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Hollow-duct radiation delivery system investigation

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Abstract. Investigation of hollow-duct structure for high-power laser-diode-array radiation delivery into the end-pumped large-aperture gain media is reported. A ray tracing method has been used to evaluate the performance of the structure designed for maximum transmission efficiency and output beam profile homogeneity. Variable hollow-duct lengths as well as emanating angles of laser-diode-array have been taken into account.

1 Introduction

High-power solid-state lasers attract a great deal of attention, in the current period. It is connected mainly with the fast progress made in the development of high-power laser-diodes over the past several years [1–3]. These improvements of laser-diodes combined with cost reductions in the laser-diode-array fabrication have resulted in reduction of the price per average watt of diode radiation. So, the compact and efficient high-power laser-diode-array pump sources gradually replace the inefficient and cumbersome flash-lamp pump systems.

For optical pumping of the laser materials, two fundamental approaches including end and side pumping have to be considered. End pumping has the potential to yield high-efficiency and high-beam-quality laser systems [4], provided that a good overlapping between the laser-diode radiation and the intracavity laser-mode inside the active material is reached. This matching is difficult to achieve in the case of high-power laser systems as they require a large mount of diode-arrays as a pumping sources with considerable emitting area dimensions and beam divergences. The problem of beam homogeneity and transfer efficiency can be solved, e.g., by employing tapered geometric structures [5–7]. These passive and robust optical devices are able to effectively couple and concentrate the pump radiation from the broad laser-diode-array area into the relatively small (in cross-section) laser gain media. In addition, scalable diode end-pumping architecture can be easily reached by simple modifying the number of laser-diode stacks. The most common version of such devices is a lens [5] and a hollow duct [6]. In spite of the lens duct, the hollow duct does not need any AR coating and can be easily used for dual-end-pumped laser design because the laser-cavity-beam passes through the duct without interaction. On the contrary, the hollow duct suffers from internal reflection losses that can be avoided in the case of the lens duct. However, by proper coating of the hollow-duct reflective planar sides [8,9], these losses can be significantly reduced.

In this contribution, hollow-duct concentrator and homogenizer, intended for longitudinally end-pumped slab-active-medium laser architecture, has been investigated and optimized in terms of its length by preserving efficient transmission and beam profile uniformity. The effect of the pump-laser-diode emitting angle has been taken into account, for the first time to our best knowledge. Optimization has been carried out in a simplified 2D-model developed in the computing environment Matlab and subsequently compared with 3D-model designed in the commercial ray-tracing software ZEMAX.

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2 Problem analysis

The transmission system investigated was formed by a *tapered* hollow-duct followed by a *flat* one, as illustrated in figure 1.

The first part is responsible for coupling of the pump radiation, spread over the relatively large area compared to the crystal dimensions, into the active medium; the second one is intended for homogenisation of the pump-radiation. If we look at the radiation-propagation through the duct like at a two-dimensional geometric task (for better understanding of the key aspects influencing the hollow-duct transmission properties; the sophisticated analytical 3D model can be found e.g. in [6]), it can be on the basis of Snell's law easily derived that angles $\beta_1, \beta_2, \ldots, \beta_i$ are given by

$$\beta_i = (2i-1)\alpha + \theta_{1/2}\,, \qquad (1)$$

where $i = 1, 2, \ldots$, and $\theta_{1/2}$ is the angle (with respect to the duct longitudinal-axis) under which the laser-diode-ray is emitted. Angle α represents a slant of the tapered hollow-duct which can be expressed in terms of the input D_1 and the output D_2 dimensions, and the length L_1 (see figure 1) as

