Thermal Lensing Effects in End pumped Er:YAG Laser

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Abstract
The most difficult challenge in the design of such high-power end-pumped lasers is the handling of thermal problems that arise due to the high heat load in the small crystal volume. Most notably, the heat load leads to large temperature gradients both in the radial and axial directions referred to the pump beam axis. Such gradients may lead to severe thermal lensing effects due to the temperature dependence of the refractive index, and to large local stresses which induce a spatially varying birefringence and depolarization and may, in the worst event, lead to crystal fracture. The effects of thermal lensing and birefringence, and methods for compensation, are treated in following sections. The occurrence of thermal lensing may have serious implications on the stability conditions of the laser resonator, so it is necessary to take this into account in the resonator design.
Keywords: Er:YAG laser, high power end pumping, thermal lensing.

List of symbols

P_h= the total heat power dissipation by the laser rod (W)
P_p= pumping power (W)
r0 =laser rod radius at the surface (mm)
r =laser rod radius (mm)
w_p= Gaussian pumping beam radius (mm)
w= Gaussian mode radius (mm)
α=thermal expansion coefficient =7.8×10-6C-1
dn/dT= 7.3.10-6/K,
δ=phase shift (mm)
λ=laser wavelength =2.94 μm
$C_{r,\phi}$=functions depending on the elastooptics coefficients in the rod material (C_r=0.017, C_ϕ=-0.0025)
F_{th}=thermal focal length (mm)
I_h=thermal heat load (W/m3)
k = thermal conductivity =0.11 W/cm.K
L=rod length =30mm
L_G= Gaussian losses
Lupper=upper losses limit
n = refractive index =1.82
n_r= refractive index for radial polarized component
n_ϕ= refractive index for tangential polarized component

1. Introduction

In the case of a cylinder laser rod ,pumped by a Gaussian pump beam which is well collimated over the length L of the rod, a fraction of the absorbed pumping light will converted to heat, there for the heat load (W/m3)can be a approximated:
$I_h(r)=(2P_h/L\pi w^2)\exp(-2(r/wp)2$ (1)
Where Ph is the total heat power dissipated and w_p is the Gaussian beam radius. It found that ,the fraction of the absorbed pump power which is converted to heat may 23%,assuming 50W pumping power, w_p=0.4mm, we obtain the $P_h \approx$14.4W.
By solving the radial heat equation in our case lead to a non –parabolic radial temperature distribution, which means that the thermal lens can no longer be describe by a precise focal length .This mean that there are aberration in the thermal lens in addition to the aberration caused by bi-focusing .We find that thermal focal length has a minimum on the rod axis:
$F_{th}(r=0)=1/[(2P_h/k\pi w_p)(0.5dn/dT)+ \alpha C_{r,\phi}\, n^3]$ (2)
We obtain the following approximate expression for the thermal focal length on the axis of Er:YAG rod by using the following values
$F_{th}= 5000w_p2/ P_h$ (3)
The thermal focal length is inversely proportional with input diode laser pumping power as shown in figure (2) in our case (i.e.,wp=0.4 mm,pp=50W,L=30mm) we have a save pumping for Er:YAG laser rod up to 925 W of pump power because at a such a pump beam radius giving induced the thermal focal length inside the laser rod and may lead to crystal fracture at high power laser pumping.

2. Stress-Induced Birefringence

As a result of non-uniform temperature distribution in the laser rod there will be a non-uniform thermal expansion, which result in stress, stress leads to deformations (strain) which in turn leads to optical birefringence in the rod via the photoelastic effect. This also gives a significant contribution to thermal lensing. In the case of radial symmetry, the birefringence occurs as a difference in the index of refraction between the radial and tangential polarization components of the laser field as illustrated in Figure 1. [3]

3. Depolarization Losses with Uniformly Pumped Laser Rod

In the case where the heat power is uniformly distributed across a rod with radius r0, the phase shift difference between the radial and tangential polarization components was calculated as shown in figure 3 using the following approximation:

$\delta= (2\pi/\lambda)(n_\phi-n_r)L=(2n^3\alpha C_B P_h/\lambda k)(r/r_0)^2=C_T P_h(r/r_0)^2$ (4)

Where n_ϕ and nr are the refractive indexes for the tangential and radial polarization component, and CB is a parameter depending on the elasto-optic coefficients of the laser material. Using the material parameter values for YAG and that CB =0.01 in YAG, we find that CT=0.042/W for λ=2.94 µm(Er:YAG) .The phase shift between the radial and tangential polarization component Er,Eϕ which they have an equal magnitude along the radial lines at ϕ=45,135,225and 315 degrees, are increases along the rod radius from the rod center, as shown in figure (3).

