THERMAL LENSING IN DIODE PUMPED 
Nd\(^{3+}:\)YVO\(_4\)/LiNbO\(_3\) GREEN MICROCHIP LASER 

M. Kerobyan\(^{1,2}\), R. Kostanyan\(^1\), V. Nersesyan\(^{1,2}\), S. Soghomonyan\(^2\) 

\(^1\)Institute for Physical Research, NAS of Armenia 
\(^2\)Spectralus CJSC, Yerevan, Armenia 

E-mail: kerobyan.mk@gmail.com 

Abstract. Thermal lens in Nd\(^{3+}:\)YVO\(_4\)/LiNbO\(_3\) microchip green laser affects stability and working regimes of the laser. Absence of any passive or active Q-switching and mode locking make the thermal lens the only method to affect working regimes and stability of the laser cavity, which is composed of planar active and nonlinear mediums. Thus, investigation of thermal lens is crucial for the optimization of working regimes of the microchip laser.

1. Introduction 
YVO\(_4\)/LiNbO\(_3\) green microchip lasers are miniature, powerful and efficient source of green light [1]. Resonator of the YVO\(_4\)/LiNbO\(_3\) green microchip laser is composed of two planar components. Active medium (Nd\(^{3+}:\)YVO\(_4\)) and nonlinear medium (LiNbO\(_3\)). Mirrors of the cavity are dielectric coatings directly applied to the surfaces of the active and nonlinear crystals. Crystals are joint by optical contacting technique. 

Resonator of the microchip laser is a plane parallel. As we know, stability of optical resonators are described by \(g_1g_2\) factor, where \(g_1 = 1 - L/R_1\), \(g_2 = 1 - L/R_2\). \(L\) is the optical length of the cavity, \(R_1\) and \(R_2\) are radii of curvature of the mirrors. Cavity is stable when \(0 \leq g_1g_2 \leq 1\). In case of microchip laser without thermal lens, where mirrors are flat \(R_1 = R_2 = \infty\) and \(g_1g_2 = 1\), which is example of unstable resonator. Because of quantum defect, in working regime, part of the pump power is released in the active medium as a heat. For the microchip laser, quantum defect is equal to \(\eta = 1 - 808\ nm/1064\ nm = 24\%\), which means that at least 24\% of pump power releases as a heat in the active medium. This heat is released in the region of the pump beam, and creates inhomogeneous distribution of the temperature. This inhomogeneous distribution of the temperature creates lensing effect in the crystal. So, we’ll have resonator, which contains a positive lens.

Thermal lens affects mode size, TEM’s and stability of the cavity, and in absence of any mode locking in the green microchip laser, investigation of thermal lens is important for optimization of working regimes of the green microchip laser.

2. Experimental 
Experiments were conducted with 1.5mm+1.5mm YVO\(_4\)/LiNbO\(_3\) microchip lasers, 808nm laser diodes from QPC, with 1W maximal power and 80um beam size. Direct measurements of focal length of thermal lens is problematic because of miniature sizes of the resonator. So focusing length was
measured indirectly. Beam size at the output mirror depends on the focal length of the thermal lens. Output beam divergence angle depends on the beam size at the output mirror. So, instead of measuring focal length, we measured beam divergence angle (all other parameters were kept constant, except pump power, e.g. pump beam waist, temperature of heat controller etc.). It is known from the theory, that stronger the thermal lens, the higher divergence angle. Measurement results are presented in the Fig.2. It can be seen from the Fig.2 that higher pump power leads to higher divergence angles.

To compare experimental results with the theory, we used theory of thermal lens developed by Innozenti et al [2]. Later other authors improve analytics and got more complex formulas. Nevertheless, in all calculations pump beam is considered to be a Gaussian beam. In case of green microchip laser, pump beam profile can’t be considered a Gaussian. To calculate focal length of thermal lens, one needs to solve non homogeneous heat equation, where non homogeneous part has very complex form. Analytical calculations are not possible, but numerical simulations shown that the analytical formula for Gaussian pump beam suits well for this problem.

3. Theory

Using theory of equivalent resonators [3], one can represent plane-parallel resonator with positive lens with focusing length of $f$ as a resonator with one concave and one flat mirror.

