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Optical limiting using spatial self-phase modulation in hot atomic sample

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ABSTRACT

In this work, we characterized the performance of optical limiting by self-phase modulation (SPM) in hot atomic vapor cell. The results indicated that the performance of the optical limiter is closely related to the position of the sample cell, which is determined by the Rayleigh lenght of beam. The lowest limiting threshold and clamp output were obtained at the sample position at −10 mm from the coordinate origin (the beam waist). The phenomenon was explained well by the theory of SPM and z-scan, which are caused by both Kerr effect and the thermal optical nonlinear effect. This useful information obtained in the meaning of this work is determining the optimal position of the sample cell in the optical limiter and other applications of SPM.

1. Introduction

A set of concentric ring diffraction patterns can be induced in the far-field when a laser beam passes though a nonlinear medium, attributed to the self-phase modulation (SPM) caused by Kerr effect [1–5]. According to the relationship between the number of the diffraction rings and the nonlinear phase shift, the nonlinear refractive index of a thick sample can be determined easily [6]. In particular, as the central intensity of the output is modulated by SPM, an optical limiter can be obtained by adding an aperture at the output side [7–9].

The central intensity of the far-field diffraction patterns influences the performance of an optical limiter based on SPM. It is interestingly found that the centers of the ring diffraction patterns are dark in some works [10], while in others, the centers are bright [11]. To achieve the low threshold and clamp output, the central intensity should be as low as possible [12]. Therefore dark centers are required. Santamato and Shen proposed that the intensity of the central spot is influenced by the wavefront curvature [11]. Afterwards, a large number of experiments [13–17] show that the centers of diffraction rings are bright when the phase shift $\Delta\phi(r)$ and the wavefront curvature $R(z)$ have the same signs and dark when the two parameters have the opposite signs. However, this law does not hold if the thermally induced optical nonlinearity cannot be neglected. Bright centers could also been obtained when the signs of the two parameters are opposite [17].

In this work, we studied the optical limiting by using SPM pattern in hot atomic sample. We found that the performance of the optical limiter was dependent on the sample position. In addition, this phenomenon was explained well by the theory of SPM and z-scan, which are caused by both Kerr effect and the thermal optical nonlinear effect. This work is useful in determining the optimal position of the sample in the optical limiting and other applications based on SPM such as all-optical switching [18], ultracold atoms trapping [19], and the hollow laser beam generation [20].

2. Experimental and theoretical methods

The experimental setup is shown in Fig. 1. A Gaussian beam was obtained from a tunable Titanium sapphire laser (Spectra-Physics, Matisse TR, CW, tunable from 780 to 990 nm) and focused into a 100 mm long Rb sample by a lens with a focal length of 200 mm, the radius of beam from laser is 0.7 mm. The output beam through the sample was collimated and passed through an aperture. The diameter of aperture is 1 mm and keeps constant. The laser wavelength was fixed at 780.2410 nm (nearly resonant to ^{85}Rb $|5S_{1/2}, F=3> \rightarrow |5P_{3/2}>$), and the temperature of the sample cell at 90 °C (controlled by a heater band) [21]. The Rb atomic sample cell can be moved forward and backward along the rail with calibrations. We took the coordinate origin at the beam waist and the propagating direction of the laser beam as the

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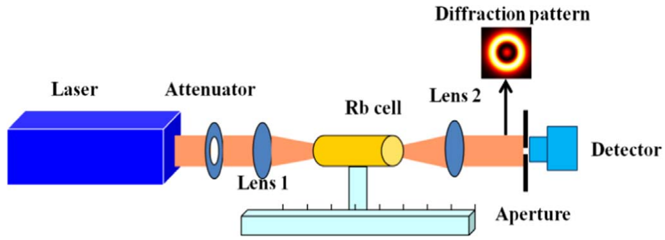

Fig. 1. Experimental setup.

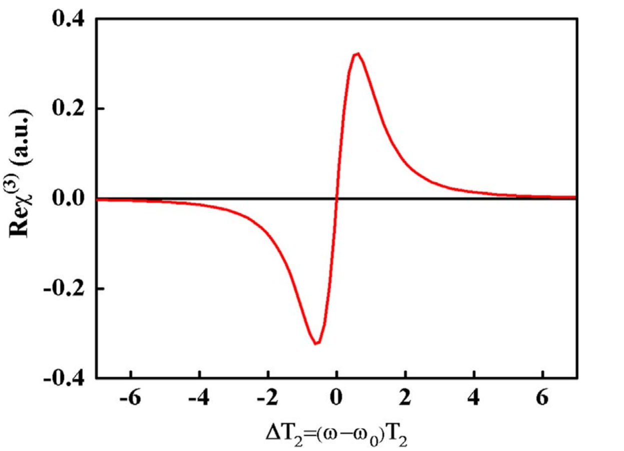

Fig. 2. The effect of ΔT_2 on the real part of the third-order nonlinear susceptibility $\mathrm{Re}\chi^{(3)}$.

positive direction. The output power was measured by a detector. And the diffraction ring patterns were observed by changing the aperture into a screen.