4. Gaussian Pump Beam and Gaussian Laser Mode

In our case of resonator design we used the Gaussian mode with a beam radius (w) ,we find the losses due this mode and it named a Gaussian losses :

$LG=0.25(\delta_G)^2 / 1+(\delta_G)^2$ (5)

Where $\delta G=C_T P_h w^2/r0^2$

Analytic expressions for the depolarization loss can only be found in the case of a uniformly pumped rod, an upper bound on the depolarization loss in the case of a Gaussian pump beam can be found by calculating the loss for a uniform pump beam with the same intensity as the peak intensity of the Gaussian pump beam. Assume a Gaussian pump beam with beam radius w_p generating a total heat power of P_h, and a Gaussian resonator mode with radius w. The heat power per unit area in the center of the rod is Ih = $2P_h/(\pi\ w_P\ 2)$. In order to find the upper bound for the loss, we assume that is Ih distributed uniformly across a rod with radius r0, which corresponds to a total equivalent heat power in the rod of Ph,eq =$2P_h(r0/w_p)2$. we obtain an upper bound for the depolarization loss:

$Lupper=0.25(2C_T P_h(w^2/w_p^2)2/(1+2C_T P_h(w^2/w_p^2))$ (6)

Figure 5,shows the calculation of the upper limit for the depolarization loss for tow wavelengths λ=1.06µm and λ=2.94µm as a function of total heat power dissipated are shown in figure 5,note that the loss is increase with Ph increasing also it decrease with laser wavelength increasing and finally the loss can be decrease with reducing the resonator mode radius w .

5. Method of Reducing Depolarization Losses

In our paper we use a simple method, for reducing the depolarized loss by use an extra quarter-wave plate, inserted between the laser rod and the laser end mirror. The plate is aligned with one of its principal axes parallel to the main direction of polarization in the laser, usually defined by a polarizer. For a double-pass, the quarter-wave plate acts like a half-wave plate, i.e. an incoming polarization vector oriented with an angle ϕ relative to the principal axis of the plate is rotated by an angle 2ϕ after a double-pass. As discussed in connection with Figure 1, maximum depolarization in the laser rod occurs along lines oriented 45 degrees relative to the main polarization direction. Along these lines the radial and tangential polarization components Er and Eϕ (refer to Figure 1) are oriented 45 degrees relative to the principal axis of the wave plate, and are therefore swapped after double-passing the wave plate. Therefore, in the return pass through the laser rod, the depolarization occurring in the forward pass will be cancelled, i.e. the depolarization is cancelled along the lines where the loss was maximal without the wave plate. [2]

6. Gaussian laser mode

In the case of a Gaussian laser mode with radius (w) we find the following expression for the compensated loss:

$L_{G,\ compensated}=3\delta_G^4/16(4+5\ \delta_G^2+\ \delta_G^2)$ (7)

Where $\delta_G=C_T P_h(w/r0)^2$

The expression corresponds to expression (5) obtained without the wave plate. The improvement factor in the case of a Gaussian laser mode becomes:

$L_G/L_{G,\ compensated}=4(4+5\delta_G^2+\ \delta_G^4)/3\ \delta_G^2(1+\ \delta_G^2)$ (8)

Our results in figures 6&7 shows the compensation obtained with the quarter-wave plate is very good for small values of δ_G. For example, for λ = 2.94 µm, P_h = 50 W , we find that $L_{G,\ compensated}$ = 0.03 % at w= r0/2 and $L_{G,\ compensated}$ =3% at w=r0.

7. Conclusion

The analysis and the results in this paper give an indication, in high power end- pump solid state laser, there will be an influence of thermal effects ,such thermal induces lensing and birefringence. in thermal lens the a focal power point can be generated due to temperature distribution inside the laser rod, so it is called thermal focal length which can be focused in or out the rod depending on the pumping power .Where thermal focal length decreases with pumping power increasing and it found in our case for an Er:YAG laser rod with 3mm×30mm dimensions, a thermal focal length on the rod axis of 55 mm is induced at 50 W pumping power with a pump beam radius of 0.4 mm. This laser rod can be pumped up to ≈925 W of pump power with such a pump beam radius giving induced thermal focal length inside the laser rod, Fig 2.The phase shift between the radial and tangential polarized pump beam components inside the rod are increase from the center along the rod radius ,Fig 3. The radial temperature distribution in the laser rod lead also to stress ,which induced birefringence, and there by a loss which can be calculate it's magnitude when the resonator mode is defined .It found:

