IRAQI JOURNAL OF APPLIED PHYSICS
Vol. (14), No. (2), April-June 2018, pp. 35-42

Haider M. Majeed [1]
Riyadh A. Jassim [1]
Ahmed J. Kadhim [2]

Numerical Analysis of Temperature Dependencies of Optical Elasticity Coefficient on Lens Induced in Solid-State Laser Crystal

[1] *Department of Physics, College of Science, Misan University, Amara, IRAQ*
[2] *Department of Physics, College of Science, Thi Qar University, Nasiriyah, IRAQ*

In this work, one effect of the optical pumping power on the characteristics of a solid-state Nd:YAG laser was studied. The main parameter considered is the change in focal length of lens induced in the Nd:YAG crystal due to temperature-dependent variation in both refractive index and optical elasticity coefficient. The pumping-induced change in focal length of such lens is an important parameter in laser design as it determines how long the optical resonator may keep its stability during operation. It also assigns the main features to be considered in order to obtain the optimum characteristics of the produced laser beam. This investigation does not consider all aspects may affect laser operation but it represents a forward step to understand the intracavity limitations of solid-state, specially Nd:YAG, laser.

Keywords: Thermal lens, Nd:YAG laser, Optical pumping, Birefringence
Received: 01 October 2017, **Revised**: 20 March 2018, **Accepted**: 27 March 2018

1. Introduction

The Nd:YAG laser is the most common solid-state laser since its first invention in 1964. The YAG ($Y_3Al_5O_{12}$) crystal is used to host the Nd^{+3} ions representing the active medium of this laser at the characteristics wavelength of (1.064μm). In Nd:YAG lasers, the optical resonator is usually opened in order to reduce the oscillating modes as the length of resonator is already larger than the laser wavelength to admit photons to oscillate. In the open resonator, only few modes, those corresponding the waves traveling along the resonator axis, have losses low enough to allow laser oscillation [1-4].

In order to obtain constructive oscillations inside the resonator, the length (L) of resonator should equal an integer (n_i) of half wavelength as follows [1-4]:

$$L = \frac{n_i \lambda}{2} \qquad (1)$$

Furthermore, an important condition should be satisfied that the electric field of the standing electromagnetic (EM) wave at both mirrors is zero. The resonance frequencies (ν) are given as a function of the velocity of light (c) as [1-4]:

$$\nu = n(\frac{c}{2L}) \qquad (2)$$

This relation implies that the resonator is under stability condition or near to stability threshold. This stability is satisfied if the beam, which is originally parallel to the axis of laser cavity, reflects forward and backward between the two mirrors. Despite, it is supposed that another beam oscillates slightly out of this axis and the stable resonator should be able to reflect such beam too.

To satisfy this situation, the resonator should have an ability to focus the optical beam. This can be achieved using one of the two mirrors, at least, with some curvature. The plane-parallel resonator cannot satisfy this situation even though the stability condition is achieved through the fine alignment. In case of Nd:YAG laser, the crystal itself can provide the necessary focusing due to the effect of thermal lensing induced inside. Considering the Nd:YAG crystal as a thick lens, the thermal lensing effect is necessary for stable operation condition [4-23].

2. Modeling and Treatment

Figure (1) represents an optical resonator of a solid-state laser. As the laser beam makes one round-trip inside the optical resonator, it is hence facing every time two reference planes represented by both mirrors and according to the theory of Gaussian beam propagation, it is possible to define the stability condition of optical resonator. This laser beam traces a certain path in every pass beginning from the rear (full reflective) mirror. Such beam has a diameter varying as it travels along the distance between the rear mirror and the active medium (Nd:YAG crystal) then passes the crystal toward the output coupler. Hence, passing the resonator includes three ABCD matrices those describe the wave traveling [4, 26-32].

