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Optical ballast and adaptive dynamic stable resonator*

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In this paper a new concept of 'optical ballast' is put forward. Optical ballast is a kind of device that can be used to decrease the variation and fluctuation of the propagation characteristics of light beams caused by the disturbance of refractive index of the medium. To illustrate the idea clearly and concretely, a fully adaptive dynamic stable solid-state laser resonator is presented as application example of optical ballast.

Keywords: optical ballast, solid-state laser, resonator, thermal lens effect
PACC: 4255, 4260H

1. Introduction

Ballast originally meant heavy material (e.g. rock, bulk of iron, bag of sand) loaded in the bottom hold of a ship to keep it steady when sailing. This basic concept has been widely applied in electricity, thermology, acoustics, and mechanics and so on. For instance, in an electric circuit, adding a proper high resistance in series, which is known as current ballast, can weaken the current fluctuation. Now it is time to introduce this concept into optics. Just as the role of the high resistance, a novel device named 'optical ballast' can be used in a solid-state laser resonator to deduce the variation and fluctuation of beam propagation characteristics which is caused by the change of refractive index of the medium.

2. Type I optical ballast

The thermal lens effect of the laser medium is a critical topic in the research of high-power solid-state laser.[1−7] As we know, the heating of the laser medium by absorption of the pump power will cause the variation of focal length of the thermal lens from infinity to almost ten centimetres and this variation will greatly influence the stabilization of the laser mode and the laser power. Therefore, optical ballast is urgently demanded in designing the laser resonator.

As shown in Fig.1(a), the intensity of a Gaussian beam with waist radius of w_0 of 10mm is measured at L=10m behind the thermal lens F_t in the far field. With the change of f_t, the curve of the detected relative intensity versus the dioptric strength of the thermal lens, that is $1/f_t$, is easily obtained, as shown in Fig.1(b). It is clear that the detected intensity changes more than three orders of magnitude when the focal length varies from infinity to 10cm.

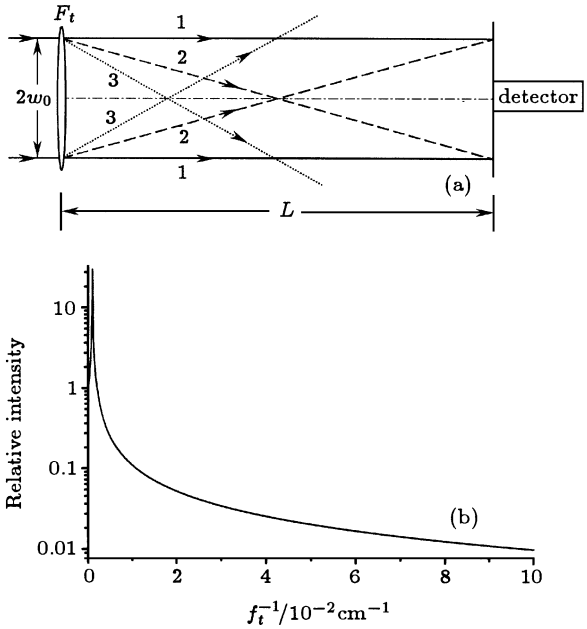


Fig.1. Detection of the Gaussian beam in the far field, at L=10m, behind the thermal lens without optical ballast. (a) The sketchy diagram for Gaussian beam propagation in the cases (1: $1/f_t$=0; 2: $1/f_t$=0.2×10^{-2}cm^{-1}; 3: $1/f_t$=0.4×10^{-2}cm^{-1}); (b) Detected relative intensity in the far field versus $1/f_t$.

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However, if we place a fixed-focus lens F_0 with a short focus length f_0 very close to the thermal lens f_t (laser rod), the situation will be absolutely different. According to the basic idea of geometrical optics, a composite lens is formed which has a focus length of $(f_0 + f_t)/f_0 f_t$. It is this composite lens that greatly decreases the intensity fluctuation in the far field. We can find that the fluctuation is suppressed and the maximum–minimum ratio is about 2:1 for $1/f_t$ from 0 to $10\times10^{-2}\mathrm{cm}^{-1}$ with f_0=10cm (Fig.2). So the fixed-focus lens acts as optical ballast (beam ballast) to keep the far optical field steady.

