Corrected ABCD Approach for Optimization of High Thermal Lensed Solid-State Lasers: Case Study of a Typical Cr,Tm,Ho:YAG Laser

Mahdi Shayganmanesh[a], Davood Razzaghi[b,*], Maryam Goli Hasanlo[a], Arezoo Jalilzadeh Heydarlou[a], Marzieh Akbari[b], Mohammad Reza Moghaddam[b]

[a]School of Physics, Iran University of Science and Technology, Narmak, Tehran, Iran
[b]Photonics and Quantum Technologies Research School, Nuclear Science and Technology Research Institute (NSTRI), Tehran, Iran

Corresponding author email: davrazzaghi@yahoo.com

ABSTRACT— In this paper, the thick thermal lens approximation is evaluated for a CTH:YAG laser with a standard telescopic resonator. An accurate relation between the thermal lensing parameter and lens-like media factor is proposed. Telescope adjustments were studied based on the practical values of the focal length of the thermal lens. The fundamental mode volume is determined regarding the Hermit-Gaussian theory, and the influence of the defocus parameter is examined. The study emphasizes the importance of considering both the fundamental mode volume and the distance to the stability boundary when selecting the optimal defocusing parameter. A merit factor was introduced that provides a comprehensive approach to selecting the most suitable defocus parameter for the system.

KEYWORDS: ABCD Matrix, CTH:YAG laser, Telescopic resonator, Thermal lens effect.

I. INTRODUCTION

Solid-state lasers have found broad applications in scientific, medical, industrial, and military sectors. In numerous applications, the extraction of a high-quality TEM_{00} mode that has maximum power density and minimal divergence plays a crucial role. In pulsed flashlamp-pumped lasers, background absorption of the lamp radiation by the crystal and absorption of the pump energy by impurities and color centers can induce transient thermal gradients in the laser rod [1], [2]. Subsequently, the rod may exhibit similar to that of a converging lens, where the focal length is inversely proportional to pump energy. This positive thermal lens effect within the laser rod, can give rise to the formation of local intensity maxima that may go beyond the damage threshold of the optical elements inside the cavity. Furthermore, it limits the output energy and decreases the beam quality and the mode spot size.

Thermal lensing is a common feature in all solid-state lasers that affects their performance, however, extensive research efforts have been dedicated to mitigating this disturbing factor through different solutions [3]-[9]. Various techniques have been employed to mitigate the adverse effects of thermal lensing. These include thermally induced birefringence compensation methods [3], filtering out heat generated during the pumping process [4], employing thermal lens compensation through additional fixed elements (such as a telescope or a single negative lens), and implementing adaptive optics within the resonator [10]-[12]. Additionally, improving heat dissipation from the gain media through more effective coolant systems have also been explored [13]. Among the techniques mentioned above, the use of telescopic resonators is interesting and has been explored even in non-solid-state lasers. This is owing to their high fundamental mode volume and the resulting good output beam quality [14]–[19]. To our knowledge, Sarkies was the first who report the employment of a resonator configuration with an internal telescope [20]. Hanna *et al.* also studied different telescopic resonators in detail. Researchers commonly apply the thin lens model for gain media, leading to derived approximate analytical expressions for resonator parameters [10].

Calculations based on thick lens ABCD matrix formalism is seriously depended on a parameter known as γ which is in turn related to the dissipated heat. Since the results of the calculations for the resonator characteristics such as the dynamical stability region, and the beam radius are strongly depended to γ, inaccurate estimation of this parameter could lead to non-optimized resonator scheme. As we know, the γ parameter can be estimated from the focal length of the heated rod which is measured experimentally. However, based on the assumptions made for a heated rod to be a thick lens, the measured focal length should be corrected to give more accurate value for γ as will be discussed later. As far as we know, this correction has not been yet proposed and evaluated.

Also, in this work we present a merit function for trading off between higher mode volume and broader dynamical stability region. Using this merit could be a straightforward method to judge about different resonator schemes according to the desired laser system performance. The calculations were made for a Cr,Tm,Ho:YAG laser (mainly used in medical applications).

