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Comparative Study of Thermal Lens Effect in End Pulsed-Pumped Ceramics and Single Crystal Yb^{3+}: YAG/ Cr^{4+}: YAG Passively Q-switched Microchip Laser

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Abstract

In this work, different thermal lens focal lengths with different pumping repetition rates for ceramic and single crystal Yb:YAGare calculated for controlling the thermal focal length without using additional optical elements . The effect of pumping energy and pump beam diameter on the thermal focal length is studied. Finally, the stability of the cavity is investigated via ABCD matrix method.

Keywords:*Q-Switched Laser, Microchip Laser, Thermal Lens, ABCD Matrix, ceramic laser.*

1 Introduction

Microchip lasers compactness and small size give them the potential for inexpensive mass production, while their CW output characteristics are comparable to the conventional devices (Zayhowski,(1999)).They are promising radiation sources for many applications, like micro-manufacturing, remote sensing, data storage, etc(Molva.(1999)). Due to better mechanical and thermal properties compared to the glass and single crystal, transparent ceramics became high power end-pumping lasers candidate in numerous fields (Hostaša, et al, 2014, and, Kracht,2005). Ceramic active medium can be heavily and homogeneously doped with laser-active ions (Ikesue et al, 2008).

Yb:YAG laser characteristics indicate a great potential for highly efficient and high power Diode Pumped Solid State (DPSS) lasers (Takaichi, K.et al(2003), Nakamura,S. et al(2014),Jiang,W.et al,(2015)). In 2003, the first CW Yb:YAG laser beam, with 345 mW output power and 26% slope efficiency, was demonstrated using ceramic Yb:YAG (Takaichi et al, 2003). An average output power of 3.80W with a pulse duration of 433 fs , a repetition rate of 90.9MHz and a peak power of 96.5kW was achieved at 1050 nm using a 2% output coupler in mode locked Yb-YAG ceramic laser (Nakamura, et al, 2014). A maximum average output power of 2.55 W, with pulse duration 11.5 ns, repetition rate of 5.71 kHz, pulse energy of 446.25 μJ and peak power of 38.8 kW was obtained by using composite Yb:YAG/ Cr^{4+}:YAG crystal with passive Q-switching at 1030 nm (Jiang, et al , 2015).

As the thermal lens coefficient is very important in the stability of laser cavity, temperature distribution and the thermal lens effect in the active medium of CW pumped Q-switched solid state lasers has been studied (Ozygus, et ;al 1995, Ozygus, et al ,1997, Blows,et al,1998, and El-Azab, et al, 2014). Also, the thermal lens focal length in the case of pulsed pumping has been determined (Lausten, et al,2003,Salin,et al 1998).

In this work, for comparing between the thermal lens effect on single crystal and ceramic Yb:YAG, thermal focal length of single crystal and ceramic Yb:YAG will be determined as a function of pumping repetition rate, More over the stability of end-pumping Q-switched Yb:YAG/Cr:YAG microchip laser was investigated in section 2. The results are represented and discussed in section 3 and concluded in sections 4.

2Thermal focal length and stability

The time dependent temperature profile of pulsed end-pumped lasers was solved(Lausten,et al, 2003, Wang, 2009, Chen, et al 2015). It is determined by using heat equation (Lausten, et al 2003);

$$C\frac{\partial T}{\partial t} = A(r,t) + K\nabla^2 T \qquad (1)$$

whereC is the heat capacity per unit volume, A accounts for heat deposition(source term), and K is the thermal conductivity. The heat source term in equation (1) can be neglected as the heat distribution time is longer than that of thermal energy deposition via pump pulse. In this case equation (1) can be reduced to;

