

# Enhancing Laser Output Power through Symmetric Cavity Design

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## Abstract

This white paper presents an innovative approach to increasing the maximum output power of laser optical cavities by leveraging cavity symmetry. This method, as detailed in patent US 2016/226211 A1 [1], effectively doubles the achievable power output while keeping beam quality. The core idea revolves around the symmetrical distribution of power within the cavity, which optimally redistributes optical modes and minimizes power-limiting effects such as thermal lensing. This paper details the theoretical framework and implementation strategy of this novel concept.

## Introduction

High-power optical cavities are critical in applications such as high-energy lasers, industrial machining, and precision scientific instruments. The maximum achievable output power is often constrained by nonlinear effects and thermal distortions. Conventional cavity designs often face limitations in power scaling due to thermal lensing.

Conventional methods to address thermal lensing involve complex cooling systems or adjustments to the cavity design, which often result in incremental improvements. The approach outlined in this paper offers a more fundamental solution by leveraging the inherent symmetry of the laser cavity. This paper explores a symmetric cavity design that effectively redistributes power, thus doubling the power-handling capability without degrading beam quality.

The standard simple case will be first considered as a reference. Then the symmetry will be introduced. Finally, a more general case will be presented, where the symmetry is not fully obtained.

## Reference cavity

Laser cavities typically comprise end mirrors and gain media, which amplify the laser beam through stimulated emission. They also possess a diaphragm to limit the lasing to the fundamental TEM<sub>00</sub> transverse mode. However, as the pump power increases, thermal lensing effects within the gain media can make the cavity unstable, limiting the achievable output power. This instability manifests as variations in the beam diameter, causing the laser to operate inefficiently.

A simple cavity can be made of 2 end mirrors, a gain medium (with some thermal lensing) and a diaphragm, as shown in Fig. 1.

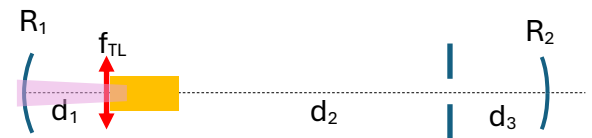


Fig. 1: Schematic of the reference cavity

$R_1$  and  $R_2$  are the radii of curvature of the linear cavity of Fig.1. This cavity has a gain medium (orange rectangle) which is end-pumped by the beam shown in light purple. It is worthwhile to calculate the beam size at the thermal lens, i.e., the pump input face in Fig. 1, where the gain mostly

is. For that purpose, the ABCD matrix is first calculated from this thermal lens, and back after one round-trip [2]:

$$\begin{aligned}
 & \begin{bmatrix} A & B \\ C & D \end{bmatrix} \\
 &= \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{2}{R_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_{TL}} & 1 \end{bmatrix} \begin{bmatrix} 1 & \frac{l_c}{n_c} \\ 0 & 1 \end{bmatrix} \\
 & \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & d_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{2}{R_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & d_3 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix} \\
 & \begin{bmatrix} 1 & \frac{l_c}{n_c} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_{TL}} & 1 \end{bmatrix} \quad (1)
 \end{aligned}$$

Using the Kogelnik's formula [2], after one round-trip, one can set:

$$q = \frac{Aq+B}{Cq+D} \quad (2)$$

Where  $q$  is the complex beam parameter just next to the thermal lens, and  $A, B, C, D$ , are the elements of the ABCD matrix calculated above. Eq. (2) can be easily solved via a 2<sup>nd</sup>-order equation; It has two distinct solutions, but obviously only one is physical. From this physical solution, the corresponding beam radius at thermal lens can be deduced.

To calculate the focal length of the thermal lens in the cavity of Fig. 1, the following equation is used [3]:

$$f_{TL} = K_{TL} \frac{w_{pump}^2}{P_{pump}} \quad (3)$$

Where  $w_{pump}$  and  $P_{pump}$  are the characteristics of the focussed pump beam, mostly at gain crystal input, and  $K_{TL}$  is a coefficient to adjust. It is a simple approximation, but it is enough for the purpose of this white paper. There is also an effect of the shape of the pump beam, which is generally a super-gaussian profile, but one can consider it is included in the coefficient  $K_{TL}$ .

