Dynamic analysis of V-folded cavity for TEM_{00} operation of end-pumped solid-state laser

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Based on graphic analysis design method of optical resonator, a simple design expression of V-folded cavity of end-pumped solid-state lasers with TEM_{00} operation is described, which satisfies two criterias of the resonator design. We give numerical simulation of spot size as a function of thermal focal length using this design approach whose advantages are validated experimentally.

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Recent advance in semiconductor laser technology has led a very significant increase in the available output power. However the availabilities of high power and high intensity pump source have further exacerbated thermal effects such as thermally induced optical aberration and thermally-induced stress-birefringence, which are particularly pronounced in end-pumped lasers owing to the high thermal loading density. Thermal lens can make resonator get unstable and beam distortion, and so achieving both high efficiency and good beam quality laser is very difficult. To overcome this problem, resonator design strategy as a kind of efficient approach to select TEM_{00} beam has been reported[1].

The V-folded cavity is widely used to diode-pumped intra-cavity double-frequency laser, because the double-frequency crystal may be put on the beam waist near the M_2 to obtain higher second-harmonic generation (SHG) conversion efficiency. Recently, V-folded cavity has been studied by using various ways[2,3]. Here, considering mode-control ability in presence of thermal lens, we analyze it from another point of view.

In structure of V-folded cavity (see Fig. 1), mirrors M_1 and M_2 are plane mirrors and folded mirror M is smaller curvature concave mirror. Ignoring astigmation, we get equivalent optical configuration of a V-folded resonator as shown in Fig. 2, f is focal length of folded mirror, l_1 and l_2 are the lengths of arms, and f_{th} is focal length of thermal lens. Based on graphic analysis design method of optical resonator[2], σ_1, the propagation-circle of mirror M_1, is imaged as σ_1' by thermal lens, similarly σ_2, the propagation-circle of mirror M_2, is imaged as σ_2' by folded mirror, as shown in Fig. 3. For $l_2 > f$, the σ_2' intersects with the axis at two points, S_{21}' and S_{22}' are their distances from folded mirror

$$S_{21}' = f, \tag{1}$$

$$S_{22}' = \frac{f l_2}{l_2 - f}. \tag{2}$$

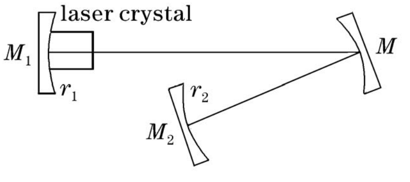

Fig. 1. Schematic diagram of a V-folded solid cavity.

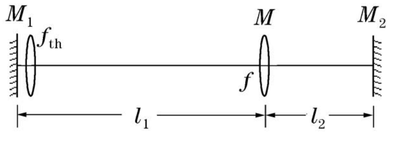

Fig. 2. Equivalent optical configuration of a V-folded cavity.

In absence of thermal lens, the M_1 may locate anywhere between S_{21}' and S_{22}' to form stable cavity. However we select the M_1 locating at the middle way of S_{21}' and S_{22}', as shown in Fig. 3, because this location is most insensitive to thermal lens[1]. We deduce the length of l_1 is

$$l_1 = \frac{2 f l_2 - f^2}{2(l_2 - f)}. \tag{3}$$

If σ_1' intersects with σ_2', the cavity is thermal stable, so we get variational range of f_{th} as

$$f_{\mathrm{th}} > l_1 - f. \tag{4}$$

We calculate spot size at mirror M_1

$$\omega_{\mathrm{t}} = f_{\mathrm{th}} \sqrt{\frac{\lambda f^4}{\pi(4 f_{\mathrm{th}}^2 (l_2 - f)^2 - f^4)}}. \tag{5}$$

According to above analysis, we can select different parameters of cavity based on different range of pump

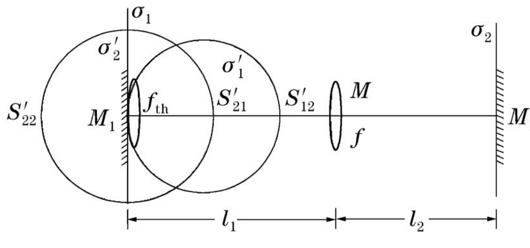

Fig. 3. Graphic analysis of V-folded cavity.

