Birefringence compensation in single solid-state rods

Lawrence Livermore National Laboratory, P. O. Box 808, L-438, Livermore, California 94550

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Various methods for compensating birefringence depolarization in solid-state rods are theoretically and experimentally analyzed and compared. Gaussian and flat top beam profiles are investigated. The efficiency in depolarization loss reduction using different techniques is discussed in terms of beam profile, rod fill factor, and thermal heat load. In Nd:yttrium–aluminum–garnet, the depolarization loss can be efficiently reduced below 5% with a compensating quarter-waveplate, up to 20 W heat load for a flat top beam and up to 70 W for a gaussian beam. © 2000 American Institute of Physics. [S0003-6951(00)03812-2]

Thermally induced birefringence in high-gain solid-state laser and amplifier rods produces significant depolarization due to large amounts of power deposited into small diameter rods as excess heat. If polarized output is required, the thermal stress birefringence results in beam distortion and polarization loss. Detailed knowledge of this thermal effect and methods to correct it is critical in the design of efficient high average power rod laser and amplifier systems.

A widely used birefringence compensation method is a 90° rotator placed between two identically pumped rods. This is very attractive for diode-side-pumped rod architectures. However, for some applications, such as an end-pumped rod system, a single rod design might be advantageous and can lead to a more compact and cost effective laser or amplifier system. Recently, Clarkson et al. suggested a quarter-waveplate as a simple method to reduce depolarization loss resulting from thermally induced birefringence. This is a very efficient method for low thermal power, however, there is limited advantage of this technique at high thermal loading. For many applications good spatial beam quality is required from a rod oscillator. Typically, the ratio of the gaussian beam width to the rod diameter will be on the order of 0.5 to avoid pronounced diffraction patterns. Whereas for a rod amplifier a flat top hat beam profile filling the entire rod might be preferred for good energy extraction.

In this letter, we compare various techniques to reduce the birefringence loss. Analytic expressions for the depolarization loss as a function of heat load in the rod are given for different techniques and are experimentally verified using a continuous wave (cw) diode-side-pumped Nd:yttrium–aluminum–garnet (YAG) rod. Input beams with either gaussian or flat top profiles are discussed. The results presented in this letter serve as design guideline for efficient birefringence compensation in high-average power solid-state rod lasers or amplifiers.

Thermally induced birefringence results from stress induced by a nonuniform temperature distribution. A detailed description can be found in Koechner. For a Nd:YAG rod, the principal axes of the induced birefringence are radial and tangential at each point within the rod cross section. Thus, the radial and tangential component of a linear polarized beam travelling through a laser rod will experience different phase retardation resulting in substantial depolarization up to 25%. Introducing a polarizer to maintain linear polarization results in decreased output power and a change in beam uniformity. Consequently, the compensation of birefringence is a very important issue for a variety of laser applications.

The goal of birefringence compensation is to achieve equal phase retardation at each point within the rod cross section for both the radial and tangential component of the polarization. Two identically pumped rods with a 90° rotator between them will in principle compensate birefringence depolarization. Polarization compensation can also be achieved for single rod architecture in two passes, for example by using a 45° Faraday rotator. A roundtrip in a 45° Faraday rotator corresponds to a single pass in a 90° rotator. The advantage of single rod architecture is the identical thermal load in the rod for back and forth passes, as well as the compact cavity design. In end-pumped systems, rod pump faces might result in nonparabolic thermal gradients and affecting the birefringence depolarization. Consequently, fewer rods may reduce this kind of depolarization effect. One drawback using a 45° Faraday rotator in a single rod setup is the 90° rotation of the linear polarization (p→s) after one round trip, which requires a folded resonator or amplifier design. This setup might require an additional aperture/ pinhole to suppress lasing when operating as four-pass amplifier. Recently, significantly reduced depolarization loss in a single rod cavity using a birefringence compensating quarter-waveplate was demonstrated by Clarkson et al. We refer to a compensating quarter-waveplate when the principal dielectric axis is adjusted to be parallel or perpendicular to the polarizer axis. In this configuration, linear polarization is not affected by the waveplate and a conventional linear laser architecture can be used. Furthermore, a quarter-waveplate is much cheaper than a Faraday rotator and self-focusing effects are more reduced due to shorter length and smaller nonlinear refractive index.

In the following, only single rod architectures are discussed. The depolarization loss accumulated after one roundtrip (RT) in a single rod with and without a 45° Faraday rotator (FR) or a compensating quarter-waveplate (CQW) for birefringence compensation are compared for gaussian and flat top beam profiles. The amount of depolarization depends on the birefringence of the rod, on the compensation element, as well as on the input beam shape. The depolarization loss can be written as

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where $I_{\text{in}}$ is the intensity beam profile and $f_{\text{depol}}$ is the depolarization loss function, both a function of radius $r$ and angle $\phi$, and $r_0$ is the rod radius. The depolarization loss function for a RT in a uniformly pumped rod is

$$f_{\text{depol}}(r, \phi) = \frac{1}{2} \left[\sin(C_T P(r/r_0)^2)\right]^2 \left[\sin(2\phi)\right]^2,$$

(2)

where $P$ is the power dissipated as heat into the rod, and $C_T = 2n_0^2\alpha C_B (1/\nu \kappa)$ with thermal conductivity $\kappa$ and thermal expansion $\alpha$. $\nu$ is the wavelength, $n_0$ is the refractive index, and $C_B$ is a function of photoelastic coefficients (see also Ref. 3). Theoretically, there is no depolarization loss for a RT in a rod followed by a CQW for both cases, a flat top beam which is a function of photoelastic coefficients

$$f_{\text{depol}}(r, \phi) = \frac{1}{2} \left[\sin(C_T P(r/r_0)^2)\right]^2 \left[\sin(2\phi)\right]^2.$$

