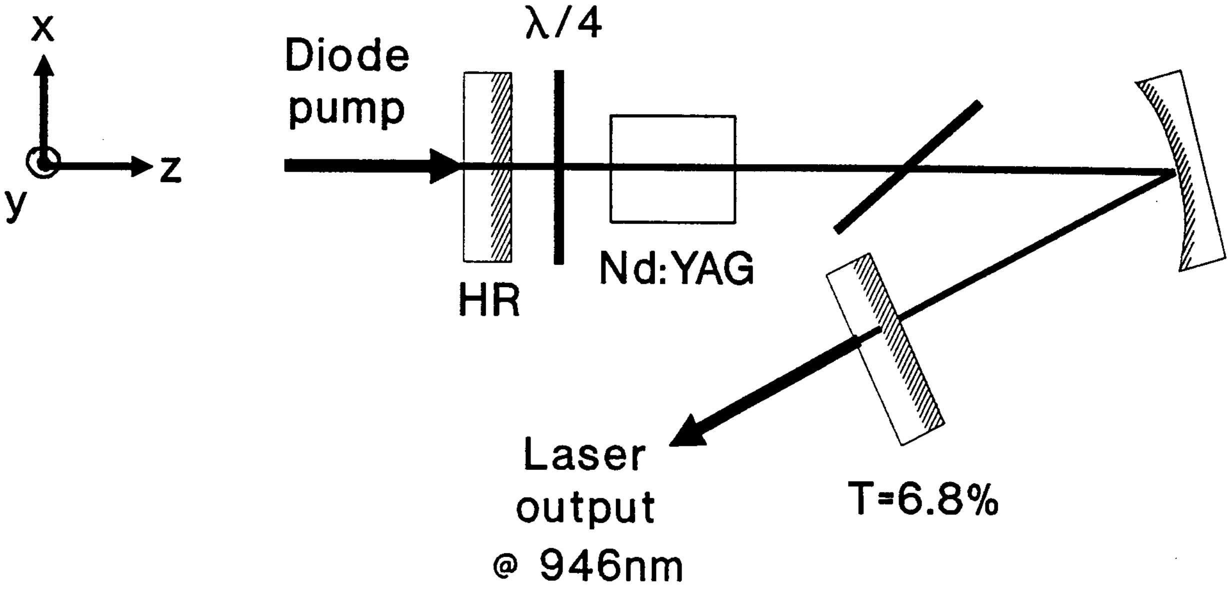

Fig.3 Diode-pumped Nd:YAG laser at 946nm with a quarter-wave plate for reducing the depolarisation loss due to stress-induced birefringence.

Fig. 4

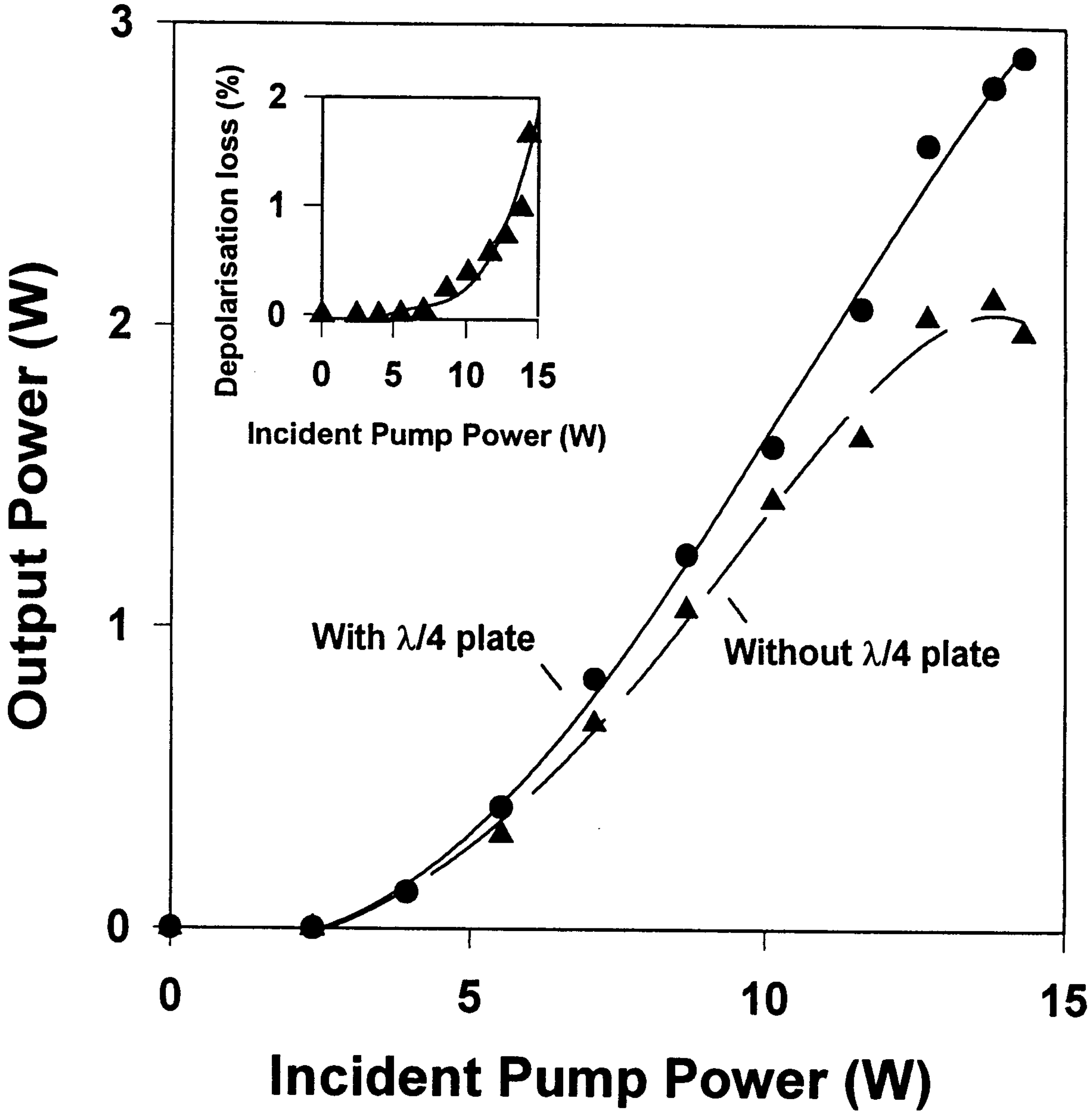

Fig.4 Laser output power versus incident pump power. (Insert: Depolarisation loss versus incident pump power without the quarter-wave plate present in the cavity).