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T \qquad (2)$$

where $\kappa = K/C$, is the thermal diffusivity. At steady state, the temperature profile at fixed repetition rate can be expressed as (Lausten, et al 2003);

$$T_\infty(r,z,t') = \frac{T_0}{\gamma l}[1-\exp(-\gamma l)] \times \sum_{n=1}^{\infty} \exp\left(-\frac{\kappa \alpha_n^2 t'}{a^2}\right) \widetilde{\emptyset_n}(r) \times \left\{\frac{1}{1-\exp\left(-\frac{\kappa\alpha_n^2 \Delta t}{a^2}\right)}\right\} + 2\frac{T_0}{\gamma l}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\left[\widetilde{\psi_m}(z) \times \exp(-\kappa m^2\pi^2 t'/l^2)\widetilde{\emptyset_n}(r) exp\left(-\frac{\kappa\alpha_n^2 t'}{a^2}\right)\right] \times \left\{\frac{1}{1-\exp(-\kappa m^2\pi^2\Delta t/l^2) exp\left(-\frac{\kappa\alpha_n^2\Delta t}{a^2}\right)}\right\} \qquad (3)$$

Where

Table (1); parameters of steady state temperature profile

parameter	Name
T_0	Starting temperature at(z=0)
γ	Absorption coefficient
l	Length of the crystal
κ	Thermal diffusivity
α_n	Zeros of Bessel function
a	Diameter of the crystal
$\widetilde{\emptyset_n}(r)$	The time dependent function of radial distribution of thermal conduction
t'	The time since the last laser shot
Δt	Time separation between successive pulses=$(1/\nu(repetition\ rate))$
$\widetilde{\psi_m}(z)$	The time dependent function of longitudinal distribution of thermal conduction

Due to the non-uniform temperature profile within the crystal, the thermal induced optical path difference includes thechange of refractive index with temperature, the end faces bulging out, and the stress induced birefringence. For YAG, the last two effects might be neglected as they are much smaller than the former part (Pfistner,et al, 1994).

Therefractive index near the center of the crystal(r=0) is well describedby a first-order expansion around the temperature of the centerT_c(Koechner, 1976),

$$n(T) \simeq n(T_c) + \left.\frac{\partial n}{\partial T}\right|_{T_c}(T-T_c) \qquad (4)$$

Thus, the difference in the optical path length is given by the expression [13].

$$\Delta l(r) = \left.\frac{\partial n}{\partial T}\right|_{T_c}\int_0^l [T_\infty(r,z,t'=0) - T_\infty(r=0,z,t'=0)]\, dz \qquad (5)$$

This shows that the thermal lensing is essentially determined by the integration of the temperature profile along z. Applying derivation method , the optical path length difference can be written as (Lausten, et al 2003);

$$\Delta l(r) \approx \left.\frac{\partial n}{\partial T}\right|_{T_c}\frac{-2E_0}{\pi r_p a C(T_c)}[1-\exp(-\gamma l)] \times \left(\frac{r}{a}\right)^2 \times \sum_{n=1}^{\infty}\frac{J_1\left(\frac{\alpha_n r_p}{a}\right)}{J_1^2(\alpha_n)}\frac{\alpha_n}{4}\frac{exp\left[-\frac{\kappa\alpha_n^2}{\nu a^2}\right]}{1-exp\left[-\frac{\kappa\alpha_n^2}{\nu a^2}\right]} \qquad (6)$$

As this optical path length difference is quadratic in r, it can be presented as spherical lens where $\Delta l(r) \approx -\frac{r^2}{2R}$, and R is the curvature of the lens. The focal length of the thermal lens can be expressed as (Born and Wolf, 1999); $f = R/(n-1)$, therefore the thermal focal length can be written as (Lausten, et al 2003);

$$f = \frac{1}{n-1} \times \frac{a^3\pi r_p C(T_c)}{\left.\frac{\partial n}{\partial T}\right|_{T_c} E_0[1-\exp(-\gamma l)] \times \sum_{n=1}^{\infty}\frac{J_1\left(\frac{\alpha_n r_p}{a}\right)}{J_1^2(\alpha_n)}\alpha_n\frac{exp\left[-\frac{\kappa\alpha_n^2}{\nu a^2}\right]}{1-exp\left[-\frac{\kappa\alpha_n^2}{\nu a^2}\right]}} \qquad (7)$$

The ray matrix of the thermal lens can be expressed as;

$$M_{T.L} = \begin{bmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{bmatrix} \qquad (8)$$