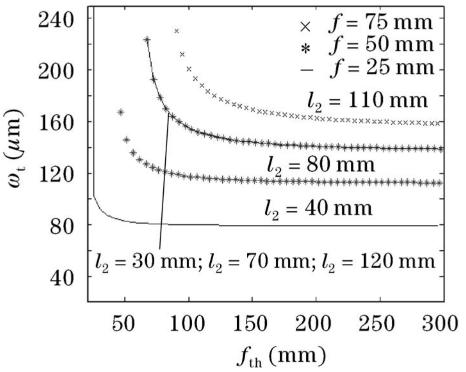

Fig. 4. TEM$_{00}$ spot radius versus thermal lens focal length.

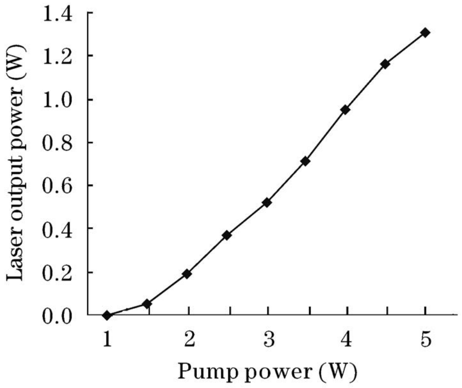

Fig. 5. Nd:GdVO$_4$ output power at 1063 nm versus pump power.

power (in inverse proportion to focal length of thermal lens) and spot size of pump light. The parameters of cavity are f = 25 mm, l_2 = 30, 40 mm; f = 50 mm, l_2 = 70, 80 mm; f = 75 mm, l_2 = 110, 120 mm. We calculate lengths of l_1 according to Eq. (3), which are respectively 87.5, 45.8, 112.5, 91.6, 155.3, and 137.5 mm. At the same time we make numerical simulation of spot size as a function of thermal focal length according to Eq. (5), whose figure is shown in Fig. 4.

From Fig. 4 we find that the resonator design satisfies thermal stable cavity and possesses mode-control ability at the same time. In addition we find that the longer the l_2, the greater the variational range of thermal lens when the focal length of folded mirror is fixed. The curves of numerical simulation are overlapped completely when l_2 = 30 mm, f = 25 mm; l_2 = 70 mm, f = 50 mm; l_2 = 120 mm, f = 75 mm. It means that different parameters of cavity may have identical behavior which makes us have more selections available for cavity parameters. It is advantage to cavity design of solid-state lasers. In the end we find that when the focal length of the folded mirror is longer, the cavity gets more insensitive to length of l_2, but the variational range of thermal lens focal length gets smaller. On the other hand, smaller focal length of folded mirror makes the astigmatism increase, so we select proper focal length of folded mirror basing on range of pump power and minishing astigmatism simultaneously. In like manner we can select proper length of l_2 based on spot size of pump light to make the best of energy of pump light.

To verify the benefits of the resonator design, the experiments on a end-pumped Nd:GdVO$_4$ laser are made. High-power laser diode array with two-mirror beam-shaping technique[4] is used as pump source, with minimum spot size $\omega_{\rm p}$ = 160 μm. Simple V-folded cavity (see Fig. 1) is used with curvature radius of folded mirror $r = 100\,$mm, $l_2 = 70\,$mm, $l_1 = 112\,$mm, $r_1 = r_2 = \infty$, and the $5\times5\times1$ (mm) Nd:GdVO$_4$ is mounted in water-cooled copper house. From Fig. 4 we can know approximately spot size of TEM$_{00}$ laser mode $\omega_{\rm t} \approx 150$ μm, which satisfies the criteria (smaller than the pump beam radius[1]) and extracts adequately energy of pump light. Experiment result is shown in Fig. 5, it was found that TEM$_{00}$ operation ($M_x^2 \approx M_y^2 < 1.3$) could be achieved, resulting in a maximum output power of 1.3 W at pump power of 5 W.

In conclusion, a simple expression of V-folded cavity design for TEM$_{00}$ operation of end-pumped solid-state lasers is described, the design forms thermal stable cavity and possesses mode-control ability. We give numerical simulation of spot size as a function of thermal focal length using this design approach. The influences of resonator parameters, including focal length of folded mirrors, resonator arm length, are analyzed based on figure of numerical simulation. In the end, using this approach we design the cavity which is used in laser diode array end-pumped Nd:GdVO$_4$ lasers, the laser has operated efficiently with near-diffraction-limited beam quality at 1063 nm.

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