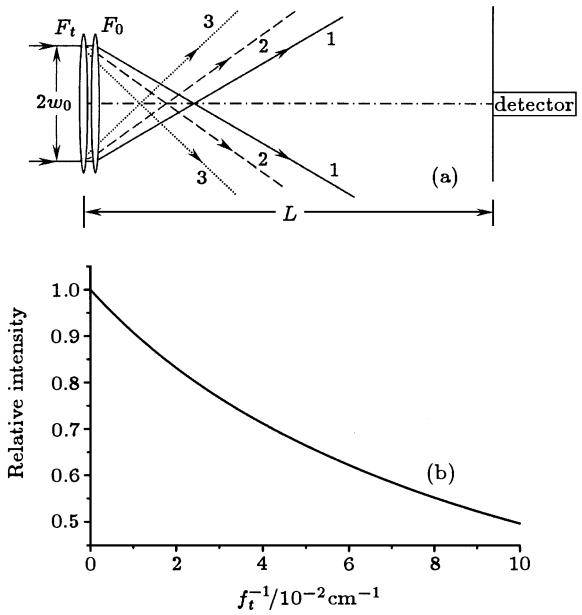


Fig.2. Detection of the Gaussian beam in the far field, at L=10m, behind the thermal lens with optical ballast—a fixed lens close to the thermal lens. (a) Sketch of Gaussian beam propagation in the cases (1: $1/f_t$=0; 2: $1/f_t$=$0.2\times10^{-2}\mathrm{cm}^{-1}$; 3: $1/f_t$=$0.4\times10^{-2}\mathrm{cm}^{-1}$); (b) detected relative intensity in the far field versus $1/f_t$.

Now we consider a planar mirror near a thermal lens (this is just the common solid-state laser resonator situation); the radius of Gaussian beam can be determined by using propagating circle approach.[8,9] From Fig.3(a) we can see that the radius of image propagating circle σ_1' (σ_1' is the image of the propagating circle σ_1 through the transformation of the thermal lens f_t) changes greatly when f_t varies from ∞ to 40cm. In this situation, it is difficult for the laser resonator to run steadily. In order to solve this problem, we replace the planar mirror with a small curvature radius concave mirror. From Fig.3(b) we can see that by replacing the planar mirror with a small curvature radius concave mirror, the change of the radius of circle σ' is much smaller than that of the planar situation. So we can say that the small curvature radius concave mirror placed very close to the thermal lens (laser rod) acts as an optical ballast.

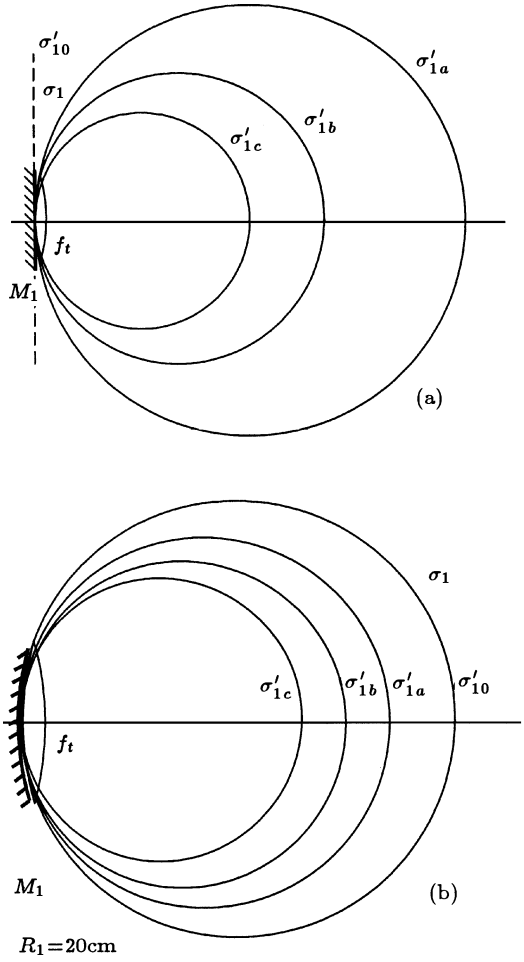


Fig.3. The image σ' circles of propagating circles of mirror M_1. (a) Sketch of image σ' circles in the cases: M_1 is a planar mirror, and σ_{10}', σ_{1a}', σ_{1b}', σ_{1c}' corresponding to $f_t = \infty$, 100cm, 60cm, 40cm, respectively; (b) Sketch of image σ' circles in the cases: M_1 is a concave mirror of radius R_1=20cm, and σ_{10}', σ_{1a}', σ_{1b}', σ_{1c}' corresponding to $f_t = \infty$, 100cm, 60cm, 40cm, respectively.

