Theoretical analysis of auto-stability in laser resonator with thermal lenses effect

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ABSTRACT

In this work a numeric analysis is carried out to calculate the thermal lens effect in the stability of a barside-pumped-resonator at 808 nm. The active medium is a Nd:YVO₄ crystal. It is demonstrated that the thermal effects produced by the radiative process, in certain conditions can take one of the planes to a non consistency, having as a consequence an oscillator that will work in intermittent form.

Keywords: Thermal lenses, ABCD matrix, Nd:YVO₄.

1. INTRODUCTION

When a laser resonator is calculated, some methods of the optics elements in the oscillator can be considered to obtain the correct position in order to get a stable behavior¹ and produce a Gaussian beam as a maximum power output which is almost free of astigmatism.

Nevertheless, the laser resonator stability is frequently affected by the thermal lenses introduced into the crystal, because the active medium heating is an inherent consequence of the laser process and it cannot be avoided just to use new concepts as a radiation balance².

When the thermal lenses are already produced, the laser resonator stability will be considerably affected in addition to the oscillator Gaussian beam “spot” size and form behavior, because the active medium heating also induces aberrations and birefringence³-⁷.

The solid state lasers pumped by diodes (DPSSL) are characterized by high power output³-⁵,⁸, and they can be used in different configurations. One of the geometries that have given better results is the side pumped in a grazing-incidence with a bounce geometry (Fig. 1) to take advantage of the crystal gain region, which is always very small¹⁹-¹². When the Nd:YVO₄ crystal is pumped, the non-uniform gain of the exponential decay in function of the crystal depth can be highly compensated by the laser beam angle. The amplifier incident inclination allows the light beam to be amplified to experiment a total inside reflection in the crystal surface pumped. This total internal reflection allows the making of the variation of the transversal gain average within the length of the light beam space profile being amplified.

The crystal Nd:YVO₄ is used in particular as an active medium in the laser constitution and it has poor thermal characteristics, this implies that when it continues to be pumped by high power laser diodes, it will invariably suffer thermal lens formation which in the end will alter the initial condition of the resonator.

Those thermal lenses will have their maximum optic power when the resonator reaches its maximum output power because the laser beam will produce an additional heat in to the crystal. If the calculations are carried out considering the thermal lenses, the resonator will not reach its maximum output level and therefore a thermal lens with high optic power

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will not be produced. In the current work we proposed a theoretical study of auto stability in laser resonators with thermal lens effect. The Gaussian beam output characteristics are analyzed in the sagital plane as much as in the tangential plane using ABCD 4 x 4 transference matrix.

2. STABILITY

Any laser resonator can be classified as stable or unstable\textsuperscript{13,14}. It is said that a resonator is stable if for any ray which is propagated in the direction of the optic axis is maintained within of the resonator after an infinite number of roundtrips between the resonator ends. In terms of transfer matrixes, a laser resonator can be analyzed in two dimensions and considered as stable if it fulfills both conditions at the same time\textsuperscript{15}:

\[-1 < G_{ss} < 1;\]

equally within the sagital plane ($G_{ss}$), as in the tangential ($G_{tt}$), where:

\[G_{ss,(tt)} = (D_{ss,(tt)} + A_{ss,(tt)}) / 2,\]

where $A_{ss}$, $A_{tt}$, $D_{ss}$ y $D_{tt}$ are the diagonal elements of a transfer matrix of 4 x 4, representing a roundtrip of a Gaussian beam inside the resonator.

The matrix method can also be applied to the Gaussian beam propagation using the complex curvature parameters ($\bar{q}$) defined by\textsuperscript{13}:

\[
\frac{1}{\bar{q}} = \frac{1}{R(z)} - i \frac{\lambda}{\pi \omega^2(z)},
\]

2.1. Stability condition of the cavity and the astigmatic compensation criterion

The numeric calculations are obtained with the use of complex Gaussian beams, of the $\bar{q}$ parameter and the ABCD matrixes of each cavity element in the study, which are related in between by:

\[
\frac{1}{\bar{q}} = \frac{D_{ss,tt} - A_{ss,tt}}{2B_{ss,tt}} - i \frac{1 - \left( \frac{D_{ss,tt} + A_{ss,tt}}{2} \right)^2}{B_{ss,tt}} = \frac{1}{r} - i \frac{\lambda}{\pi \omega^2};
\]

from here, the curvature ratio ($r$) and the spot size ($\omega$) are:

\[
r = \frac{2B_{ss,tt}}{D_{ss,tt} - A_{ss,tt}},
\]

\[
\omega = \left\{ \frac{\lambda |B_{ss,tt}|}{\pi \left[ 1 - \left( \frac{D_{ss,tt} + A_{ss,tt}}{2} \right)^2 \right]^{1/2}} \right\}^{1/2}
\]

The auto consistence is needed to reach the stability because it is required equally in the sagital and in the tangential plane. In the computer analysis the mirrors, the empty spaces, the mirrors or other compensating plates, such as the thermal lenses are presented by separate matrixes.