After defining the reference plane, the light beam can propagate through the resonator and then return to the original reference plane. Then there are six matrices describe every round-trip through the resonator. Multiplication of these six matrices can be reduced to the ABCD matrix equivalent to the oscillation as:

$$M = \begin{vmatrix} A & B \\ C & D \end{vmatrix} \quad (3)$$

According to such expression, the complex beam factor (q) at different positions inside the resonator can be defined as [2]:

$$q = \frac{Aq + B}{Cq + D} \quad (4)$$

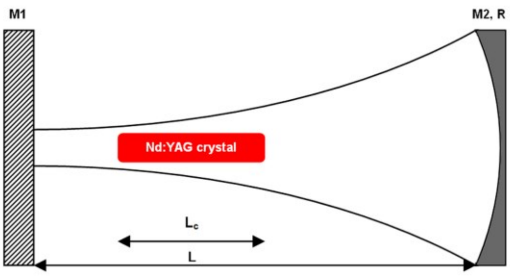

Fig. (1) Simple Nd:YAG solid-state laser resonator

The resonator is said to be stable if the following condition is satisfied:

$$\left(\frac{A+B}{2}\right)^2 < 1 \quad (5)$$

The stable resonator usually confines a Gaussian mode (TEM_{oo}) with a certain radius and the value of beam factor (q), at any of the reference planes, should be deduced after one complete round-trip in order to consider the resonator is stable. The following proved numerical solution to deduce the value of beam factor (q) can be used as [5-10, 33-37]:

$$\frac{1}{q} = \frac{D-A}{2B} \pm \frac{i}{2B}\sqrt{4-(A+D)^2} \quad (6)$$

where the second term containing (i) is the imaginary part of this solution. In order to keep the beam radius always real, the term under square root should be kept positive [9-10].

Presence of the active medium inside the optical resonator changes the optical path length of light beam through the resonator as well as the distribution of transverse modes. Such change in the optical path occurs due to the effect of thermal lens in the active medium crystal in addition to that of the mechanically induced birefringence. For simplicity, this effect can be represented by a simple thin lens of a focal length (f), despite the fact that the Nd:YAG crystal behaves in a manner more complicate than a simple thin lens [4, 38-39].

The focal length (f) can be used to determine the stability of resonator throughout two parameters, each is a function to the resonator length and the optical components inside. These parameters are defined as:

$$g_1 = 1 - \frac{L_2}{f} - \frac{L_o}{R_1} \quad (7a)$$

$$g_2 = 1 - \frac{L_1}{f} - \frac{L_o}{R_2} \quad (7b)$$

where R_1 and R_2 are the radii of both mirrors and L_o is given as:

$$L_o = L_1 + L_2 - (\frac{L_1 L_2}{f}) \quad (8)$$

where f is the focal length of the real lens, L_1 and L_2 are distance from the rear and output mirrors, respectively, to the thermal lens.

If the two mirrors are plane and identical, then it is possible to indicate that the ratio between the two resonator parameters is equal to the ratio between the two spot sizes or beam radii at mirrors as [3,14,16,22]:

$$\frac{g_1}{g_2} = \frac{w_1^2}{w_2^2} \quad (9)$$

The resonator parameters g_1 and g_2, hence the beam radii w_1 and w_2, are determined as a function of the focal length (f) of the supposed thin lens as:

$$g = g_1 = g_2 = 1 - \frac{L}{2f} \quad (10a)$$

$$w_1^2 = w_2^2 = (\frac{\lambda L}{\pi})(1-g^2)^{-\frac{1}{2}} \quad (10b)$$

The Nd:YAG crystal has several characteristics make it the most common among the too much crystals used as active media to produce lasers. In order the crystal to be a suitable host for the active ions, it should be transparent for the pumping light and a small absorption as possible as for the produced laser wavelength in addition to good mechanical properties [4, 40-44].

Knowing the fact that the crystal is subjected to severe thermal stresses due to flash lamp pumping, it is necessary that the crystal should have good thermal conductivity and low thermal expansion modulus. These two properties are necessary to ensure that heat being dissipated efficiently and the crystal dimensions do not change during operation. Also, the crystal melting temperature should be high enough to prevent the applied pumping energy, as well as heat generated from, rise crystal temperature to the melting point [3-4].

The Nd:YAG crystal is optically symmetric and has a cubic structure which is a characteristic for garnet crystals. Furthermore, its optical properties make it an ideal choice as an active medium for laser [45-52].

One of the very good physical properties of Nd:YAG crystal is the stable crystalline structure from the lower temperatures to the melting point, hence no solid-phase transformations does occur [3]. Despite that the toughness and hardness of Nd:YAG crystal are lower than those of ruby, Nd:YAG crystals do not break in held and can be produced by the ordinary manufacturing techniques. Attempts to increase doping levels in YAG crystals with Nd^{+3} ions, in order to satisfy higher gain, lead to distortions through the lattice of YAG crystal because the neodymium ion is slightly larger in diameter than the yttrium atoms. This also led to shorten the fluorescence lifetime. So, doping level is determined to 2% [3, 11-20].