Figures 4 and 5 illustrate that the steady far-field intensity can be obtained by setting the thermal lens both at the front or the back focus spot of the fixed-focus lens. The theoretic deduction is as follows. The focal length of the composite lens is

$$f = \frac{1}{\dfrac{1}{f_0} + \dfrac{1}{f_t} - \dfrac{d}{f_0 f_t}} = f_0,$$

where $d = f_0$ is the distance between two lenses. The first principal plane of the composite lens, H_1, is located at a distance of $\dfrac{f_0^2}{f_t}$ from the lens F_0, while the

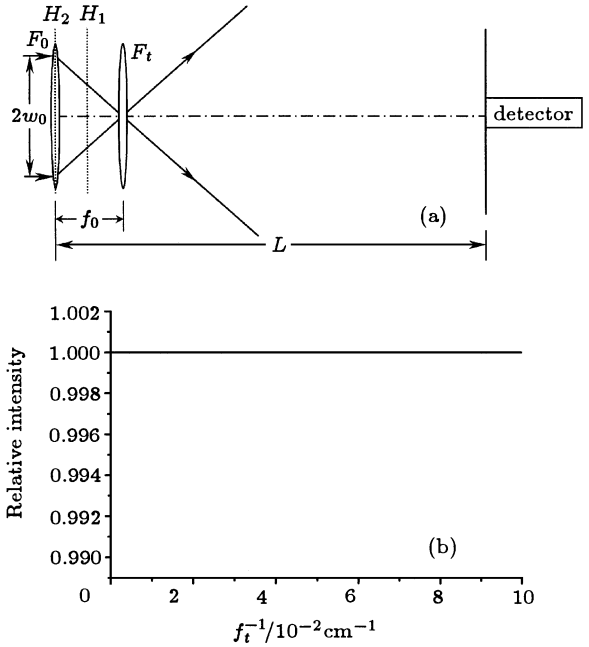


Fig.4. Detection of the Gaussian beam in the far field, at L=10m, behind the thermal lens with improved optical ballast—thermal lens at the front focus of the fixed lens. (a) Sketch of Gaussian beam propagation; (b) detected relative intensity in the far field versus $1/f_t$.

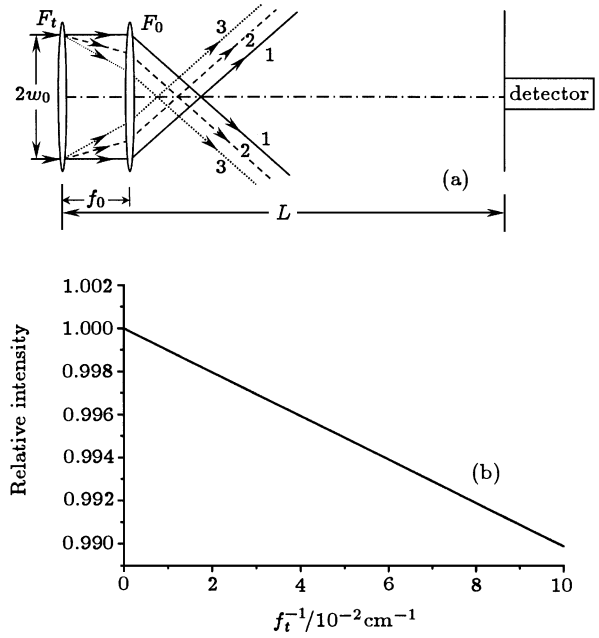


Fig.5. Detection of the Gaussian beam in the far field, at L=10m, behind the thermal lens with improved optical ballast—thermal lens at the back focus of the fixed lens. (a) Sketch of Gaussian beam propagation in the cases (1: $1/f_t$=0; 2: $1/f_t$=0.2×10^{-2}cm^{-1}; 3: $1/f_t$=0.4×10^{-2}cm^{-1}); (b) detected relative intensity in the far field versus $1/f_t$.

second principal plane, H_2, is located just at the position of the lens F_0. Consequently, the variation of focal length of the thermal lens will not affect the composite focal length and the position of H_2. Just as mentioned above, when the thermal lens is set at the front focus point of the fixed lens, the intensity in the far field remains constant, but the centre of the laser medium (thermal lens) may be damaged by strong pumping light focused by the fixed lens; therefore, this set-up is only suitable for the low-power laser beam situation instead of a high-power laser beam. For the latter, the thermal lens should be put at the back focus spot of the fixed lens (Fig.5). In this case, the fluctuation of far-field intensity is as small as only 1%.