3. THE THERMAL LENS.

The crystal heating caused by the laser diode bar pumping and its cooling system creates a stationary temperature distribution that varies in gradient giving as a consequence the formation of the thermal lenses in the crystal ends, that it is why the temperature gradient causes the refraction index to changes in any point of the crystal according to\textsuperscript{16}:
\[
\Delta n(x, y, z) = \left( \frac{dn}{dT_{\text{slab}}} \right) T(x, y, z) - B_{\text{slab}} \sigma_{ii},
\]  
(7)

where \( \sigma_{ii} \) is the crystal tension in the \( ii \) direction.

The \( dn/dT_{\text{slab}} \) and \( B_{\text{slab}} \) values depend on the light polarization and laser propagation angle \( \theta \) inside the crystal. To calculate the temperature distribution it is necessary to solve the heat equation:

\[-K \Delta T = \alpha P(x, y, z),
\]  
(8)

with:

\[
\Delta T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2},
\]  
(9)

where \( K \) is the crystals’ thermo conductivity coefficient, \( \alpha \) is the crystals absorption coefficient and \( P(x,y,z) \) is the pump power distribution in the active medium. Once the temperature distribution \( T(j) \) is known, for \( j=(x,y,z) \), it is possible to calculate the thermal lens induced through the approximation:

\[
\Delta p(j) = p(0) + p_1 j + p_2 j^2 + \ldots p_n j^n,
\]  
(10)

where \( p(0) \) is the incident beam optic way length at the center of the crystal face (pumped region), \( p_1 \) is the prismatic lineal component deviation, \( p_2 \) is the second order component associated with the thermal lens in the \( j \) coordinate, with the thermal lens dioptric power induced \( Dp \) and focal length \( f_{sx,ty} \) determined by:

\[
D_p = \frac{1}{f_t} = -2 p_2.
\]  
(11)

4. RESULTS

For the configuration shown in Fig. 1; that is formed by \( 20 \times 51 \) mm\(^3\) Nd:YVO\(_4\) crystal. The side present an approximate 2.16° cut and they are pumped from a laser diode array of 25W at 808 nm. The focal length of the lenses mentioned in Fig. 1 were set at distances \( D_1=2.3 \) cm, \( D_2=5.4 \) cm, \( D_3=2.3 \) cm, \( D_4=10.0 \) cm and \( D_5=2.1 \) cm, at \( \phi=4.3^\circ \) angle. The stability parameters for these conditions are:\( G_s=-0.045 \) y \( Gr=0.965 \). It can be noted that the stability parameter for the \( y \) axis is almost at the margin. The spot size is 0.23 mm in the tangential plane (\( y \)) and 0.024 mm in the sagital plane (\( x \)) (Fig. 2).

Fig. 1. The resonator formed by a Nd:YVO\(_4\) crystal as a laser active medium, two cylindrical lenses (L1, L2) and an spherical (L3), a plane mirror (M) and an output coupler (OC).

Using the J.C. Bermudez et al numeric analysis in\(^1\) to calculate the thermal lens in a similar configuration in the current proposal, where we solely consider the crystal heating caused by the radiative process in the active medium (Stokes lost) and the heat produced by the radiative process is discarded, it is found that the thermal lenses induced are \( f_{T_s}=56 \) cm y \( f_{T_t}=732 \) cm. Introducing those lenses in the original calculations we find obtain the following \( G_s=-0.018 \) y \( Gr=1. \) The spot...
size is now 0.92 mm in the tangential plane ($y$) and 0.026 mm in the sagittal plane ($x$). If we now consider the radiative process (with its transversal absorption coefficient ($\alpha$) at 1.06 $\mu$m) where the contribution for the thermal lens will be $\approx 3\%$ from the thermal lens value produced by the pump ($= 1.6$ cm for the tangential plane), we will have $f_{Ts}=54.4$ cm, resulting in $G_r=1.01$ causing a non consistency in the tangential plane which will therefore stop the oscillation. When the oscillation is stopped, the total contribution of thermal lenses will disappear, making it oscillate once again.

Fig. 2. Spot size behavior of the resonating Gaussian beam, in the tangential and sagittal planes.

### 5. CONCLUSIONS

In this work we carry out a numerical analysis to calculate the thermal lenses effect in the resonator stability. It is shown that the thermal effects produced by the radiative process, in certain conditions can lead to a non consistency in one of the planes, having as a consequence an oscillator that will work in intermittent form.

### REFERENCES