II. Thermal Lens and ABCD Approach

Thermal lensing and the ABCD approach are widely known concepts. However, for a comprehensive analysis, it is important to dedicate some discussion to address the limitations of their accuracy here.

As we know, in solid-state lasers, thermal lensing is a common occurrence where its focal length can be determined using the Eq. (1) [1]:

$$f_{th} = \frac{KA}{P}\left[\frac{1}{2}\frac{dn}{dT} + \alpha C_{r,\phi} n_0^3 + \frac{\alpha r_0 (n_0 - 1)}{L_R}\right]^{-1} \quad (1)$$

where K is the thermal conductivity, A is the rod cross-section, $P = QAL_R$ is the total absorbed power (Q is the thermal energy deposited in the rod), $C_{r,\phi}$ is the radial or azimuthal photo-elastic coefficients, n_0, L_R, r_0, and α are the refractive index, the length, radius, and the thermal expansion coefficient of the laser rod, respectively, and dn/dT is the rod thermo-optic coefficient. By applying Gaussian beam theory and modeling thermal lensing using thick or thin lenses, we can design active stable resonators [21]. Basically, within optically pumped laser rods, the refractive index changes with distance from the optical axis (r) quadratically due to temperature gradient (Fig. 1). This dependency can be expressed with Eq. (2) [1]:

$$n(r) = n_0\left(1 - \alpha_n \phi(Q)\frac{r^2}{2}\right) \quad (2)$$

where α_n is the thermal coefficient of the refractive index, and $\phi(Q)$ is a function of dissipated heat. Such an optical element acts like a thick lens with a matrix description corresponding to a rod of length (L_R) as follows, Eq. (3) [21], [22]:

$$M_{Rod} = \begin{bmatrix} \cos(\gamma L_R) & (n_0\gamma)^{-1}\sin(\gamma L_R) \\ -n_0\gamma\sin(\gamma L_R) & \cos(\gamma L_R) \end{bmatrix} \quad (3)$$

in which:

$$\gamma^2 = \alpha_n \phi(Q) \quad (4)$$

The matrix in Eq. (3) is a key component within the round-trip matrix of a laser resonator. Therefore, the γ factor also holds crucial significance in establishing the stability condition, determining beam radius, and evaluating mode volume. Accurately estimating the γ factor from experimental data is essential for conducting precise resonator analyses and ensuring optimal design outcomes.

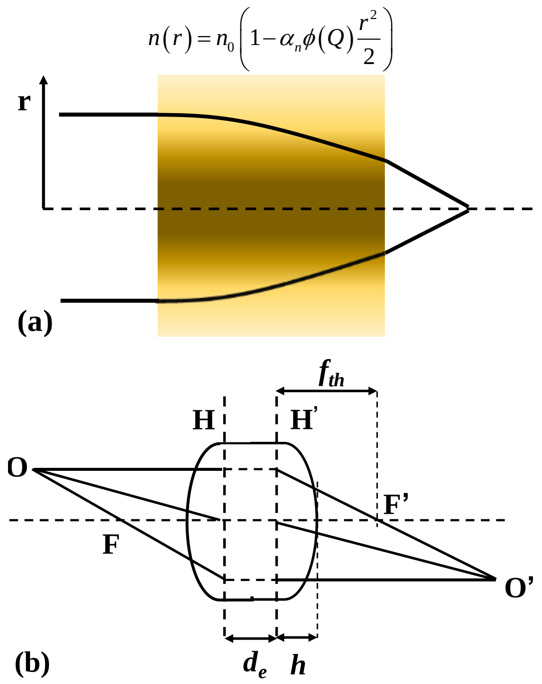

Fig. 1 a) The laser rod as a thick thermal lens, and b) equivalent thick lens-like media.