1-The loss increase with pumping power increasing, Fig 4
2-The loss increase with resonator mode radius increasing, Fig 4
3- The loss increase with laser wave length decreasing, Fig 5

It can be reduces the loss from several % for few watts of pumping power to a negligible % by simple method (quarter-wave plate), Fig 6-7

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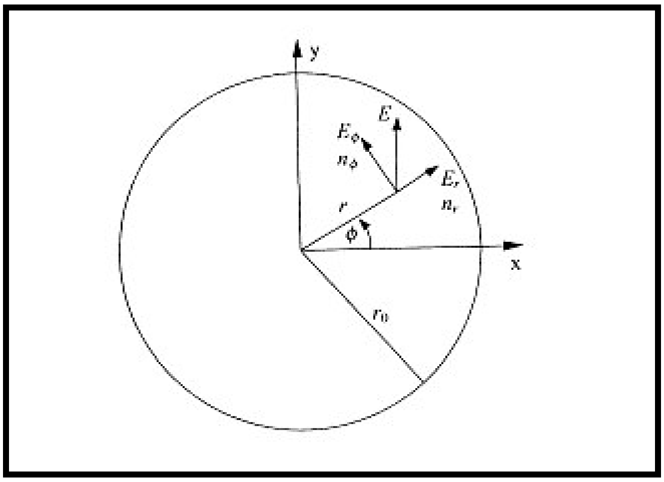

Figure 1. Birefringence in laser rod with radially symmetric temperature distribution.

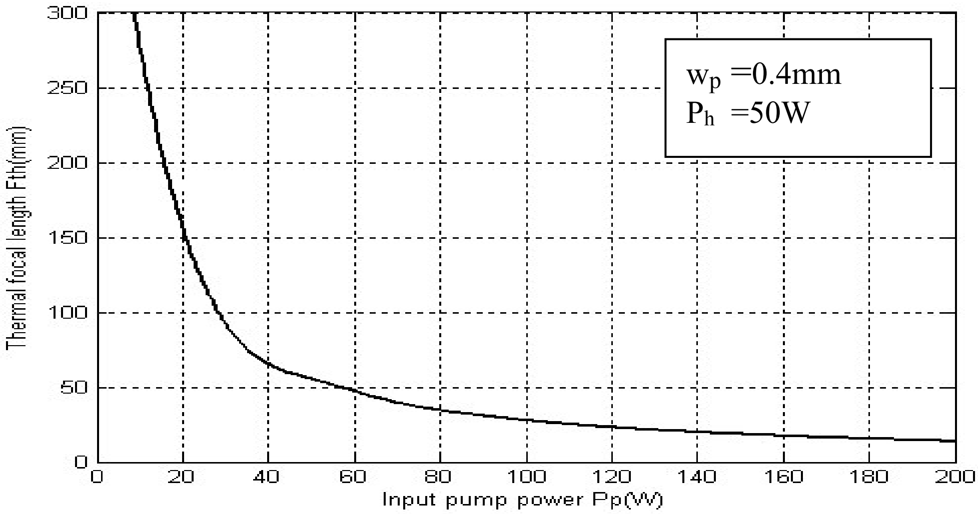

Figure 2. Thermal focal length inside the Er:YAG laser rod as a function of input pumping power.