Table (1) indicates the mechanical, optical and physical properties of common Nd:YAG crystals considered in the treatment and computations.

3. Results and Discussion

As someone may consider this investigation a historical review, the following viewpoint is worthy to be assigned. In order to present a conceptual treatment in both analytical and numerical frames, as well as explain the development of pumping theory and its effects on laser operation since the first decade of laser invention to nowadays, a wide survey for the previous works interesting to the aim of this investigation was performed. Hence, the treatment presented forward mainly represents an improvement for results presented in reference [52] and it had considered results of references [5-55].

The thermal lens induced in crystal is a result to the high thermal stresses generated in the crystal during the pumping, so its effect depends extremely on pumping power and cooling system efficiency. Such effects are too important and cannot be neglected in laser system design. In pulsed laser systems, it is noted that thermal equilibrium condition is not satisfied at repetition rates lower than 5Hz [21-25] whereas it is neglected in case of CW laser systems. The resultant of thermal stresses is merely gradient in laser beam quality due the thermal lens and the possible fracture of laser crystal if the thermally induced stress exceeds tensile strength of the material [26-31].

Table (2) the mechanical, optical and physical properties of common Nd:YAG crystals considered in the treatment and computations

Property	Value
Refractive index (n)	1.82
Extinction Ratio	30 dB
dn/dT	7.3×10^{-6} K^{-1}
Stimulated Emission Cross-Section (σ)	2.8×10^{-19} cm^2
Young’s modulus	310 Gpa
Poison’s ratio	0.27
Specific Heat (c_p)	0.14 cal/g.°C
Coefficient of Thermal Expansion	7.8×10^{-6} /°C
Density (ρ)	4.56 g/cm^3
Melting Temperature	1970 °C
Coefficient of Heat Transfer by Convection (h_c)	1.25 W/cm^2.°C
Thermal Conductivity (k)	0.13 W/cm.K
Radial Optical Elasticity Coefficient (C_r)	0.017
Tangentional Optical Elasticity Coefficient (C_ϕ)	- 0.0025
Outer Diameter of Crystal ($2r_o$)	5 mm
Length of Crystal (L_c)	5 cm

In order to determine the focal length of crystal theoretically, it should first introduce the effect of changing refractive index depending on temperature and stress as follows:

$$n(r) = n_o + \Delta n(r)_T + \Delta n(r)_S \qquad (11)$$

where $n(r)$ is the change in refractive index in radial direction, n_o is the refractive index at center of crystal, $\Delta n(r)_T$ is the temperature-dependent change in refractive index, and $\Delta n(r)_S$ is the stress-dependent change in refractive index

The heat (Q) generated per unit volume in laser crystal due to pumping process is given as:

$$Q = \frac{P_a}{\pi r_o^2 L_c} \qquad (12)$$

Where L_c and r_0 are the length and outer radius of Nd:YAG crystal, respectively, and P_a is the thermal power absorbed by the crystal as the steady-state condition being satisfied, i.e., the absorbed heat is equal to the heat dissipated by cooling at surface of crystal, and is given by:

$$P_a = \pi r_o^2 L_c Q = 2\pi r_o L_c (\frac{1}{2} r_o Q) = 2\pi r_o L_c (h_c \Delta T) \quad (13)$$

where h_c is the coefficient of heat transfer by convection, and ΔT is given by

$$\Delta T = T(r_o) - T_F \quad (14)$$

where T_F is the cooling temperature

Figure (2) indicates the variation of absorbed power by the Nd:YAG crystal with the difference between surface and cooling temperature. Then, equation (12) can be rewritten as:

$$Q = \frac{2h_c \Delta T}{r_o} \quad (15)$$

and

$$T(r_o) = T_{outer} = \frac{T_L + T_R}{2} \quad (16)$$

where $T(r_0)$ is the temperature at the surface of crystal, T_L and T_R are crystal temperature from the left and right side, respectively