$$\alpha = \arctan\left(\frac{D_1 - D_2}{L_1}\right). \qquad (2)$$

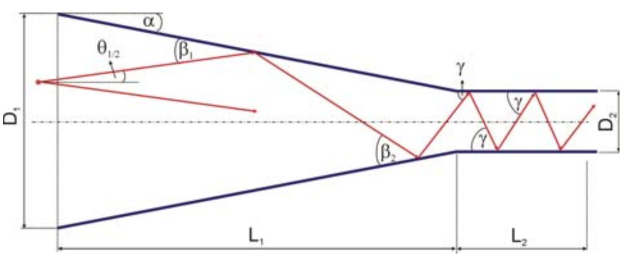

Fig. 1. Schematic layout of ray propagation through the hollow-duct-system

From eq. (1) it follows that each subsequent incident angle β is magnified by 2α. In order to propagate a given ray in the forward direction through the tapered hollow-duct, the following condition has to be fulfilled

$$\beta_i < \pi/2 - \alpha. \tag{3}$$

Otherwise, the ray will propagate in a reverse direction and could disturb or even damage the source of the radiation. Provided, the ray enters the flat hollow-duct under the γ-angle, it has to be than transmitted as indicated in figure 1. The γ-angle value influences just the number of reflections from the flat hollow-duct planar-sides executed on the distance L_2. Taking into account the finite reflectivity of the hollow-duct structure, the transmission T_j of the j^{th}–ray can be described as

$$T_j = \begin{cases} (1-L)^N & \text{if } \beta_i < \pi/2 - \alpha \\ 0 & \text{if } \beta_i \geq \pi/2 - \alpha \end{cases} \tag{4}$$

where L introduces ray-energy-losses at one reflection from the waveguide planar-sides and N is the number of reflections the ray will undergo on the distance $L_1 + L_2$. Finally, for the j-number of rays participating in the transmission process, the total transmission efficiency of the hollow-duct structure is given by

$$T = \frac{\sum_j T_j}{j}. \tag{5}$$

From expression (1) and (3) it is obvious (for the given parameters D_1 and D_2) that the transmission efficiency is mainly dependent on the $\alpha = \alpha(L_1)$ and $\beta_1 = \beta_1(\alpha, \theta_{1/2})$ angles. For a high transmission, the angle β_1 has to be kept reasonably small. But, by shortening the hollow-duct length, the α angle becomes greater, which adversely affects β_1. This obstacle can be overcome by proper routing of the laser-diode-emission-angle φ related to the longitudinal-axis; than $\beta_1 = \beta_1(\alpha, \theta_{1/2}, \varphi)$. By doing this, the hollow-duct length can be significantly shortened while retaining the high transmission efficiency, as reported in the following section of this contribution. As a result, fabrication costs and space demands can be substantially reduced.

3 Simulation and numerical results

3.1 2D model

Firstly, on the basis of the 2D hollow-duct analysis performed, a ray-tracing model in the Matlab environment has been developed. Schematic layout of the 2D-hollow-duct transmission system investigated is seen in figure 2. The 20 laser-diode sources in each branch were uniformly spread over the line (plane in the case of 3D model) tilted at $\omega = 45°$ with respect to the entrance plane. This arrangement enables to deploy a greater amount of laser-diodes while preserving the dimension y_{min}. Continuous laser-diode radiation from each diode was approximated by a large number of rays equally distributed within the laser-diode half-angle divergence $\theta_{1/2} = 4°$. Furthermore, the following design parameters were used: y_{min}=60 mm, D_1=600 mm, D_2=120 mm, and L_2=100 mm. Results of numerical simulations describing the hollow-duct transmission properties