It can be easily demonstrated that the M_{Rod} matrix represents a thick lens with a focal length f_{th}, in which f_{th} is given by Eq. (5). The effective thickness, d_e, and the parameter h, as defined by Eq. (6) and Eq. (7), respectively, are also shown in Fig. 1. Note that, the h parameter denotes the distance of the principal planes from the rod ends [21].

$$\frac{1}{f_{th}}=n_0\gamma\sin(\gamma L_R) \tag{5}$$

$$d_e=\frac{\sin(\gamma L_R)}{n_0\gamma} \tag{6}$$

$$h=\frac{\tan\left(\frac{\gamma L_R}{2}\right)}{n_0\gamma} \tag{7}$$

The plane-plane telescopic resonator under consideration (a CTH:YAG laser), depicted schematically in Fig. 2(a) comprises four primary elements: the back mirror, the output coupler, CTH:YAG rod, and the telescope. The telescope's two lenses are separated by $l_2=d+\delta$, where $d=f_1+f_2$, and δ is the telescope defocusing [10]. By employing the full ABCD formalism, the self-consistency condition, under the paraxial approximation, can be applied to determine the radius of curvature, R, and the spot size, w of the TEM_{00} beam at any given reference plane within the resonator. Therefore, at an arbitrary reference plane, the complex beam parameter, q satisfies Eq. (8) [22], [23]:

$$q=\frac{Aq+B}{Cq+D} \tag{8}$$

where $\frac{1}{q}=\frac{1}{R}-i\frac{\lambda}{\pi w^2}$ (λ is the wavelength in the medium), and, A, B, C, and D, are ray matrix elements of one round trip in the resonator (with the equivalent thick lens), with the start and the end at the selected reference plane. In this way, R, and w at the chosen reference plane can be derived as Eq. (9) and Eq. (10):

$$R=\frac{2B}{D-A} \tag{9}$$

$$w=\left(\frac{\lambda}{\pi}\right)^{1/2}\frac{|B|^{1/2}}{\left[1-\left(\frac{A+D}{2}\right)^2\right]^{1/4}} \tag{10}$$

The spot size (w) at various locations within the resonator is computed (by Eq. 10) and depicted in Fig. 2(b) for the telescopic resonator shown in Fig. 2(a). The telescope has been employed in a Galilean configuration, with lens focal lengths of -20 mm and 80 mm, respectively.

Thermal lensing can be measured straightforwardly using the stability borders of the resonator or by using other methods such as the probe beam technique [24]-[26]. Hence, the γ factor can be determined by solving the nonlinear Eq. (5) using the bisection numerical method. Recently, by measuring the transmission of a probe beam, we have investigated the time-resolved evolution of the thermal lens effect and measured the thermal lens focal length of a CTH:YAG laser for a range of pumping energies under lasing and without lasing conditions [25], [26]. For a CTH:YAG laser rod with dimensions of 12 cm in length, and 5 mm in diameter, featuring doping concentrations of 0.36%, 5.7%, and 1% for Ho, Tm, and Cr, respectively, the focal length of thermal lens, was measured experimentally to be 130 cm under pumping of 240 J [25].

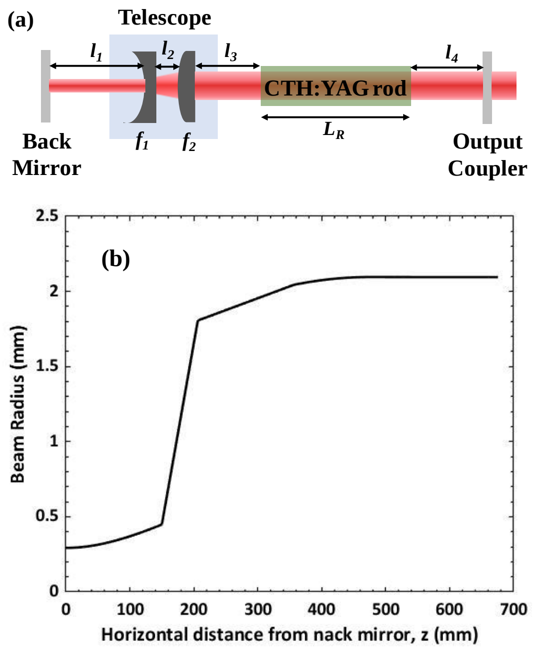

Fig. 2. a) The schematic diagram of the telescopic resonator setup, and b) the beam radius at different points in the resonator.