Equation (16) is in fact the average temperature between both sides of crystal. Hence

$$P_a = 2\pi r_o L_c T(r_o) - T_F \quad (17)$$

Also, the temperature at the center of crystal is given by:

$$T_c = T_F + P_a [\frac{1}{4\pi k L_c} + \frac{1}{2\pi r_o L_c h_c}] \quad (18)$$

and the radial distribution of temperature ($T(r)$) is determined by:

$$T(r) = T(r_o) + (\frac{Q}{4k})(r_o^2 - r^2) \quad (19)$$

Regarding to eq. (11), the temperature-dependent change in refractive index is determined by change in temperature between surface and center of crystal. So, the change in refractive index due to thermal effects is determined as [3, 32-35]:

$$\Delta n(r)_T = [T(r) - T(0)](\frac{dn}{dT}) \quad (20)$$

and as a function to heat generated as [3, 36-37]:

$$\Delta n(r)_T = -\frac{Q}{4k}(\frac{dn}{dT}) r^2 \quad (21)$$

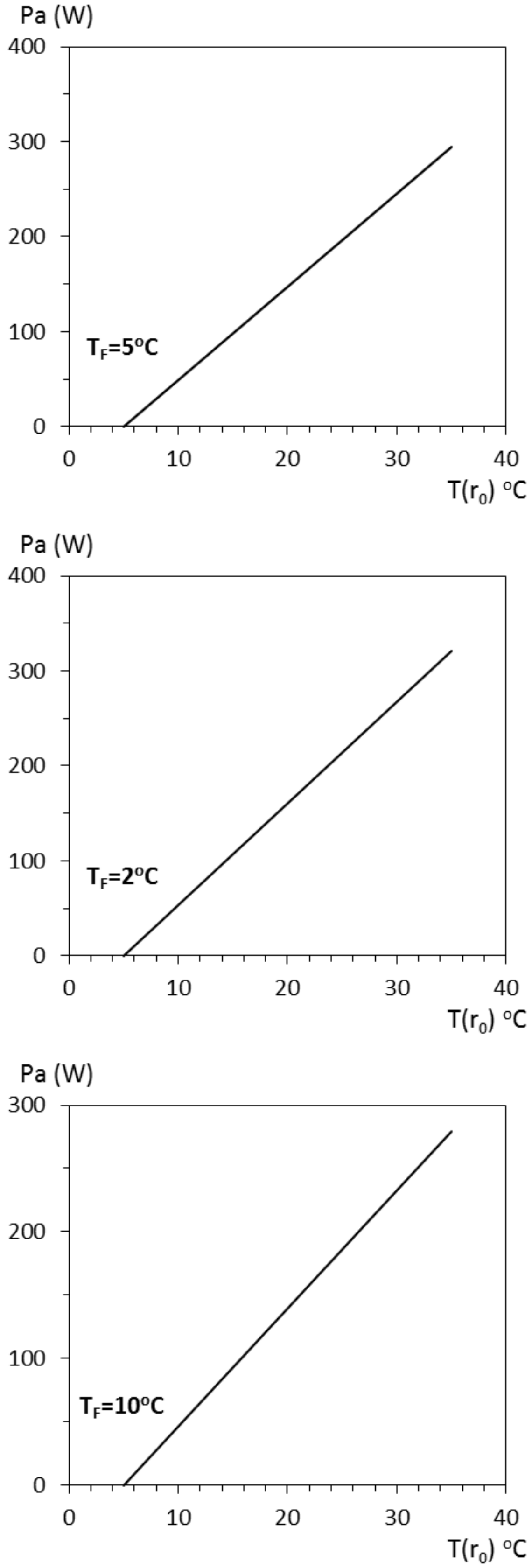

Fig. (2) Variation of absorbed power by the Nd:YAG crystal with the different values of the difference between surface and cooling temperatures

As shown, refractive index changes with the squared value of radius (r) and the laser beam will have a spatial change in phase as it travels along the crystal axis. This effect is identical to that resulted from a spherical lens, then the refractive index is given as [3]:

$$n(r) = n_o(1 - \frac{2r^2}{b^2}) \qquad (22)$$

where b is the transverse derivative

Before submitting the definition of the transverse derivative, it is worthy to introduce the concept of quadratic duct.