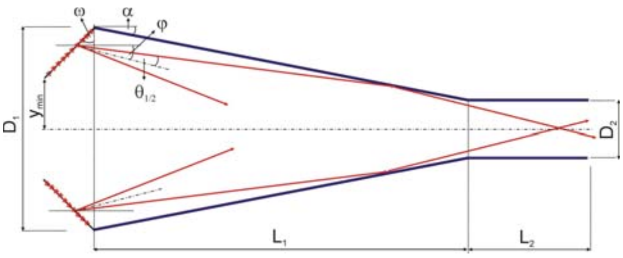

Fig. 2. Schematic layout of two-dimensional hollow-duct-system investigated

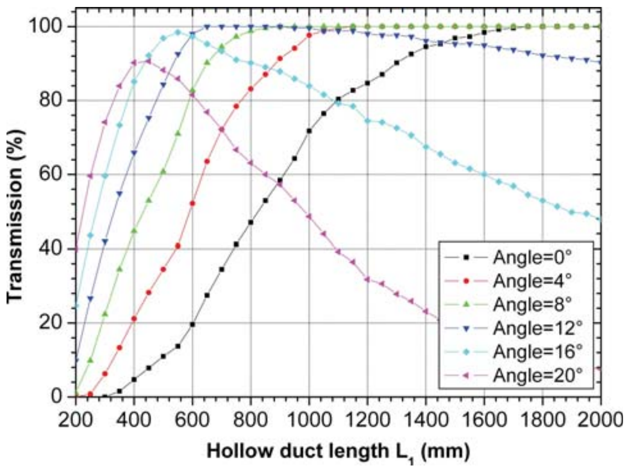

Fig. 3. Hollow-duct transmission as a function of its length L_1 for different value of laser-diode emission angles φ; reflection losses from the sidewalls are not taken into account. Performed for simplified 2D model in computing environment Matlab

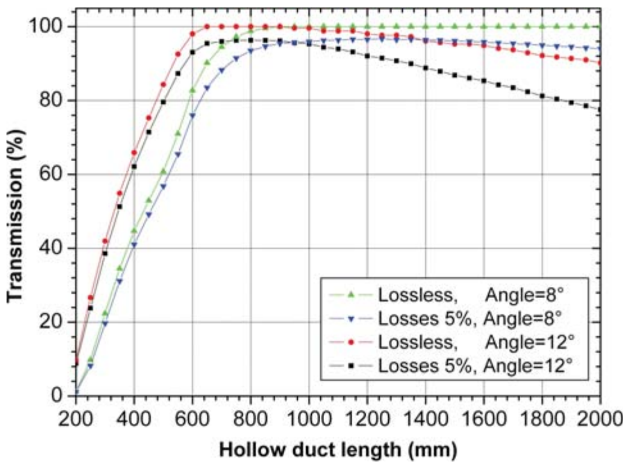

Fig. 4. Comparison of hollow-duct transmission curves if reflection losses from the waveguide sidewalls are/are-not taken into account. Performed for two selected laser-diode emission angles φ in simplified 2D Matlab model

in dependence on its length L_1 for different laser-diode-emission angles φ and no reflection losses are depicted in figure 3. If reflectance R=95% of the waveguide sidewalls is taken into account, the corresponding curves for two selected diode-emission angles are displayed in figure 4.

From figure 3 and figure 4 it can be concluded that the hollow-duct length L_1 (for the given input parameters – D_1, D_2, L_2, and φ) can positively influences the number of rays passed through the structure (for the lossless propagation curves), but, on the contrary, it increases the number of ray-

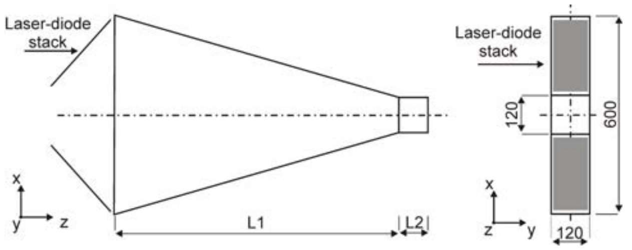

Fig. 5. Schematic layout of three-dimensional hollow-duct-system investigated

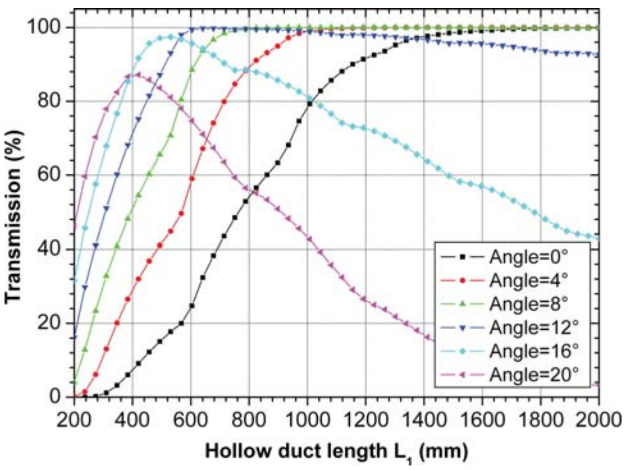

Fig. 6. Hollow-duct transmission as a function of its length L_1 for different values of laser-diode emission angles φ; reflection losses from the sidewalls are not taken into account. performed for 3D model in commercial software ZEMAX