Wheref is the thermal focal length. The ray matrix of Yb: YAG active medium can be written as;

$$M_{A.M} = \begin{bmatrix} 1 & \frac{l}{n} \\ 0 & 1 \end{bmatrix} \qquad (9)$$

where(l) is the length of the active medium and n is the refractive index of the active medium. Also saturable absorber has the following ABCD matrix, where $l_{S.A.}$ is the length of saturable absorber and $n_{S.A.}$is the refractive index of saturable absorber;

$$M_{S.A} = \begin{bmatrix} 1 & \frac{l_{S.A.}}{n_{S.A.}} \\ 0 & 1 \end{bmatrix} \qquad (10)$$

The laser beam waist at thermal focal length can be determined via ABCD law (Kogelnik, et al, 1966);

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D} \qquad (11)$$

where(q) is the complex beam parameter which is defined as (Kogelnik, et al, 1966);

$$\frac{1}{q} = \frac{1}{R} - j\frac{\lambda}{\pi\omega^2} \qquad (12)$$

where(R) is curvature radius of the beam wave front, λ is the laser wave length and, (ω) is the laser beam radius.

Stable cavity can be defined as the cavity that be designed from perfectly aligned mirrors that keep ray near the optical axis and the general condition for stability of the laser cavity is (Verdeyen, 1981);

$$-1 \le \left(\frac{A+D}{2}\right) \le 1 \qquad (13)$$

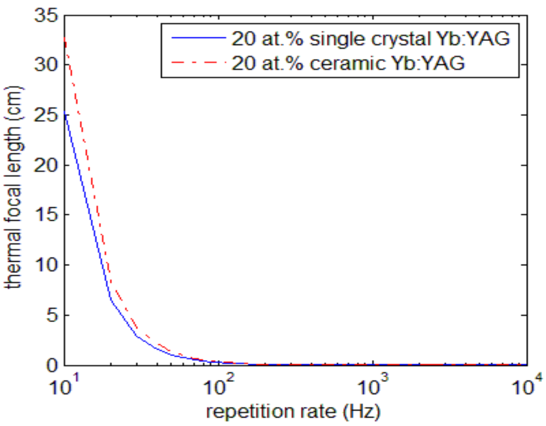
3 Results and discussion

The parameters of Yb:YAG passively Q-switched using Cr:YAG used for numerical simulation are listed in table (2), and by using MATLAB code the following results were obtained.

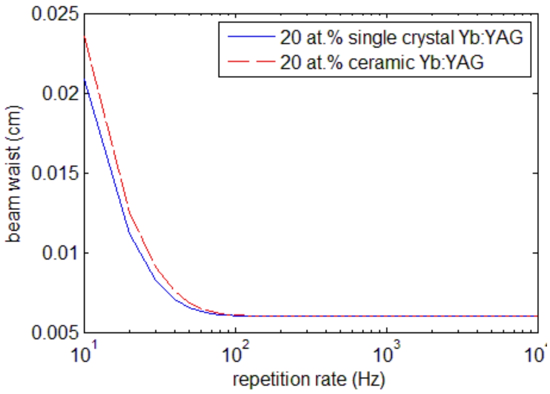
parameter	Name	value
n	Refractive index of Yb:YAG	1.82
a	Diameter of the active medium	1 mm
r_p	Pump beam radius	60 μm
C	Volumetric heat capacity of ceramic Yb:YAG	2.6754 $Jcm^{-3}k^{-1}$
	Volumetric heat capacity of single crystal Yb:YAG	2.673 $Jcm^{-3}k^{-1}$
	Volumetric heat capacity of Cr:YAG	2.736 $Jcm^{-3}k^{-1}$
$\partial n/\partial T$	For Yb:YAG	$9 \times 10^{-6}k^{-1}$
	For Cr:YAG	$7.8 \times 10^{-6}k^{-1}$
E_0	Pumping energy	1 J
γ	Absorption coefficient for ceramic Yb:YAG	26 cm^{-1}
	Absorption coefficient for single crystal Yb:YAG	13.6 cm^{-1}
l	Length of Yb:YAG	1.2 mm
	Length of Cr:YAG	1.5 mm
κ	Thermal diffusivity of ceramic Yb:YAG	0.024 cm^2sec^{-1}
	Thermal diffusivity of single crystal Yb:YAG	0.0193 cm^2sec^{-1}
	Thermal diffusivity of Cr:YAG	0.041cm^2sec^{-1}
ν	Repetition rate	10-10000 Hz