In theory, when a Gaussian beam passes through the optical Kerr medium, the refractive index becomes dependent on the laser intensity, expressed as:

$$n = n_0 + \Delta n = n_0 + n_2|E|^2 \tag{1}$$

in which n_0 is the linear refractive index, Δn is the change of the refractive index that caused by optical Kerr effect [22,23], and n_2 is the Kerr coefficient which can be expressed as:

$$\begin{aligned} n_2 &= \frac{12\pi^2}{n_0^2 c}\mathrm{Re}\chi^{(3)} \\ &= \frac{12\pi^2}{n_0^2 c} \times \left(-\frac{4}{3}N\left(\rho_{bb} - \rho_{aa}\right)^{eq}|\mu_{ba}|^4 \frac{T_1 T_2^2}{\varepsilon_0 \hbar^3}\frac{\Delta T_2}{(1 + \Delta^2 T_2^2)^2}\right) \end{aligned} \tag{2}$$

in which,

$\chi^{(3)}$: third-order nonlinear susceptibility,

$(\rho_{bb} - \rho_{aa})^{eq}$: population difference between the excited and the ground states in thermal equilibrium,

μ_{ab}: electric dipole moment,

N: atomic number density,

T_1: longitudinal relaxation time,

T_2: transverse relaxation time,

Δ: frequency detuning.

Considering isotopes and hyperfine structure, there are four transitions for Rb D2 lines: ^{87}Rb $|5S_{1/2}, F=1> \rightarrow |5P_{3/2}>$ at 780.2289 nm; ^{85}Rb $|5S_{1/2}, F=2> \rightarrow |5P_{3/2}>$ at 780.2322 nm; ^{85}Rb $|5S_{1/2}, F=3> \rightarrow |5P_{3/2}>$ at 780.2424 nm; ^{87}Rb $|5S_{1/2}, F=2> \rightarrow |5P_{3/2}>$ at 780.2459 nm. We chose ^{85}Rb $|5S_{1/2}, F=3> \rightarrow |5P_{3/2}>$ as a representation. As indicated in Eq. (2), Kerr coefficient n_2 is dependent on the frequency detuning Δ. As shown in Fig. 2, the maximum absolute value of n_2 can be obtained at the frequency detuning about of ± 0.7 GHz. The corresponding laser

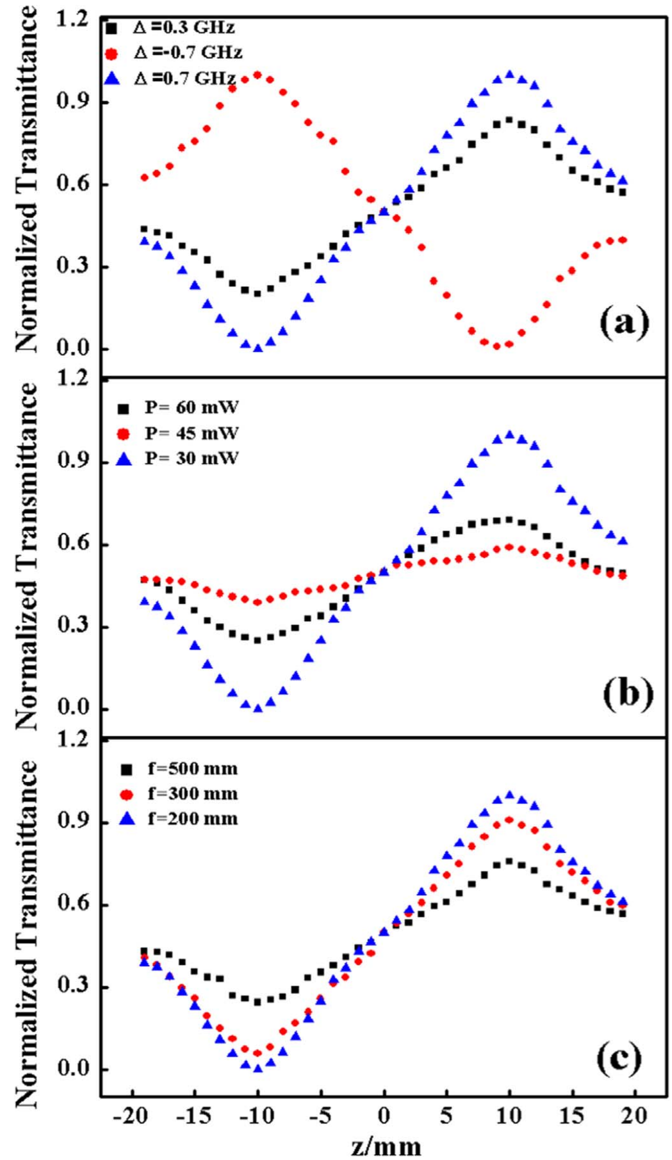

Fig. 3. (a) The effect of detuning frequency on the optimal position, (b) and (c) are effect of power and beam waist radius on the optimal position respectively. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

wavelengths at $\Delta = 0.7$ GHz and $\Delta = -0.7$ GHz are 780.2410 nm and 780.2438 nm respectively. Considering 780.2410 nm is farther away from the resonant wavelengths of the adjacent transitions, in order to get maximum Kerr effect, we fixed laser wavelength at 780.2410 nm during the experiment.

The change of the refractive index causes an additional lateral phase shift after the laser beam passing through the medium. Consequently, the transverse additional phase shift $\Delta\phi(r)$ induced on the exit plane of the medium can be expressed as:

$$\begin{aligned} \Delta\phi(r) &= k_0 \int_0^l \Delta n(z, r)dz \\ &= k_0 \int_0^l n_2 I(0, 0)\frac{r_0^2}{\omega_p^2} exp(-\alpha(z-z_0))\exp\left(\frac{-2r^2}{\omega_p^2}\right)dz \\ &\approx \Delta\phi_0 \exp\left(-\frac{2r^2}{\omega_p^2}\right) \end{aligned} \tag{3}$$