Experimental observation of optical bistability based on self-defocusing

Recently, many papers about cavityless self-focusing optical bistability have been published [1-3]. In this letter we report what is, to our knowledge, the first experimental observation of self-defocusing bistability. This kind of bistable system may have some interesting device applications due to the negative logical operation.

The expression for the refractive index on the cross-section of a laser beam in a thermal self-defocusing medium is [2]

\[ n = n_0 + \frac{\partial n}{\partial T} \Delta T \]

where \( \Delta T \) is the temperature variation on the cross-section of the laser beam \( \frac{\partial n}{\partial T} < 0 \) is the temperature coefficient of the refractive index and \( n_0 \) is the constant of refractive index. Because of the traverse distribution of the refractive index, self-defocusing of the laser beam occurs. At the first stage of thermal defocusing the power of the beam is lower, the eikonal change of ray occurs without any essential change of the beam amplitude profile. This is non-aberrational self-defocusing.

Increasing the power of the input beam, rays which are at different radial distances from the axis of the beam may obtain different inclinations while leaving the non-linear thermal self-defocusing medium, and can therefore cross and interfere outside the medium. In the far field the initial Gaussian beam acquires a ring angular structure described by the Airy functions [4]. A ring distribution of intensity is obtained. This phenomenon is called the aberrational self-defocusing.

Analysis of the expressions derived shows that the aberrational ring appears when the initial beam divergence is doubled [5]; that is, \( \theta = \theta_0 + \theta_{\text{NL}} = 2\theta_0 \), where \( \theta_0 \) is the initial beam divergence and \( \theta_{\text{NL}} \) is the non-linear divergence of defocused beam. In the central portion of beam, after aberrational self-defocusing a circular spot of uniform amplitude is conserved. The angular radius of this spot is about \( 2\theta_0 \). The majority of the power is in the external ring. In contrast with the non-aberrational case, the dependence of this aberrational defocusing upon power is non-linear. When the system changes from non-aberrational to aberrational defocusing the intensity ratio between the beam central portion and the external ring decreases drastically.

Our experimental observations have also confirmed the above results. Fig. 1 shows photographs of the laser intensity distribution before and after aberrational self-defocusing in the far field. The change of intensity ratio is very clear. We therefore conjecture that if a concave spherical mirror with a small aperture at the centre is used to reflect the defocused beam back into the sample, then the increased optical intensity in the sample will further strengthen the defocusing and decrease the output. Optical bistability with a negative logical operating character will thus occur.

Fig. 2 is a schematic diagram of the experimental layout used. A TEM_{01} mode argon laser power modulator and 1 is an optical isolator used to prevent the beam from going back into the laser. The input beam waist is transformed to
Figure 1. The laser spot in the far field, (a) before and (b) after aberrational defocusing.

$W_m$ by the lens $\ell$. The distance $l_1$ from $W_m$ to the sample $S$ is $3.5Z_c$, here $Z_c$ is the confocal distance of the input beam. When the beam waist locates at a distance $3.5Z_c$ before the sample, a maximum of the relative intensity change of the beam central portion before and after self-defocusing is obtained [6].

A concave mirror $M$ with a small aperture is placed at distance $l_2$ from the sample, $l_2 > l_1$. The thickness of the sample is much less than $l_1$, so we can consider the thermal lens in the medium as a thin lens. The mirror $M$ is aligned normally to the laser beam to provide output power and optical feedback. For the best feedback efficiency the distance $l_2$ and the radius of curvature of $M$ are selected to make the waist of the feedback beam enter the sample just as aberrational defocusing starts. The optical axes of the input and feedback beams must be strictly aligned along the same line. The aperture size at the centre of $M$ is adjusted to satisfy two criteria. First, it must be large enough that in the absence of aberrational self-defocusing essentially all of the light passes through the aperture as the output power. Second, it must be small enough that after just starting aberrational self-defocusing, all of the light in the external ring is immediately fed back into the non-linear medium by the spherical mirror. This strong feedback reinforces the self-defocusing in the medium, and in turn increases the light power reflected by the mirror. At the same time the system changes rapidly from a high output state into a low output state. The strong feedback allows the aberrational self-defocusing to be maintained even if the input power is subsequently reduced below the critical power of the aberrational self-defocusing.

In our experiments the focal length of lens $\ell$ was $f = 100$ mm, the waist spot size $W_m$ was about $0.08$ mm, $z_c = \pi W_m^2/\lambda$ was about $39$ mm, the radius of curvature of mirror $M$ was $R = 160$ mm, the reflectance $r$ was about $0.9$; the radius of the output aperture on the centre of the mirror was $a = 0.5$ mm. Acetone was used as the non-linear absorbing medium. The thickness

Figure 2. The experimental layout.

Figure 3. The experimental curves for output versus input power, (a) without and (b) with mirror feedback. Absorption $\delta = 0.02$, radius of aperture $a = 0.5$ mm.
of the liquid was 5 mm. A small amount of fuchsin was added to the pure acetone to increase the absorption. Fig. 3a and b shows the curves of transmitted power through an aperture placed at a distance \( l \) from the sample and at the centre region of the exit beam versus the incident power without and with the mirror feedback, respectively. The absorption \( \delta l \) of the solution used in the experiments of Fig. 3 was 0.02. Because the beam radii are smaller than the radius of aperture before aberrational self-defocusing, at low intensity almost all of the transmitted beam from the sample passes through the aperture and a linear relationship between input and output is obtained. When the power is higher than 12 mW the slope of the curve decreases. At a higher power than 17 mW the transmitted power begins to decrease as the incident power increases. This means that aberrational self-defocusing occurs. When the incident power is increased from 17 to 24 mW the output power decreases from about 10 to 5 mW. When the incident power is higher than 24 mW the output power keeps approximately stable at about 5 mW then increases slowly. If the incident laser were lowered, then curve a would be reproduced almost exactly, showing the absence of hysteresis. Fig. 3b is the experimental result when the feedback mirror \( M \) was added, the transmitted light power as a function of the incident power exhibiting a typical hysteresis of bistable optical operation. Switch-down operation nearly occurred at the incident power level of aberrational self-defocusing threshold (approximately 17 mW).

Fig. 4 shows the experimental curves for the different acetone and fuchsin solutions with different absorption \( \delta l \). They show that the higher the absorption is, the lower the switch power, and the narrower the bistable region. For the various \( \delta l \) the powers of the switch-down are just the threshold powers occurring for aberrational self-defocusing in these different media. However, when \( \delta l > 0.08 \) the hysteresis disappears because the feedback power is too weak. These experiments were repeated several times and the same experimental curves were reproduced. The operating conditions of the system are very important. If the input power is too high or the absorption \( \delta l \) is too large, then the symmetry of the defocused spots and the repeatability of the experiments are destroyed by convection in the medium.

In conclusion, the optical bistability based on the aberrational self-defocusing in the acetone the fuchsin solutions has been demonstrated by our experiments. Although the response time of thermal defocusing is quite long (hundreds of milliseconds) and the solution is not ideal for logical devices, this kind of bistable system can undoubtedly be used for other self-defocusing media with faster response times. The detailed quantitative theoretical study of these experiments is being done, and will be reported in another paper [7].

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