table (2)parameters which are used in numerical simulation

Figure (1-a) shows that, with different pumping repetition rates, 20at. % ceramic Yb:YAG active medium has a thermal focal lengths higher than 20at. % single crystal Yb:YAG at room temperature. At high repetition rates, both of them have the Convergent values of thermal focal length. Figure (1-b) shows the variation of the beam waist at focal point with the variation of repetition rates.



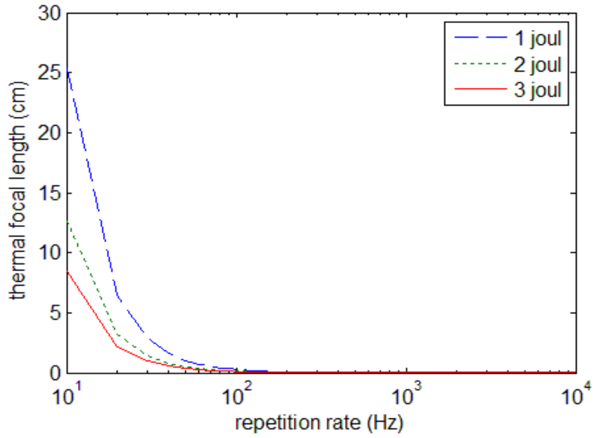
(a)



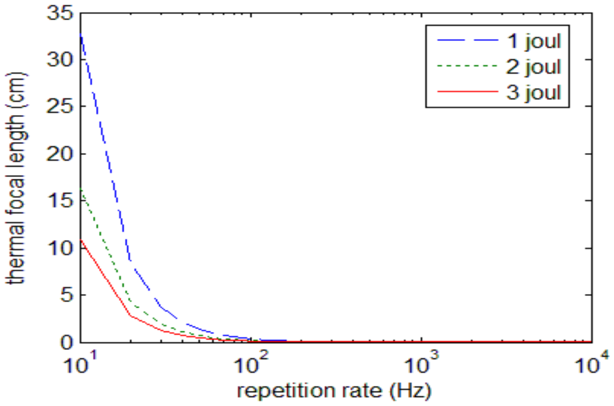
(b)

Figure (1): thermal focal length (a) and beam waist (b) ofYb: YAG single crystal and Ceramic

By increasing pump energy from 1 joul to 3 jouls at 10 Hz repetition rate, thermal focal length of 20 at.% ceramic Yb:YAG decreases from 32.68 cm at 1 joulto 10.89 cm at 3 jouls. On the other hand thermal focallength of 20 at. % single crystal Yb:YAG decreases from 25.37 cm at 1 joul to 8.45 cm at 3 jouls, as illustrated in figure (2). This is due to the higher thermal diffusivity of ceramic Yb:YAG than that of single crystal Yb:YAG.



(a)



(b)

Figure (2): thermal focal length of 20 at. % Yb: YAG (a) single crystal and (b) ceramic at different pump energies

As in the figure (3), with pump beam radii of 60, 100 and 200 µm the thermal focal length of ceramic Yb: YAG is 33.46 cm, 20.18 cm and 10.33 cm at 10 Hz repetition rate, respectively. At repetition rates more than 300 Hz, thermal focal length associated with 200 µm is higher than that of 100 µm and after the repetition rate of 500Hz, the thermal focal length of 200 µm is higher than both 60 µm and 100 µm. It is noted that after repetition rate of 1000 Hz the thermal focal length associated with 100 µm is higher than that associated with 60 µm, and this can be explained by increasing of the repetition rate of pump energy which leads to increasing in the deposited thermal energy that yield decreasing in the focal length as reported in equation (7).