In a similar manner, the beam radius at aperture can be calculated. These 2 locations (gain medium and aperture) mostly drive the gain and losses of the laser, respectively, which makes them essential. Fig. 2 is the plot of these values vs. the

pump power, for the cavity parameters detailed in the caption.

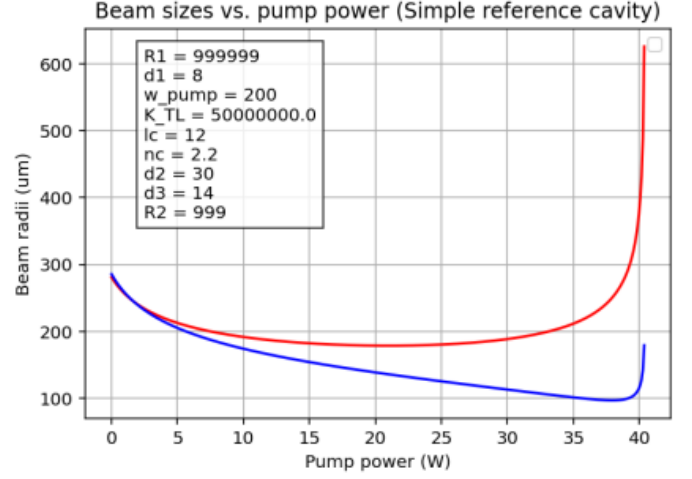


Fig. 2: Beam radii at thermal lens (red) and aperture (blue). The dimension

### Purely symmetrical cavity

Similarly, the same approach can be performed with the cavity shown in Fig 3:

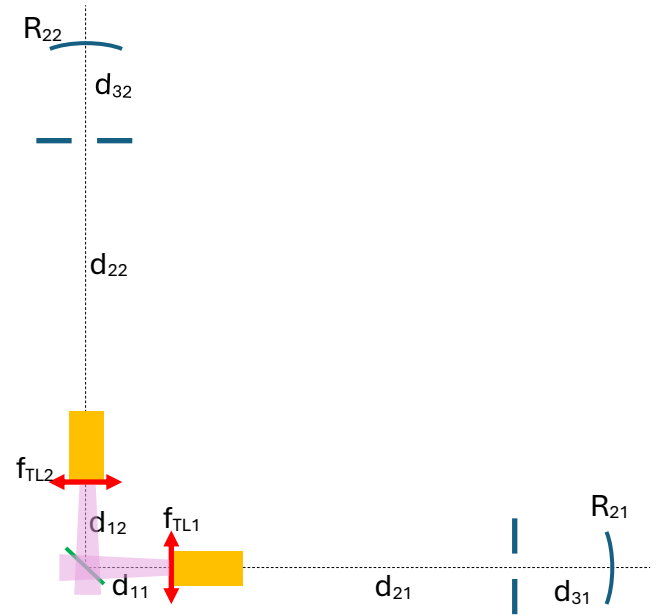


Fig. 3: Schematic of the symmetrical cavity, basically the reference cavity unfolded symmetrically.

In this case, the junction between the 2 arms is a plane mirror (in green in Fig. 3), which is basically the reference cavity unfolded because  $R_1$  was big, i.e., very close to a plane mirror.

In a similar manner as previously, the ABCD matrix can be calculated over this new cavity, and the beam radii can be calculated. The result is

shown below in Fig. 4. It is worthwhile to notice that  $P_{\text{pump}}$  is the total pump power, shared symmetrically between the 2 arms, so there is only  $P_{\text{pump}}/2$  in each arm. This is the core of the idea: Sharing symmetrically the pump powers, i.e., the thermal load, and the total gain, between the 2 arms.