III. Results and Discussion

A. *The γ factor*

As it was mentioned in the previous section, the thermal lens focal length is determined through experimental measurements on a rod with a particular length and various pumping levels. This focal length can then be employed to calculate the γ factor, as shown in the preceding section (Eq. 5).

Figure 3(a) shows the variation of the γ factor with thermal lens focal length for two distinct rod lengths, i.e., 6 cm, and 12 cm. This figure reveals that as the focal length increases, the γ factor decreases for rods of any length; however, longer rods tend to have a lower γ factor. This trend is consistent with classical optics principles and can be interpreted through the paraxial approximation of a lens transformation [27]. It's worth mentioning that the γ factor is influenced by the pumping and various rod physical characteristics like the diameter, refractive index, thermo-optic, and photo-elastic coefficients.

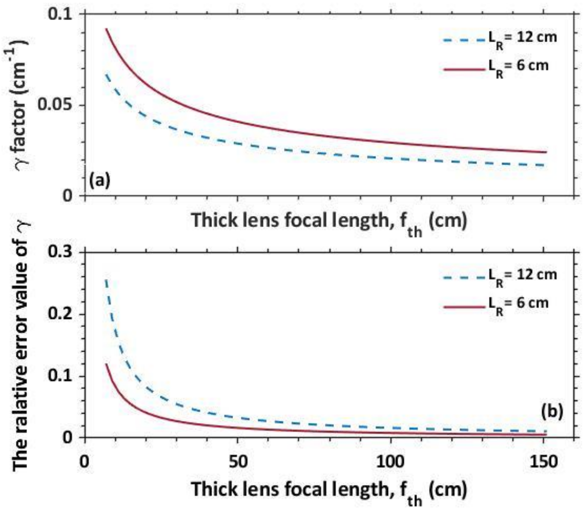

Fig. 3. The plots of the (a) γ factor and (b) $\delta\gamma/\gamma$ versus thermal lens focal length for two lengths of rod.

It is important to note that in Eq. (5), the focal length refers to the distance between the principal plane and the focal point [21]. However, in practice, the thermal lens focal length is usually measured as the distance between one end of the rod and the focal point (see Fig. 1(b)). In the first approximation, the measured focal length (f_{th}^{m}) can be taken as equal to the theoretical thermal focal length (f_{th}^{t}), leading to Eq. (11) [21]:

$$f_{th}^{m} \cong f_{th}^{t} = \frac{1}{n_0 \gamma \sin(\gamma L_R)} \tag{11}$$

However, in some situations, like in the case of strong thermal lens effect, according to Fig. 1, Eq. (11) may not be a correct estimate of the focal length, and it is necessary to use a more accurate value such as that obtained from Eq. (12):

$$f_{th}^{m} = f_{th}^{t} - h = \frac{1}{n_0 \gamma \sin(\gamma L_R)} - \frac{\tan\left(\frac{\gamma L_R}{2}\right)}{n_0 \gamma} \tag{12}$$

To assess the potential error introduced by utilizing the first formula (Eq. 11) in calculations, the γ factor was calculated using two equations, and its relative error value,

$\delta\gamma/\gamma$ was calculated and plotted for two different rod lengths and a range of thermal lens focal lengths. The resulting values were then plotted to show the discrepancy between the two formulas (Eq. 11 and Eq. 12), as depicted in Fig. 3(b). It becomes apparent from this figure that however, the error decreases as the thermal lens focal length increases for both rod lengths, at severe thermal lensing (which means higher pumping rate), when calculated using Eq. (11), introduces greater errors in evaluating the resonator parameters. For example, for a 12 cm length rod, up to 26% error can be anticipated in the calculations. For instance, Lancaster *et. al.* obtained the thermal lens focal lengths as short as 15 cm for a 7.5 cm CTH:YAG laser rod operating at a 7Hz repetition rate with a 1.2 kW flashlamp power [28]. According to Fig. 3(b), at this specific focal length, up to 10% error in the calculation γ may be introduced if the correct formula is not used.