Supposing a light beam propagates through a crystal, the partition of beam near to the outer edge conflict to a region of refractive index lower than that at the center. This causes the outer partition of beam to traverse faster due to the lower value of refractive index, whereas the inner partition traverse slower. As a result, the light beam is bending always toward the central axis of crystal and this concept is known as stable quadratic duct as shown in Fig. (3). Accordingly, the refractive index will change in both radial and tangential directions as follows [2, 17, 34-37]:

$$n_2(r,z) = n_o(z) - \frac{1}{2}n_2(z)r^2 \qquad (23)$$

where $n_o(z)$ is the change along crystal axis and $n_2(z)$ is defined as:

$$n_2(z) = -\frac{\partial^2 n(r,z)}{\partial r^2}\bigg|_{r=0} \qquad (24)$$

For testing, the value of n_2 is usually chosen at $0.5r_o$ but it can be determined precisely by integration from $r=0$ to $r=r_o$. Equation (24) represents the downward bending term of refractive index at the central axis. For Nd:YAG crystal considered in this investigation, the value of $n_2(z)$ is (3.1062x10^{-5} cm^{-2}). Accordingly, the transverse derivative (b) can be defined as [34-35]:

$$b^2 = \frac{n_2}{n_o} \qquad (25)$$

The focal length of a quadratic duct, as in an Nd:YAG crystal, is given by [3]:

$$f \approx \frac{b^2}{4n_o L_c} \qquad (26)$$

where the focal length is supposed very long compared to crystal length (L_c). Then the transverse derivative can be expressed by:

$$b^2 = \frac{4k}{Q}(\frac{1}{2n_o}\frac{dn}{dT} + n_o^2 \alpha C_{r,\phi})^{-1} \qquad (27)$$

where α is the thermal expansion coefficient, k is thermal conductivity of crystal material and $C_{r,\phi}$ is the polarization-dependent optical elasticity coefficient, which is definitely wavelength-dependent but in this treatment, then, for simplicity, it is supposed that the polarization state is constant with wavelength.

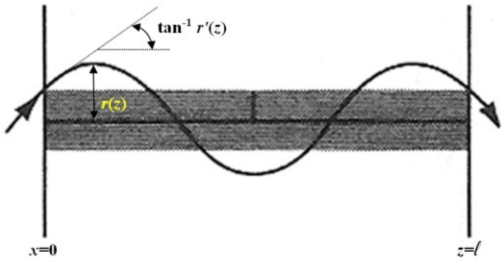

Fig. (3) Path of a ray in a medium with a quadratic index variation [4]

The total change in refractive index due to both thermal and stress effects is given as [3, 38-40]:

$$n(r) = n_o[1 - \frac{Q}{2k}(\frac{1}{2n_o}\frac{dn}{dT} + n_o^2 \alpha C_{r,\phi})r^2] \qquad (28)$$

Now, the focal length of a lens with a refractive index varying as in eq. (28) is given by [3]:

$$f = \frac{k}{QL_c}(\frac{1}{2}\frac{dn}{dT} + \alpha C_{r,\phi} n_o^3)^{-1} \qquad (29)$$

The change of refractive index due to the thermal strain depends on the polarization case of the incident light, so the optical elasticity coefficient ($C_{r,\phi}$) has two components, tangential (f_r) and radial (f_ϕ), as shown in Fig. (4):

$$f_r = k\frac{A}{P_a}[\frac{1}{2}\frac{dn}{dT} + \alpha C_r n_o^3 + \frac{\alpha r_o(n_o - 1)}{L_c}]^{-1} \qquad (30)$$

$$f_\phi = k\frac{A}{P_a}[\frac{1}{2}\frac{dn}{dT} + \alpha C_\phi n_o^3 + \frac{\alpha r_o(n_o - 1)}{L_c}]^{-1} \qquad (31)$$

where A is the crystal cross-section area

Regarding to the description considered in light beam propagation in a thin lens-like medium of focal length (f), equation (29) can be rewritten as:

$$\frac{1}{f} = \frac{QL_c}{k}(\frac{1}{2}\frac{dn}{dT} + \alpha C_{r,\phi} n_o^3) \qquad (32)$$