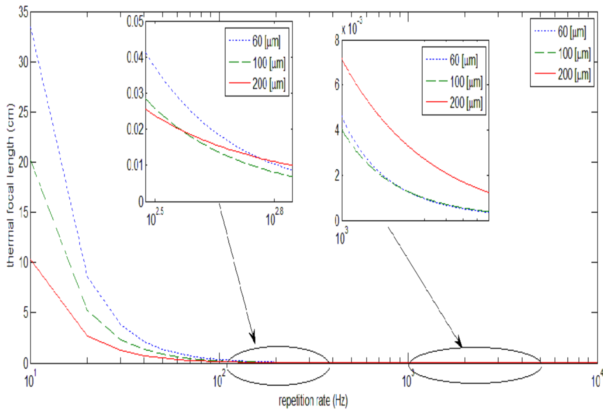


Figure (3): thermal focal length of ceramic 20 at.% Yb:YAG with different pump beam radii

As in the figure (4), with pump beam radii of 60, 100 and 200 µm the thermal focal length of single crystal Yb:YAG is 25.97 cm, 15.67 cm and 8 cm at 10 Hz repetition rate, respectively. At repetition rates more than 200 Hz, thermal focal length associated with 200 µm is higher than that of 100 µm and after the repetition rate of 500 Hz, the thermal focal length of 200 µm is higher than both 60 µm and 100µm. Also after repetition rate of 700 Hz the thermal focal length associated with 100 µm is higher than that associated with 60 µm, and this can be explained by increasing of the repetition rate of pump energy which leads to increasing in the deposited thermal energy that yield decreasing in the focal length as reported in equation (7).

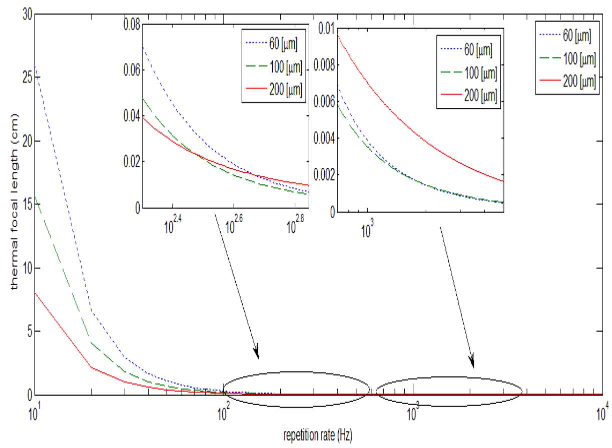


Figure (4): thermal focal length of 20 at% single crystal Yb:YAG at different bump beam radii

Ceramic Yb:YAG shows more stable cavity than that of single crystal as shown in figure (5), where the ceramicYb:YAG cavity becomes not stable after more than 150 Hz.

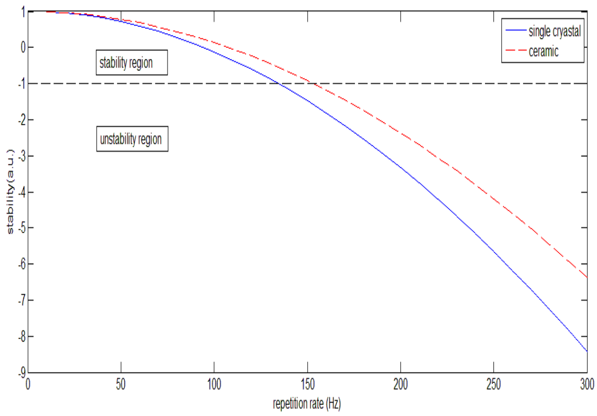


Figure (5): stability of end pumped q- switched Yb:YAG/Cr:YAG cavity.

4 . Conclusion:

Ceramic Yb:YAG laser was more efficient in decreasing the thermal lens effect, as the ceramic Yb:YAG has the longer thermal focal length than that of single crystal Yb:YAG, at the same pump energy and pump repetition rates. Moreover it was found that, the focal length and the laser beam waist can be controlled by using the pump repetition rate without using additional optical elements which leads to compactness and ease of the laser system usage. The stability of the cavity was achieved in the cavity of ceramic Yb:YAG with higher number of repetition rates more than in the case of single crystal.

5. References

Blows,J., Dawes, J. and Omatsu,T. (1998) 'Thermal lensing measurements in line-focus end-pumped neodymium yttrium aluminium garnet using holographic lateral shearing interferometry', J. Appl. Phys., 83(6): 2901.