![Figure 1. Schematic drawing of resonator with thermal lens and equivalent resonator. M1, M1’ and M2 are mirrors, L is the thermal lens.](image)

Radius of curvature of the first mirror is equal to the focal length of the thermal lens. Refractive indices of YVO₄ and LiNbO₃ are approximately the same and their difference is negligible in this case. Thus, $g_1 g_2 = 1 - nL/ f$, where $n$ is the refractive index of the material of the cavity.

Beam radius at the mirrors $\omega_1$ and $\omega_2$ are given by the following formulas

$$\omega_1 = \left(\frac{\lambda R_1}{\pi}\right)^2 R_2 - d \frac{d}{R_1 - d + R_2 - d}$$

$$\omega_2 = \left(\frac{\lambda R_2}{\pi}\right)^2 R_1 - d \frac{d}{R_1 - d + R_2 - d}$$

where $\lambda$ is the wavelength of the circulating wave (fundamental wave), $R_1$ and $R_2$ are radii of curvatures of the mirrors, $d$ is the length of the cavity. As long as output mirror of the cavity is flat, beam waist will be at the output mirror and equal to $\omega_0 = \omega_2$, which is given in the formula [1].

$$\omega_0 = \sqrt{\frac{\lambda f}{\pi}} \left(\frac{d}{f - d}\right)^{1/4}$$

This formulas are calculated for fundamental wave (1064nm). It is known from the theory of SHG that beam waist of the second harmonic wave is $\sqrt{2}$ times less than beam waist of the fundamental wave. Thus, total angular spread of output green light will be equal to

$$\Theta = \frac{\sqrt{2}\lambda}{\pi \omega_0} = \sqrt{2} \left(\frac{1}{df} - \frac{1}{f^2}\right)$$

Note that in the formula [3] $\lambda = 1064nm$ is the wavelength of the fundamental wave, not the second harmonic wave. Focal length in the formula [3] is equal to
\[ f = \frac{\pi K_c \omega_p^2}{P_{ph} \gamma \left(1 - \exp(-\alpha l)\right)} \]  \hspace{1cm} [4]

Where \( K_c \) is thermal conductivity of the crystal, \( \omega_p \) is the beam size of the pump beam in the crystal, \( \gamma \) is a sum of thermo-optic coefficient and thermal expansion coefficient, \( \alpha \) is the absorption coefficient at the pump wavelength, \( l \) is the length of the active medium, \( P_{ph} \) is the part of pump wave, which is gone as a thermal loss.

As it was mentioned above, in the experiments we have measured divergence angle of the output green light versus pump power, and in the Fig.2 measurement results are compared to the theoretically calculated value according to the formula for focal length of thermal lens in the Innozenti et al work.

**Figure 2.** Angular spread of laser beam. “—” – theory, “●” – measurement.

**Figure 3.** Focal length of thermal lens. “—” – theory, “●” – measurement.
In the Fig.3 measured and calculated focal length versus pump power is presented. Focal length is calculated from the formula [3], by expressing $f$ trough $\Theta$. One can see that for high values of pump power, theory and measurements are well correlated for both divergence angle and focal length of the thermal lens, unless for low pump powers. It is supposed that difference between theory and experiments in low pump powers is caused by non-Gaussian pump, which plays important role in case of low pump powers, unless in the case of high pump powers, where the shape of pump beam is not as much important. Nevertheless it is a matter for future investigation.

4. Conclusion

In this work we have investigated focal length dependence of the thermal lens on the pump power. Knowledge of focal length of thermal lens, one can calculate mode sizes on the on the mirrors, which can be used for mode matching, also it is important parameter for understanding cavity stability.

References

[1] Essaian S., Khaydarov J., Slavov S., Ter-Mikirtychev V., Gabrielyan G., Kerobyan M., Soghomonyan S., Proceedings of SPIE, 8240, 2012, pp. 82400I-1 – 82400I-8

[2] M. E. Innocenzi, H. T. Yura, C. L. Fincher, and R. A. Fields, Applied Phys. Letters, 56, 1990, pp. 1831-1833

[3] Walter Koechner, Solid-State Laser Engineering, Springer, New York, 2006