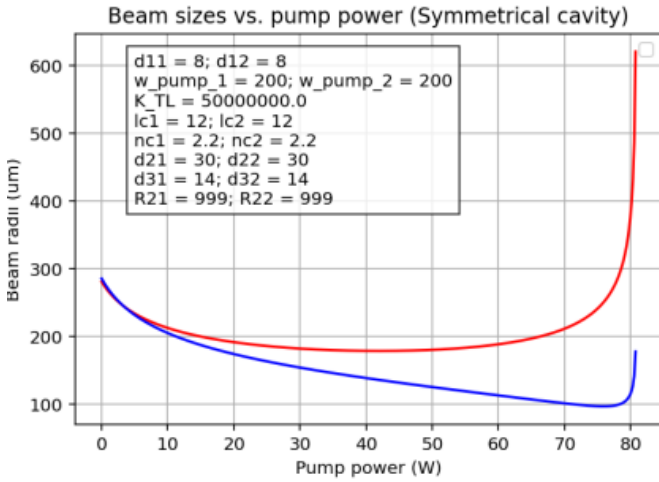


Fig. 4: Similar to Fig. 2, but for the symmetrical cavity. It is worthwhile to notice the rollover basically occurs at twice more power vs. the reference cavity.

It is worthwhile to notice that Figs. 2 and 4 are very similar, but the x-axis is doubly expanded in Fig. 4. The numbers used here are just an example, without losing generality. To illustrate more widely the symmetry, it is interesting to look at the caustic for a few specific total pump powers. Fig. 5 compares the caustic of the reference cavity (a) and of the symmetrical one.

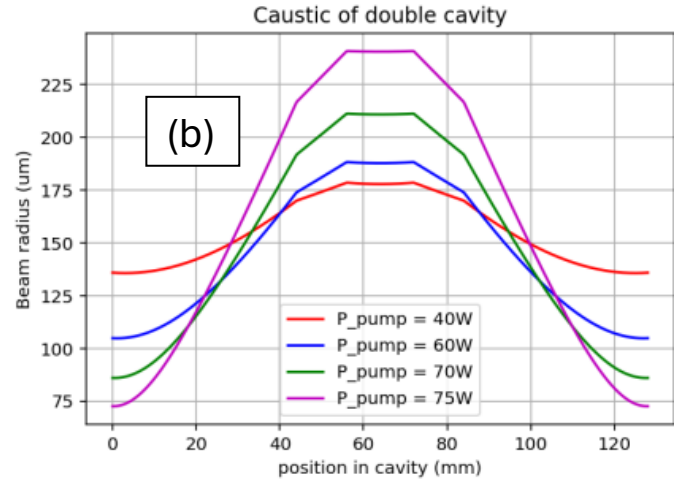
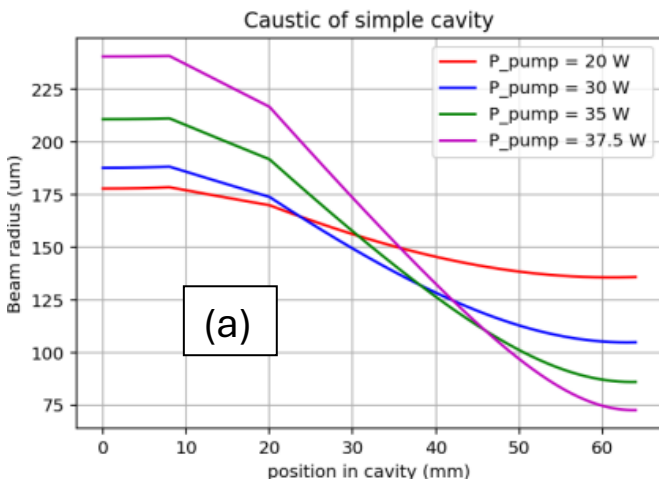


Fig. 5: Caustics of the reference simple cavity (a) and of the double symmetrical cavity (b). Note the sets of pump powers and the symmetry. The powers are doubled for the symmetrical cavity and the symmetry is clearly seen

It can be clearly seen that the effect of symmetry allows to double the available pump power. The symmetry allows to obtain the same efficiency, so reaching twice more pump power effectively doubles the output power, for the same efficiency.

### Slight asymmetry

In practice, it is difficult to make the cavity fully symmetrical, especially the pumping, i.e., the thermal lensing, whatever it is with the pump powers, the pump sizes, or the pump waist positions in both gain media.