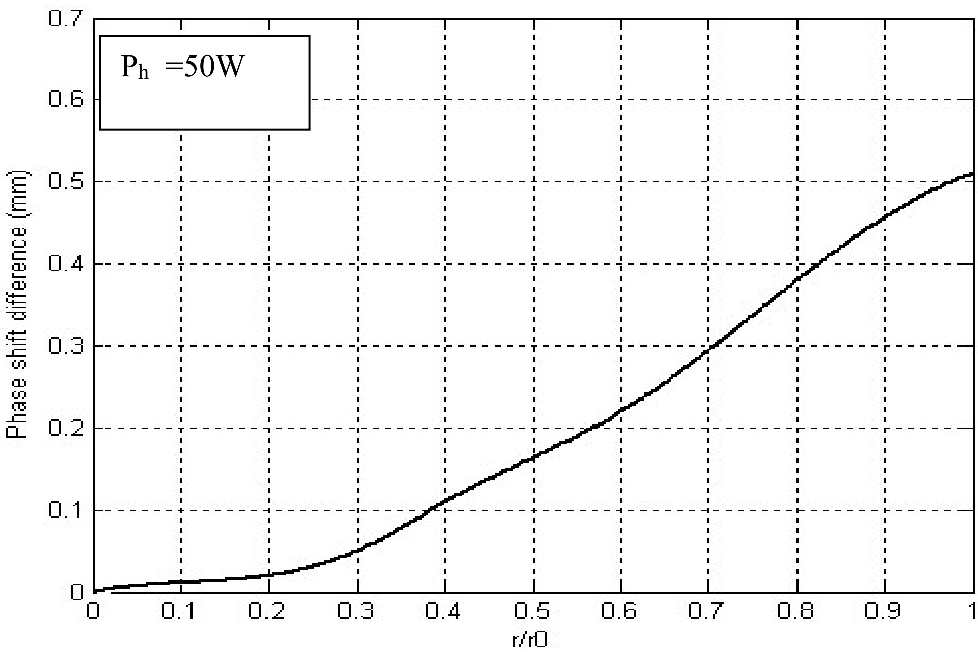

Figure 3. Phase shift difference between the radial and tangential polarization components for the diode laser pump beam pass through the Er:YAG laser rod.

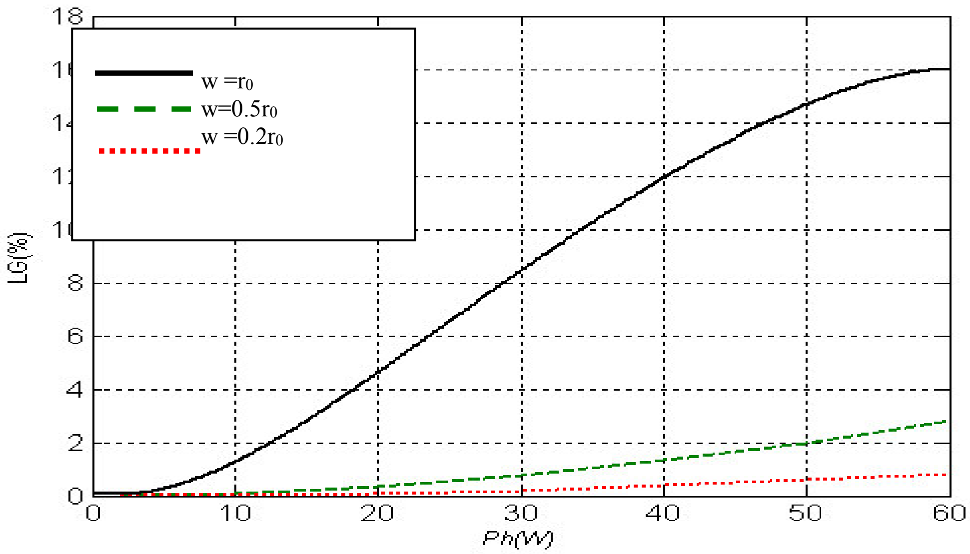

Figure 4 .Loss due to stress-induced birefringence in a uniformly pumped Er:YAG rod at 2.94 µm laser wavelength at different Gaussian resonator mode radius vs. power heat generated.