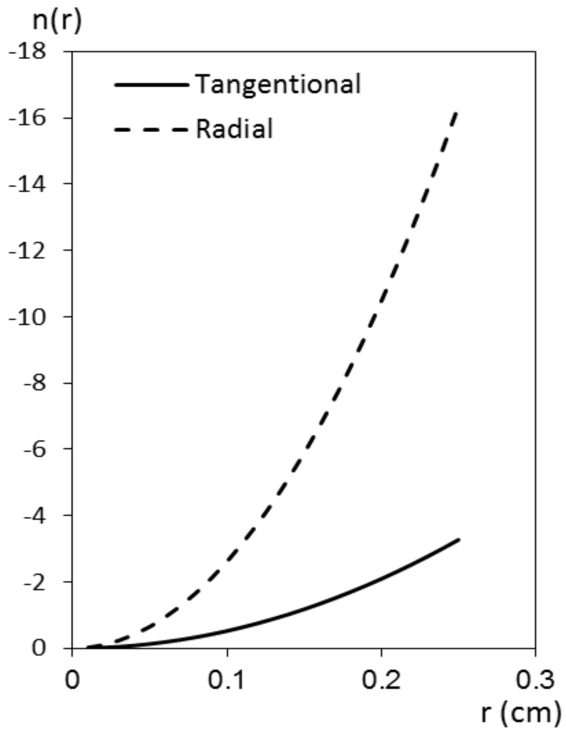

Fig. (4) Variation of refractive index with the lens focal length due to the thermal strain depends on the polarization case of the incident light

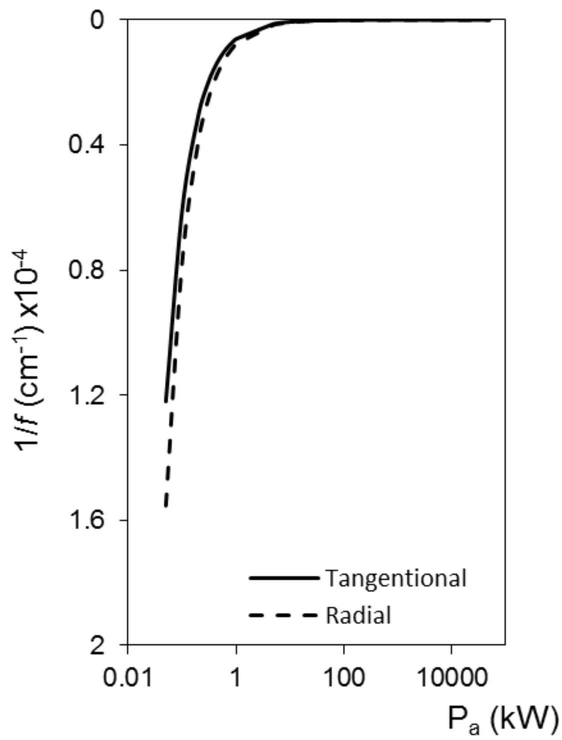

Fig. (5) Variation of the induced focal length (1/*f*) of the lens with the absorbed power (*P_a*) for both cases of polarization at ΔT=1°C

Physically, the Nd:YAG crystal cannot be considered as a thin lens as its length does not match such suppose. Although, thin lens approximation can be applied at a localized region inside Nd:YAG crystal where the effect of thermal lensing being supposed to appear.

The main conclusion of this investigation is the following expression:

$$\frac{d(\frac{1}{f})}{dP_{in}} = \frac{d}{dP_{in}}[\frac{QL_c}{k}(\frac{1}{2}\frac{dn}{dT} + \alpha C_{r,\phi} n_o^3)] \qquad (33)$$

where P_{in} is the optical pumping power

Equation (33) is a relation between the optical pumping power and the corresponding change in the crystal focal length and is also represented in Fig. (5).

Such relation represents a sensitivity factor of the active medium crystal. It may be shown that if the thermal lens appears at the beginning of crystal (*z=0*) and it is required to confine its effect inside the crystal (i.e., $f=L_c$) then the absorbed power should not exceed (0.7mW). The expression in eq. (33) can be introduced as the pumping-induced change in focal length of thermal lens.