B. *Optimization and the Telescope Defocusing Parameter*

It has been shown that in a telescopic resonator, the spot size and the mode volume depend on the telescope defocusing parameter [10], [29]. The mode volume that refers to the effective volume in which the electromagnetic field of a particular mode is confined within the laser active medium can be defined by Eq. (13) [23]:

$$E_0^2 V = \int_0^{L_R}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y,z)E^*(x,y,z)\,dx\,dy\,dz \tag{13}$$

where E_0 is the peak value of the electric field and V is the rod volume. For a single TEM_{00} mode Gaussian beam, all phase factors are eliminated and the TEM_{00} mode volume can be evaluated as Eq. (14):

$$V_{00} = w_0^2 \int_0^{L_R}\int_0^{r_0} \frac{e^{-\left(\frac{r^2}{w^2(z)}\right)}}{w^2(z)} 2\pi r\, dr\, dz \tag{14}$$

where w_0 represents the beam waist radius and needs to be determined. By utilizing at least two beam radius values at distinct planes, one can calculate the beam waist radius. In this context, we have determined the beam waist radius through an iterative method using the beam radius at the first and end faces of the gain medium. It is straightforward to write an equation that relates the beam waist radius and its position (relative to the rod) as shown below, Eq. (15):

$$w_0^2 = \frac{w^2(D_0) \pm \sqrt{w^4(D_0) - \frac{4D_0^2\lambda^2}{n^2\pi^2}}}{2} \tag{15}$$

where D_0 represents the distance from the beam waist to the face of the gain media where the beam radius is considered.

Exploring the influence of γ factor on the mode volume can be interesting. For example, when analyzing a straightforward scenario involving a rod as a thick lens within a resonator with mirrors positioned at the rod ends (without a telescope), the application of Eq. (10), yields a constant beam spot size across the rod, i.e., $w = \left(\frac{\lambda}{\pi n_0 \gamma}\right)^{1/2}$. Consequently, the resulting mode volume (using Eq. 14) denoted as $V_{00} = \pi L_R \sqrt{\frac{\lambda}{n_0\gamma}}\, erf\left(\frac{r_0 \pi n_0 \gamma}{\sqrt{2}\lambda}\right)$, is influenced by the γ factor. As previously discussed, it highlights the significant role that the γ factor plays in the accurate modeling and design of resonators.

Figure 4 shows the TEM_{00} mode volume and beam radius (at the center of the gain medium) with respect to the defocus parameter, δ for two distinct thermal lens focal lengths, i.e., 130 cm and 135 cm for a telescopic resonator shown in Fig. 2(a). These curves have two asymptotes, that define the boundaries of the stability region. The distance between the two asymptotes determines the range of the defocus parameter, δ, over which the resonator remains stable (stability region). As this figure reveals, when the focal length of the thermal lens increases, the dynamic stability region shifts toward a greater defocus parameter, while the length of the dynamical stability region remains almost constant. This behavior is expected as telescope defocusing compensates for the thermal lens effect. As depicted in this figure, the mode volume experiences a significant increase at the periphery of the stability region, in line with expectations outlined by Gaussian beam theory. In fact, as one approaches these boundary areas, the resonator exhibits characteristics like those of a plane-parallel resonator, demonstrating maximal TEM_{00} mode volume while proving to be highly sensitive to disturbances.