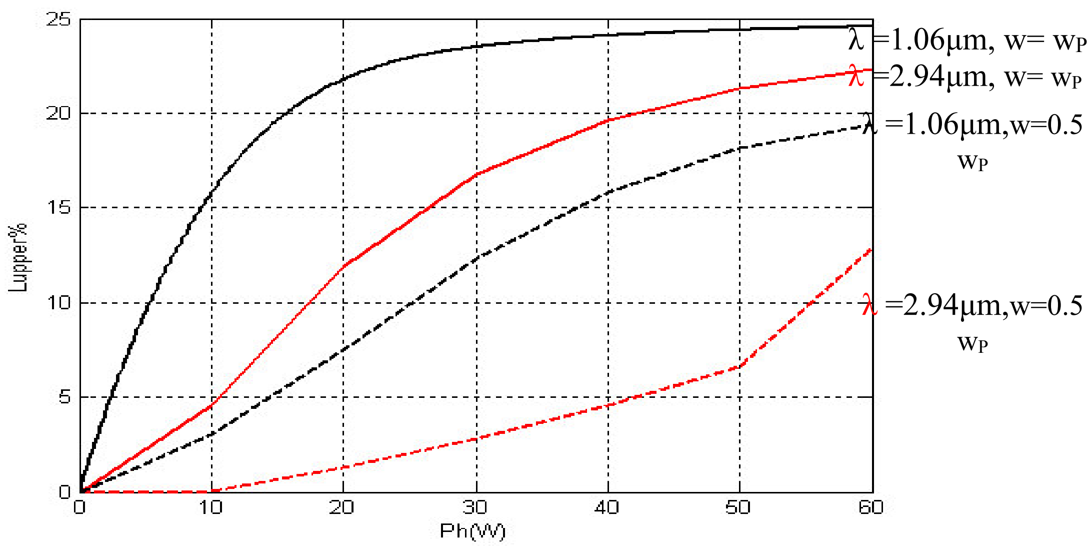

Figure 5 .Upper limit for the depolarization loss for a Gaussian pump beam with radius w_p and a Gaussian laser mode with radius w, as a function of the generated heat power P_h.

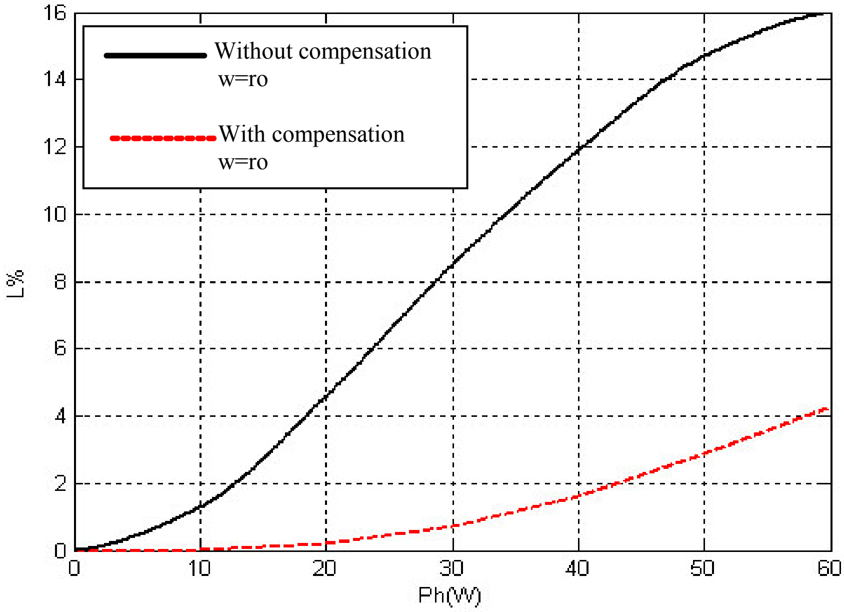

Figure 6 .calculated loss for Gaussian laser mode in Er:YAG laser rod ,with and without the use of birefringence compensation.

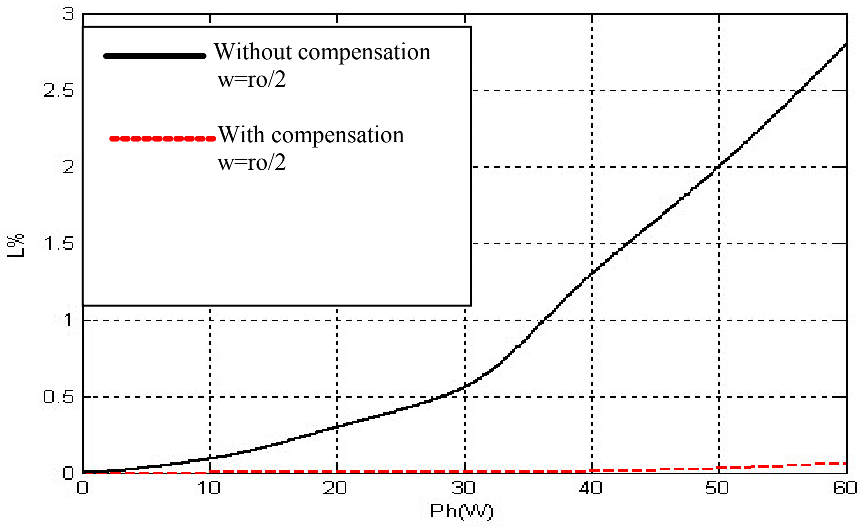

Figure 7: calculated loss for Gaussian laser mode in Er:YAG laser rod ,with and without the use of birefringence compensation.