4. Conclusions

According to the treatment presented in this investigation, it can be concluded that the effect of optical pumping power on a solid-state laser operation includes two main components, thermal-dependent and stress-dependent changes. With respect to the second aspect, it mainly affect the lattice of crystal in a manner distorting its uniform responding to the incident pumping light beam. Such effect can be avoided, to a tolerated degree, throughout enhancing mechanical and physical properties of crystal as they determined by manufacturing processes. Recently, there is a large interest to such considerations. While the first aspect is the most important since it relates originally to the pumping process. Thermal effect affects several parameters in a solid-system laser system such as refractive index, optical elasticity coefficient and physical dimensions of crystal, hence the focal length of thermal lens generated inside the active medium (crystal) as termed above. The change of term (*1/f*) with the input power represents an important parameter describing the responsivity of active medium to the input pumping power. Also, it is very important in laser design since it ensures that the resonator still active over the total range of operation power. The laser system should be able to held several changes affecting the change of this parameter with input power such as flash lamp aging and fluctuations in power supply and cooling system.

References

[1] Svelto, O., "**Principles of Lasers**", Plenum Press (NY), 1980.
[2] Siegman, A.E., "**Lasers**", University Science Books (CA), 1986.
[3] Koechner, W., "**Solid State Laser Engineering**", Springer-Verlag (Berlin), 1992, Ch.6.
[4] Yariv, A., "**Optical Electronics in Modern Communications**", 5th edition, 1997, Oxford University Press (NY), p.41, 47.
[5] Vainshtein, L.A., *JETP*, Vol.17, 1963, pp.709-719.
[6] Geusic, J.E., Marcos, H.M., Van Uitert, L.G., *Appl. Phys. Lett.*, Vol.4, 1964, pp.182-185.
[7] Heurtley, J.C., Streifer, W., *J. Opt. Soc. Am.*, Vol.55, 1965, pp.1472-1479.
[8] Byhov, V.P., Vainshtein, L.A., *JETP*, Vol.20, 1965, pp.338-344.
[9] Kogelnik, H., *Appl. Opt.*, Vol.4, 1965, pp.1562-1569.
[10] Kogelnik, H., Li, T. *Appl. Opt.*, Vol.5, 1966, pp.1550-1567.
[11] Laures, P., *App. Opt.*, Vol.6, 1967, pp.747-755.
[12] Arnaud, J.A., Kogelnik, H., *Appl. Opt.*, Vol.8, 1969, pp.1987-1693.
[13] Levions, N., Technical Bulletin 171-1, Holobeam, Inc., NJ 07652, 1972.
[14] Casperson, L., *Appl. Opt.*, Vol.12, 1973, pp.2434-2441.
[15] Suydam, B.R., *IEEE J. Quantum Electron.*, Vol.11, No.6, 1975, pp.225-230.
[16] Suzaki, Y., Tachibana, A., *Appl. Opt.*, Vol.16, 1977, pp.1481-1482.
[17] Siegman, A.E., *IEEE J. Quantum Electron.*, Vol.13, No.5, 1977, pp.334-337.
[18] Budin, J., Neubauer, M., *IEEE J. Quantum Electron.*, Vol.14, 1978, pp.831-839.
[19] Jayhowski, J.J., Mooradian, A., *Opt. Lett.*, Vol.14, No.1, 1989, pp.24-26.
[20] Woodward, W., *Photon. Spectr.*, May 1990, pp.139-144.
[21] MacKinnon, N., Sinclair, B., *Opt. Commun.*, Vol.94, No.4, 1992, pp.281-288.
[22] Weber, H., *Opt. Quantum Electron.*, Vol.24, 1992, pp.S861-864.
[23] Wright, D., Greve, P., Fleicher, J., Austin, L., *Opt. Quantum Electron.*, Vol.24, 1992, pp.S993-S1000.
[24] Martinez-Herrer, R., Mejias, P.M., Sanchez, M., Neira, J.L.H., *Opt. Quantum Electron.*, Vol.24, 1992, pp.S1021-S1026.
[25] Pare, C., Belanger, P.A., *Opt. Quantum Electron.*, Vol.24, 1992, pp.S1051-S1070.
[26] Frauchiger, J., Albers, P., Weber, H.P., *IEEE J. Quantum Electron.*, Vol.28, No.4, 1992, pp.1046-1056.
[27] Tidwell, S.C., Seamans, J.F., Bowers, M.S., Cousins, A.K., *IEEE J. Quantum Electron.*, Vol.28, No.4, 1992, pp.997-1009.
[28] Hughes, D.W., Phillips, M.W., Barr, J.R.M, Hanna, D.C., *IEEE J. Quantum Electron.*, Vol.28, No.4, 1992, pp.1010-1017.
[29] Cousins, A.K., *IEEE J. Quantum Electron.*, Vol.28, No.4, 1992, pp.1057-1069.
[30] Brioschi, F., Nava, E., Reali, G., *IEEE J. Quantum Electron.*,Vol.28, No.4, 1992, pp.1070-1074.
[31] Welford, D., Rines, D.M., Dinerman, B.J., Martinsen, R., *IEEE J. Quantum Electron.*, Vol.28, No.4, 1992, pp.1075-1080.
[32] Ruff, J.A., Siegman, A.E., *Appl. Opt.*, Vol.31, 1992, pp.4907-4909.
[33] Porras, M.A., Alda, J., Bernabeu, E., *Appl. Opt.*, Vol.31, 1992, pp.6389-6402.
[34] Siegman, A.E., *Opt. Lett.*, Vol.18, No.5, 1993, pp.675-677.
[35] Siegman, A.E., *Proc. SPIE*, Vol.1868, 1993, pp.2-12.
[36] Siegman, A.E., Townsend, S., *IEEE J. Quantum Electron.*, Vol.29, No.4, 1993, pp.1212-1217.
[37] Siegman, A.E., *Appl. Opt.*, Vol.32, No.10, 1993, pp.5893-5901.
[38] Baesso, M.L., Shen, J., Snook, R., *J. Appl. Phys.*, Vol.75, 1994, pp.3733-3739.
[39] Belanger, P.A., Champagne, Y., Pare, C., *Opt. Commun.*, Vol.105, 1994, pp.233-242.
[40] Pfistner, C., Weber, R., Weber, H.P., Merazzi, S., Gruber, R., *IEEE J. Quantum Electron.*, Vol.30, No.7, 1994, pp.1605-1615.
[41] Ruff, J.A., Siegman, A.E., *Opt. Quantum Electron.*, Vol.26, 1994, pp.629-632.
[42] Repasky, K.S., Brausseur, J.K., Wessel, J.G., Carlsten, J.L., "Correcting an