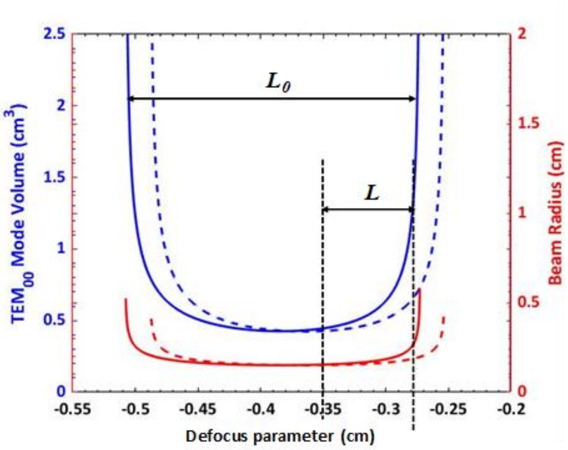

Fig. 4. The TEM_{00} mode volume (the blue curves) and the beam radius (the red curves) as a function of defocus parameter for two thermal lens focal lengths, i.e. 130 cm (the solid lines) and 135 cm (the dotted line).

A well-designed resonator scheme should aim to optimize the TEM_{00} mode volume while also ensuring a wide dynamical stability region. This configuration enables efficient extraction of stored energy in the gain media in the TEM_{00} mode, enhancing beam quality essential for diverse laser applications. Furthermore, a wide dynamic stability region in such resonators guarantees reliable operation, even in challenging environments like industrial settings. The investigation of TEM_{00} mode volume and stability behavior in response to the defocus parameter in a telescopic resonator (Fig. 4) encouraged us the formulate a merit factor as Eq. (16). Since the defocus parameter significantly influences the performance of the telescope resonator, accurately determining its value is essential for optimizing the system's efficiency and achieving the desired optical characteristics. Therefore, in this paper, we propose the use of a merit factor for identifying the optimal value of this parameter. In this approach, a defocus parameter value is chosen such that, based on the specific application, the merit factor reaches its maximum value. This merit factor is defined for every thermal focal length and defocus parameter.

$$M = \left(\frac{V}{V_0}\right)^{\alpha} \left(\frac{L}{L_0}\right)^{\beta} \qquad (16)$$

where V is the TEM_{00} mode volume and the V_0 is the minimum mode volume throughout the dynamical stability region. As depicted in Fig. 4, L is the minimum distance of a specific δ (like -0.35 cm in Fig. 4) to δ at the resonator's stability limit and L_0 is the maximum range of δ within which the resonator remains stable. The α and β should be selected by a designer based on the targeted application requirements. For example, in a robust laser system where the defocus parameter and thermal lens focal length are tightly controlled, the α should exceed the β. Conversely, in a laboratory laser setup, it is preferable to have β greater than α. Figure 5 shows the variations in the defined merit factor concerning the defocus parameter for a plane-plane telescopic resonator in several cases. The calculations in Fig. 5, were carried out for $f_{th} = 130cm$. These curves can aid in determining the optimal defocus parameter. When $\alpha = \beta = 1$, indicating equal importance on mode volume and stability, the optimal defocus position is located in the middle of the stability region, as depicted in Fig. 5. As shown in Fig. 5, in this case, the merit factor is maximized at the center of the stability region, while it decreases towards the stability region's boundaries. Therefore, in this situation, the optimal value lies at the midpoint of the stability region; $\sim -0.4cm$ for our case. However, as the α to β ratio increases, indicating greater emphasis on mode volume, causes the optimal defocus parameter to shift towards the edges of the stability region. For instance, in the case of $\alpha = 3$ and $\beta = 1$, the merit factor is maximized at the center of the stability region, but remains almost constant at other points within the region, maintaining the midpoint as the optimal value. Nevertheless, as the ratio increases further, as seen in the case of $\alpha = 5$ and $\beta = 1$, the merit factor is maximized at values near the edges of the stability region, and the center of the stability region is no longer the most suitable choice. As shown in this figure, for cases with a high β to α ratio, the merit factor exhibits a sharp maximum at the center of the stability region. This indicates that the optimal value is at the midpoint of the stability region, and other points should be avoided for selection.