We refer to these devices analysed above as 'type I optical ballast'. The optical device with configuration of Fig.4 is a superior selection for optical ballast resisting the influence of thermal lens effect.

3. Type II optical ballast

As we know, a wedge-like effect will occur in the medium while there exists an inhomogeneous lateral temperature or pressure field in the optic path, and will cause optical beam deflection as a result. From Fig.6 we can see that an inverted telescope is very helpful to reduce the deflection angle.

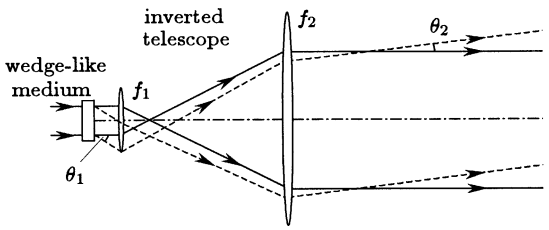


Fig.6. An inverted telescope resists the influence of the wedge-like effect on beam propagation.

It is easy to obtain that the reduction of the deflection angle is equal to $\theta_2 \approx \frac{f_1}{f_2}\theta_1$. We refer to this as 'type II optical ballast'.

4. A fully adaptive dynamic stable resonator

Here we put forward a fully adaptive dynamic stable resonator of solid-state laser as an application example of type I optical ballast. The mode property of the resonator can be obtained visually by the 'propagating circle' graph-analytic method.[8] Figure 7 is a fully adaptive dynamic stable resonator, which is composed of a laser rod and two concave mirrors with small curvature radius. The radius of the propagating circle[10] σ_1 of the concave mirror M_1 is $R_1/2$. When

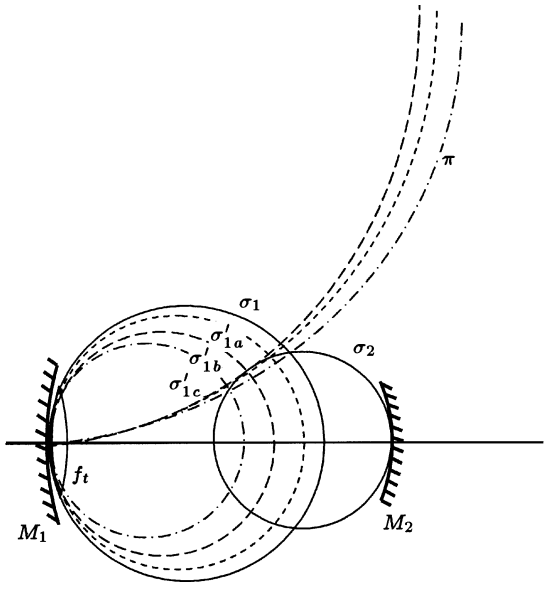


Fig.7. Fully dynamic stable resonator for solid-state laser with optical ballast.

the thermal effect is small enough to be ignored, the image circle σ'_1 of σ_1 is σ_1 itself. When the dioptric strength of the thermal lens $1/f_t$ increases, the radius of the image circle σ' of σ_1 (for example σ'_{1a}, σ'_{1b}, σ'_{1c}) decreases, but it varies only a little. In order to obtain a stable Gaussian beam, the propagation circle σ_2 of concave mirror M_2 must approximately orthogonally intersect with circle σ'_1. The spot diameter of the fundamental Gaussian beam at f_t can be determined by π circle which is tangential to the optic axis at f_t and passes the point of intersection of σ' and σ_2. Because the variation of σ' is small, the change of π also is small and the spot diameter of fundamental Gaussian beam at f_t only varies a little. With elaborately choosing the radii of the two concave mirrors and the length of resonator, we can expect that the solid-state laser resonator runs stably when the focus length of the thermal lens f_t varies from ∞ to 15cm. We name this resonator the 'fully adaptive dynamic stable resonator' without modulating the positions of any components of the resonator.

5. Conclusion

In this paper, we put forward two types of optical ballast that can resist the influence of either lens-like effect or wedge-like effect of the medium separately. An application of optical ballast in adaptive dynamic stable resonator for solid-state laser is also described. This suggests an easy way to produce a stable and high-power laser beam. Undoubtedly, the new concept of optical ballast will accelerate the development of the laser industry greatly and may also prove useful in many optic systems.

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