In Fig.6 below, a slight asymmetry is introduced, and the effect can be seen. For example, the 2<sup>nd</sup> pump spot radius  $w_{\text{pump}2}$  is made slightly smaller. Another type of asymmetry could be chosen (for ex. with pump powers or pump waist position, or distances) but the effect would be similar.

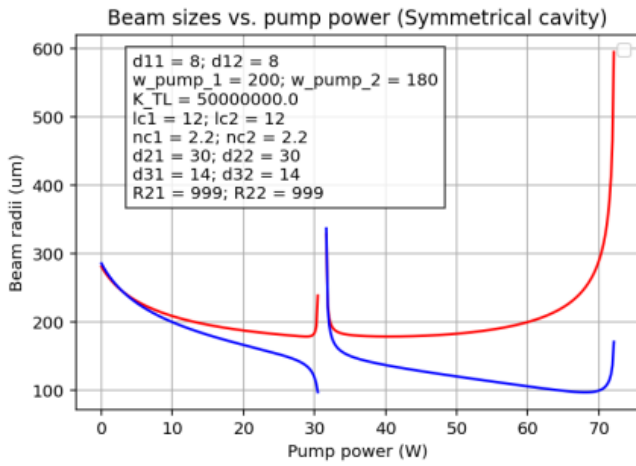


Fig. 6: Beam curves of the slightly asymmetrical cavity, with the distances in mm and the pump beam radii in  $\mu\text{m}$ .

Comparing to fig. 4, a narrow unstable zone appears at about half-pump power, and the rollover is slightly earlier.

However, in practice, this effect is hardly visible. Indeed, the visible threshold turns out to be high and close to this zone. Moreover, thanks to diffraction effects [4] the cavity is made more stable in this narrow zone.

Besides, since the asymmetries can be of different types, any asymmetry could be compensated by another. For example, the asymmetry of Fig. 6 being due to the pump spot sizes, it could be compensated by adjusting the distances; For example, setting  $d_{32}$  to 15.8mm instead of 14mm allows to compensate the asymmetry introduced in Fig. 6. This can be seen in Fig.7. The rollover is not extended back, though, albeit still high. This compensation could also be done by balancing the pump powers in each arm, which might be easier in some configurations.

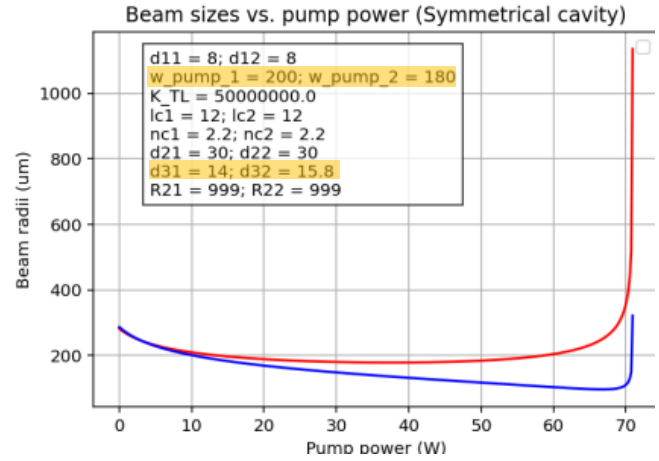


Fig. 7: Example of a compensation of asymmetry.

In the caption box, the 2 compensating asymmetries are highlighted, and the curves are clearly continuous, like in Fig.4. Only the pump power at rollover is still smaller, but not by much.

## Conclusion

The symmetric cavity design represents a significant advancement in laser technology, offering a straightforward yet effective solution to the challenges posed by thermal lensing. By doubling the maximum output power and enhancing cavity stability, this approach opens new possibilities for high-power laser applications across various industries.

## References

- [1] A. Cox and J.-C. Cotteverte, "Laser", U.S. Patent Application 2016/0226211 A1, Aug. 4, 2016. [Online]. Available: <https://worldwide.espacenet.com/patent/search/family/052705437/publication/US2016226211A1>
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