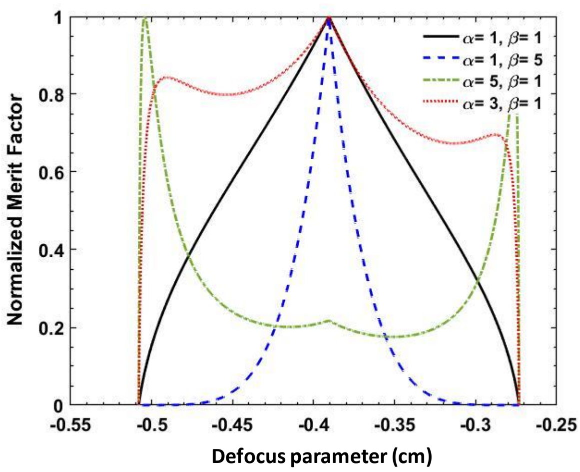

Fig. 5. The merit factor versus defocus parameter for various α and β.

As discussed above, the merit factor serves as a mathematical tool designed to minimize or eliminate the need for extensive and often time-consuming laboratory testing. By providing a reliable predictive measure, it enables more efficient evaluation of system performance.

IV. CONCLUSION

In this work, a more accurate computational formulation based on the ABCD approach was applied to analyze telescopic resonators. The thermal lens effect within the laser rod was taken into account by incorporating a lens-like medium matrix. The relation between the γ factor of the lens-like media and the focal length of a thick equivalent lens was thoroughly examined, leading to the establishment of a more precise relation. The findings indicated that when utilizing the simplified relation, an error of up to 28% could be anticipated in determining the γ factor. Additionally, in this research, an investigation was conducted on the changes in mode volume concerning the defocus parameter, and a merit factor was introduced. This merit factor considers both the mode volume and the stability range simultaneously, serving as a valuable metric for optimization purposes.

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Mahdi Shayganmanesh was born in Tehran, Iran, in 1975. He received the M.Sc. degree in Atomic and Molecular Physics from University of Tehran, Tehran, Iran, in 2001, and the Ph.D. degree in Atomic and Molecular Physics from Iran University of Science and Technology (IUST), Tehran, Iran in 2009. Now he is a faculty member at the Department of Physics, IUST since 2011.

His current research interests include laser development, laser beam propagation and laser material processing.

Dr. Shayganmanesh has been a staff member of the Iranian National Center for Laser Science and Technology (INLC), Tehran, Iran for three years.

Davood Razzaghi was born in Tehran, Iran, in 1975. He received MSc degree in physics from Sharif University, Tehran, Iran, in 1999. He graduated jointly from the Amirkabir University of Technology and NSTRI, Tehran, Iran, and received his PhD in Physics in 2013.

His current research interests include optics and laser technology, laser spectroscopy, and quantum technology.

Maryam Goli Hasanlo was born in Tehran, Iran, in 1992. She received her B.Sc. degree in Atomic and Molecular Physics from Shahid Beheshti University, Tehran, Iran, in 2015. She received her M.Sc. in Atomic and Molecular Physics from Iran University of Science and Technology (IUST), Tehran, Iran in 2018.

Her research experience is telescopic resonator for solid-state lasers.

Arezou Jalilzadeh Heydarlou was born in Tehran. She received BSc degree in Atomic and Molecular Physics from Urmia University, Urmia, Iran, in 2019. She received her MSc degree in Photonics from Iran University of Science and Technology, Tehran, Iran, in 2022.

Her research interests include laser physics and laser optics.

Marzieh Akbari was born in Tehran. She received BSc degree in Atomic and Molecular Physics from Shahid Beheshti University, Tehran, Iran, in 2007. She received her MSc and PhD degrees in Atomic and Molecular Physics from Iran University of Science and Technology, Tehran, Iran, in 2009, and 2017, respectively.

Her recent research interests include laser physics, optics and laser technology, and quantum technology.

Mohammad Reza Moghadam was born in Tehran in 1968. He received MSc degree in Solid State Physics from Tarbiat Moalem University, Tehran, Iran, in 1997 and received his PhD in Physics from UM University, Kuala Lumpur, Malaya, in 2012. His current research interests include solid-state laser physics.