ISSN 1813 - 2065

astigmatic non-gaussian beam", 1995, Private Communications.
[43] Comasky, B., Moran, B.D., Albrecht, G.F., Beach, R.J., *IEEE J. Quantum Electron.*, Vol.31, No.7, 1995, pp.1261-1264.
[44] Jabczynski, J., Kopczynski, K., Szczesniak, A., *Opt. Eng.*, Vol.35, No.12, 1996, pp.3572-3578.
[45] Chen, Y.F., Huang, T.M., Kao, C.F., Wang, C.L., Wang, S.C., *IEEE J. Quantum Electron.*, Vol.33, No.8, 1997, pp.1424-1429.
[46] Eichenholz, J.M., Richardson, M., *IEEE J. Quantum Electron.*, Vol.34, 1998, pp.910-919.
[47] Aus der Au, J., Loesel, F.H., Morier-Geoud, Moser, M., Keller, U., *Opt. Lett.*, Vol.23, No.4, 1998, pp.271-273.
[48] Baesso, M., Bento, A., Andrade, A., *Phys. Rev. B*, Vol.57, 1998, pp.10545-10549.
[49] Siegman, A., *IEEE J. Selec. Topics in Quantum Electro.*, Special Issue, 1999, pp.100-108.
[50] Wyss, C.P., Lathy, W., Weber, H.P., Vlasov, V.I., Zavartsev, Y.D., *Appl. Phys. B: Lasers and Optics*, Vol.68, No.4, 1999, pp.659-661.
[51] Azcarate, M., Codnia, J., Diodati, F., Hnilo, A., Laratonda, M., "Development of all-solid state laser technology", 1999, Private Comm.
[52] Andrade, A., de Souza, D., Nunes, L., Catunda, T., *Ann. Opt.*, 2002, pp.59-62.
[53] Ismael, M.R., Hamadi, O.A., *J. Eng. Technol.*, Vol.22, No.1, 2003, pp.28-34.
[54] Moser, T., Ahmed, M.A., Pigeon, F., Parriaux, O. Wyss, E., Grof, Th., *Laser Phys. Lett.*, Vol.1, No.5, 2004, pp.234-236.
[55] Wang, H., Huang, W., Zhou, Z. and Cao, H., *Opt. Laser Technol.*, Vol.36, 2004, pp.69-73.