reflections from the planar sides resulting in a gradually decreasing transmission efficiency from its maximal value. Thus, if reflection losses can not be neglected, the hollow-duct length has to be retained reasonably small. As follows from figure 3, the length can be substantially shortened if suitable laser-diode-emission-angle routing with respect to the longitudinal-axis is employed.

3.2 3D model

Furthermore, employing the commercially available ray-tracing software ZEMAX, the transmission properties of the 3D hollow-duct model (see figure 5) of the same parameters as proposed for the 2D model, just extended about the third dimension (depth), has been evaluated and compared with the simplified 2D model. The hollow-duct structure depth was 120 mm and the incident radiation source in one branch was formed be arrays of 50 × 100 laser-diodes with assumed half-angle divergences $\theta_{1/2x} = 4°$ and $\theta_{1/2y} = 1°$. The 3D-hollow-duct transmission as a function of its length L_1 for different laser-diode-emission-angles φ and no reflection losses are depicted in figure 6.

By comparing figure 3 and figure 6, it can be seen that the simplified 2D-model based on the geometric-optics fundamentals is very well reproduced by the 3D-model. So, for the primary insight into the tapered-hollow-duct transmission capabilities, the 2D-model is enough to take into account, provided that the laser-diode divergence in the third-dimension direction is kept small.

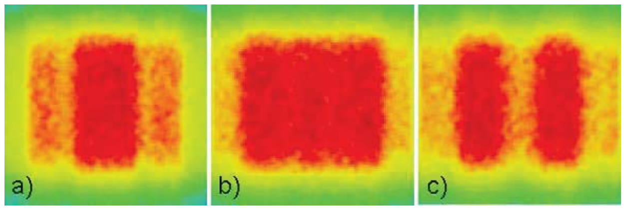

Fig. 7. Spatial output-beam profiles in dependence on the hollow duct L_2 length – a) L_2=120 mm, b) L_2=165 mm and c) L_2=200 mm – in the proximity of the waveguide-structure output-plane

The output-beam structure has also been assessed for the optimised tapered-hollow-duct in terms of transmission efficiency, In this case, different L_2-lengths of the flat-hollow-duct acting as a beam homogeniser were considered. As illustrated in figure 7, the beam homogeneity is strongly dependent on the parameter L_2, and an optimum field distribution can be reached for the certain L_2-value (figure 7b). The beam profiles (square in shape) are depicted in the proximity of the waveguide-structure output-plane. In the greater distance from the waveguide, the beam shape becomes more rectangular due to the big angular divergence in the waveguide fast-axis.

4 Conclusion

To conclude, two models based on a ray-tracing method for evaluation of tapered-hollow-duct structure design for high-power laser-diode-array radiation delivery in terms of maximum transmission efficiency and output-beam-profile homogeneity has been reported. Numerical simulation has been carried out in simplified (laboratory-developed) 2D and realistic 3D-model in computing environment Matlab and sophisticated ray-tracing software ZEMAX, respectively. It transpired that the simplified 2D-model based on the geometric-optic fundamentals conforms well with the realistic 3D-solution, if laser-diode divergence in the third-dimension (depth) is kept small. Therefore, for the primary insight into the tapered-hollow-duct transmission capabilities, the 2D-model is satisfactory.

Furthermore, hollow-duct transmission efficiency for different values of laser-diode emission angles has been firstly investigated, as we believe. It came out that by adjusting the proper angle, the hollow-duct length can be significantly shortened while maintaining the high transmission efficiency, which can substantially reduce the space requirements and fabrication costs.

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