(3)

The depolarization loss functions were derived using the Jones matrices for rod and CQW, which can be found in Refs. 4 and 5 for example. For a flat top beam profile the depolarization loss for a RT in the rod is

$$L_{\text{depol}}^{\text{rod,flat}} = \frac{1}{2} \left[1 - \sin(2\alpha)\right],$$

(4)

where

$$\alpha = C_T P(r_b/r_0)^2$$

(5)

and $r_b$ is the beam radius. The depolarization loss for a RT in the rod followed by a CQW is

$$L_{\text{depol}}^{\text{CQW,flat}} = \frac{3}{16} - \frac{1}{2} \sin(\alpha) + \frac{1}{2} \sin(2\alpha).$$

(6)

For a gaussian beam profile with $I_{\text{in,gauss}} = \exp[-2(r/r_0)^2]$, where $r_0$ is the beam width at $1/e^2$ of the peak intensity, the exact analytic expressions for the depolarization loss are more complicated and are listed in the Appendix. For $r_b/r_0 < 1$ the analytic expression for the depolarization loss can be approximated by a more simple expression. In this case a RT in the rod results in a depolarization loss of

$$L_{\text{depol}}^{\text{rod,gauss}} \approx \frac{1}{4} \left(1 + \frac{1}{\alpha^2}\right)^{-1},$$

(7)

and a RT in the rod followed by the CQW is

$$L_{\text{depol}}^{\text{CQW,gauss}} \approx \frac{3}{16} \left(1 + \frac{5}{\alpha^2} + \frac{4}{\alpha} \right)^{-1}.$$

(8)

It is important to note that the depolarization loss only depends on the ratio of the beam width to the rod radius.

Figure 1(a) shows the depolarization loss of a rod as a function of power for flat top and gaussian beam profiles. Eventually, for high thermal loading the depolarization loss will be 0.25 independent of beam shape and rod fill factor. However, for low thermal power the depolarization loss is substantially reduced for a smaller ratio $r_b/r_0$. In this case more photons are located close to the center of the rod where the birefringence effect is less effective—the depolarization loss increase in the radial dimension. The same behavior can be found for the case when inserting a CQW [Fig. 1(b)]. For large amount of heat the depolarization loss will converge to 0.19. Thus, in principal the CQW compensates only a few percent of the introduced birefringence loss. Figures 1(a) and 1(b) depict the calculated depolarization loss using the exact (A1, A2) as well as the approximate (7,8) expressions for the gaussian beam profile. For $r_b/r_0 < 1$ the approximate expressions are a very good approach. No difference can be seen for $r_b/r_0 = 0.5$, which is a typical rod fill factor for a laser system operating in TEM$_{00}$ mode. Figure 1(c) compares the depolarization loss of a rod without compensation with a rod followed by a CQW for both cases, a flat top beam which is matching the rod and a gaussian beam with $r_b/r_0 = 0.5$. These two cases were chosen, because they extract very efficiently the stored energy in the rod without losing much energy by the rod aperture. For the flat top beam profile, a CQW can reduce the depolarization loss below 0.05 for up to 20 W heat load. Whereas for the gaussian beam profile with $r_b/r_0 = 0.5$ the depolarization loss is lower than 0.05 for as high as 70 W heat load.

To experimentally demonstrate birefringence depolarization compensation, we propagated a linear polarized cw probe beam ($\lambda = 1.061 \mu m$) through a uniformly, diode-side-pumped Nd:YAG rod. The experimental setup is shown in Fig. 2. The linear polarized cw probe beam passes through...
the rod and a concave lens. The latter compensates for the rod thermal lensing. The telescope lenses image the principal plane of the rod thermal lens to the end mirror and back to itself. The compensating element is placed in front of the high reflector. The depolarized portion of the probe beam is deflected at the polarizer and relay imaged onto a camera or detected with a photodiode. If the rod were not pumped then the complete probe beam would transmit through the polarizer and relay imaged onto a camera or detector.

In conclusion, analytical formulas for the depolarization loss as a function of heat load in the rod were derived for different birefringence compensation techniques and experimentally verified. The compensating quarter-waveplate, which would enable a simple cavity design, reduces the birefringence loss very efficiently for a gaussian beam up to 70 W heat load. In this regime, the compensating quarter-waveplate is a simple, cost-effective option to a Faraday rotator.

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APPENDIX

For a gaussian beam, the exact formula for the depolarization loss for a RT in the rod is

\[ L_{\text{depol,gauss}} = \frac{1 + a^2 - \alpha^2 \exp(2(r_0/r_b)^2) - \cos(2C_T P) + \alpha \sin(2C_T P)}{4(1 + a^2)(1 - \exp[2(r_0/r_b)^2])}. \]  

The exact formula for the depolarization loss for a RT in the rod followed by a CQW is

\[ L_{\text{depol,CQW}} = \frac{-12 - 15a^2 - 3a^4 + 3a^6 \exp(2(r_0/r_b)^2)}{16(4 + 5a^2 + a^4)[-1 - \exp[2(r_0/r_b)^2]]} + \frac{16[1 + a^2 \cos(C_T P) + (4 + a^2)\cos(2C_T P)]}{16(4 + 5a^2 + a^4)[-1 - \exp[2(r_0/r_b)^2]]} \]

\[ + \frac{16[8a \sin(C_T P) + 8a^3 \sin(C_T P) - 4a \sin(2C_T P) - 2a^3 \sin(2C_T P)]}{16(4 + 5a^2 + a^4)[-1 - \exp[2(r_0/r_b)^2]]}. \]  