Born, M., and Wolf,E. (1999) Principles of optics. Cambridge: Cambridge University Press.

Chen,X. Wu,J. Wu,C.Sun, H. Yu, Y. and Jin.G. (2015) "Analysis of thermal effects in a pulsed laser diode end pumped single-ended composite Tm:YAG laser", Laser Physics,25(4):045003.

El-Azab,J.,Kandel,H.,Khedr, M., and El-Ghandoor,H. (2014) 'Numerical Study of Transient Temperature Distribution in Passively Q-Switched Yb:YAG Solid-State Laser', Optics and Photonics Journal,4(3): 46-53.

Hostaša,J., Matějíček,J.,Nait-Ali, B. Smith,D. Pabst ,W. and Esposito,L. (2014) 'Thermal Properties of Transparent Yb-Doped YAG Ceramics at Elevated Temperatures', Journal of the American Ceramic Society, 97(8):2602-2606.

Ikesue,A. and Aung, Y.(2008).Ceramic lasermaterial",Nature Photonics, . 2(12): 721-727.

Jiang,W., Liu, Y., Chen, W.,Zhu,S., Chen,Z. Zhang,G.Chen,Y.andChe.Z.(2015)"CompositeYb:YAG/Cr ^4+:YAG/YAG crystal passively Q-switched lasers at 1030 nm", Appl. Opt., 54(7): 1834.

Koechner,W. (1976) Solid state laser engineering. New York: Springer-Verlag.

Kogelnik, H. and Li, T.(1966) "Laser beams and resonators", Proceedings of the IEEE,. 54(10): 1312-1329.

Kracht,D.,Frede,M., Wilhelm, R. and Fallnich.C. (2005) "Comparison of crystalline and ceramic composite Nd:YAG for high power diode end-pumping", Opt. Express, . 13(16):6212.

Lausten, R., and Balling, P. (2003) 'Thermal lensing in pulsed laser amplifiers: an analytical model', Journal of the Optical Society of America B, 20(7): 1479.

Molva ,E.(1999) 'Microchip lasers and their applications in optical microsystems', Optical Materials,. 11(2-3): 289-299,.

Nakamura,S., . Hikita, Y.,Sone,H., Ogawa T. and Wada. S. (2014). "High-power diode-pumped mode-locked Yb:YAG ceramic laser", OPT REV,21(3): 401-403.

Ozygus,B.and Erhard,J. (1995) 'Thermal lensdetermination of end-pumped solid-state lasers with transverse beat frequencies', Appl. Phys. Lett,. 67(10): 1361.

Ozygus,B.and Q. Zhang. (1997) 'Thermal lens determination of end-pumped solid-state lasers using primary degeneration modes', Appl. Phys. Lett,. 71(18): 2590.

Pfistner,C.,Weber,R.,Weber,H., Merazzi, S., andGruber, R. (1994). "Thermal beam distortions in end-pumped Nd:YAG, Nd:GSGG, and Nd:YLF rods", IEEE Journal of Quantum Electronics,. 30(7): 1605-1615.

Salin,F.,Blanc,C.,Squier,J. and Barty,C. (1998) 'Thermal eigenmode amplifiers for diffraction-limited amplification of ultrashort pulses', Optics Letters,.23(9): 718.

Takaichi,K.,Yagi,H.,Lu,J. Shirakawa,A.,Ueda,K.Yanagitani,T., and Kaminskii,A. (2003). "Yb3+-doped Y3Al5O12 ceramics– A new solid-state laser material", phys. stat. sol. (a), 200(1): R5-R7.

Verdeyen, J. (1981).Laser electronics. Englewood Cliffs, N.J.: Prentice-Hall.

Wang,S.,Wang, X. Riesbeck, T., and Eichler,H. (2009) "Thermal lensing effects in pulsed end pumped Nd lasers at 940 nm", Laser Resonators and Beam Control XI,7194: 71940J-1.

Zayhowski,J. (1999) 'Microchip lasers', *Optical Materials*,11(2-3): 255-267.