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# ANALYSIS ON OPTIMIZING OPTICAL LIMITING IN INFRARED FOCUSED OPTICAL-DETECTING SYSTEMS *

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**Abstract** The effect of geometry arrangements of optical-limiting media with cubic nonlinearities in infrared focused optical-detecting systems on the optical limiting was calculated and analyzed by using beam propagaton and Gaussian decomposition (GD) methods, and optimum geometry arrangements were given in the analysis. The results show that the optical limiting for the near-field geometry arrangement is very different from that for the far-field geometry arrangements, and in some geometry arrangements nonlinear media with positive nonlinear index can not be employed as optical-limiting media, which is different from previous suggestions for the far-field geometry arrangements. It is also shown that focused geometry arrangements can be employed for measurements of nonlinear refractive index with a higher sensitivity than that of common Z-scan techniques.

**Key words** optical nonlinearity, optical-limiting, infrared focused optical-detecting system.

# 红外聚焦光探测系统中光限制效应的优化分析*

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**摘要** 计算和分析了红外聚焦光探测系统中光限制材料的几何排布对光限制效应的影响，给出了优化的几何分布．结果显示，近场条件下的光限制效应与远场条件下的完全不同，在某些情况下，具有正光学非线性系数的材料不能被用作光限制之用，这与远场情况不同．分析也表明，聚焦几何排布可用于非线性折射系数的测量，并具有比常规 Z 扫描方法更高的灵敏度．

**关键词** 光学非线性，光限制，红外聚焦光探测系统．

光限制效应，优化分析

## Introduction

Passive optical limiting resulting from irradiance-dependent nonlinear-optical processes in materials has been widely studied[1~3]. The significant application of optical limiters is to protect sensors (especially infrared sensors) from being damaged by intense input laser. The characteristics of an ideal optical limiter should be that it has a high linear transmission for low input (e.g., energy $E$ or power $P$), but low transmission for high input. Since high transmission for low input is expected, low linear absorption in optical-limiting materials is needed. This leads to the use of nonlinear absorption and nonlinear refraction. Great efforts have been made for getting applicable limiters[3~5] although some shortcomings exist, such as narrow-band operation and high limiting power.

M. Sheik-Bahae *et al.* got a better optical limiter for protecting an infrared sensor from being damaged by a 300ns (FWHM) 10.6μm $CO_2$ laser pulse, in which the thick $CS_2$ medium with impurities absorber was used and placed at an optimum position[3]. In this paper we give a theoretical anal-

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ysis for optimizing the optical limiting resulting from a cubic nonlinearity in infrared focused optical-detecting systems by employing Gaussian decomposition and $q$ transformation approach. Some useful results such as optimum geometry arrangement and limiting characteristics are obtained. Our calculations show that the optical limiting for the near-field geometry arrangements is very differnet from that for the far-field geometry arrangements, and in some geometry arrangements nonlinear media with positive nonlinear index can not be employed as optical limiting media as suggested previously for the far-field geometry arrangements. Meanwhile, it is also presented that the focused geometry arrangements can be employed for measurements of nonlinear refraction with a higher sensitivity than that of common Z-scan. We think that the optimization of geometry arrangements of optical limiting is one of the nost important ways for applications of optical limiters in infrared focused optical-detecting systems.

## 1 Theory and Calculation

Previous discussions on optical limiters usually have a geometry arrangement analogous to that in Z-scan[3,6,7], where the detecting plane locates in the far-field. But usually in some kinds of optical-detecting systems such as infrared positioning systems (we call them infrared focused optical-detecting systems) and optical imaging systems, sensitive detectors need to be placed on the focal plane, therefore, the optical irradiance on the detectors will be very large when a laser is incident on the optical-detecting systems. The protection of these systems from optical damage is most practical and pressing. Figures 1 (a) and (b) give two possible kinds of geometry arrangements of optical limiting in these kinds of optical-detecting systems. Other configurations of optical-limiting in focused optical-detecting systems can be equivalent to one of the two kinds. In the following calculation, we assume that the optical-limiting material is thin. This means that changes in the beam diameter within material due to either diffraction or nonlinear refraction can be neglected. This assumption can simplify the problem considerably. At the same time we only consider the optical limiting resulting from cubic nonlinear refraction without the

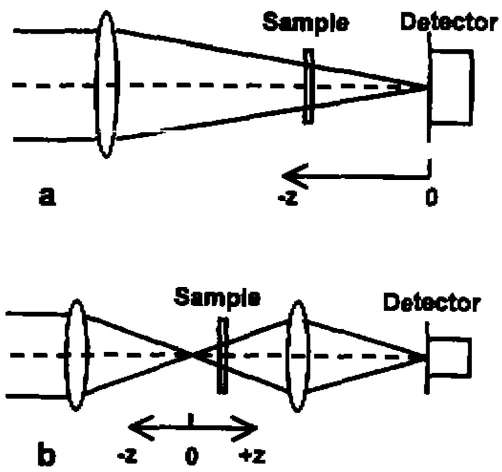


Fig. 1 The geometry arrangements of optical limiting
图 1 光限制的几何排布形式

existence of nonlinear absorption. Assuming a $TEM_{00}$ Gaussian beam of beam waist radius $\omega_0$ travelling in the $+z$ direction, we can write $E$ as

$$E(z,r,t) = E_0 \frac{\omega_0}{\omega(z)} \exp\left(-\frac{r^2}{\omega^2(z)} - i\frac{kr^2}{2R(z)}\right) e^{-i\varphi(z,t)}, \tag{1}$$

where $\omega(z)=\omega_0\left(1+\frac{z^2}{z_0^2}\right)^{\frac{1}{2}}$ is the beam radius at $z$, $\omega_0$ is the beam waist radius, $R(z)=z\left(1+\frac{z^2}{z_0^2}\right)$ is the radius of curvature of the wavefront at $z$, $z_0=\frac{k\omega_0^2}{2}$ is the diffraction length of the beam, $k=\frac{2\pi}{\lambda}$ is the wave-vector and $\lambda$ is the laser wavelength. $E_0(t)$ denotes the electric field at the focus. The term $e^{-i\varphi(z,t)}$ contains all the radically uniform phase variations.

The complex electric field $E_e$ exiting the sample with a cubic nonlinearity can be expressed as[6]

$$E_e(z,r,t) = E(z,r,t)e^{-\frac{\alpha L}{2}} \sum_{m=0}^{\infty} \frac{(-i\Delta\varphi(z,t))^m}{m!} \exp\left(-\frac{2mr^2}{\omega^2(z)}\right), \tag{2}$$

with $\Delta\varphi(z,t)=\frac{\Delta\varphi_0(t)}{1+z^2/z_0^2}$,

where $\Delta\varphi_0=\frac{2\pi}{\lambda}\Delta n_0(t)L_{eff}$, $L_{eff}=(1-e^{-\alpha L})/\alpha$, $L$ is the sample length, $\alpha$ is the linear absorption coefficient, and $\Delta n_0(t)$ is the instantaneous on-axis index change at the focus.

For the geometry arrangement of optical limiting shown in Fig. 1(a), by $q$ transformation approach, one can obtain the on-axis electric field on the focal plane as

$$E_D(z,r=0,t)=E(z,r=0,t)e^{\left[-\frac{\alpha L}{2}\right]}\sum_{m=0}^{\infty}\frac{(-i\Delta\varphi(z,t))^m}{m!}\frac{1}{g+i\frac{z}{d_m}},\tag{3}$$

where $g=1-\frac{z}{R(z)}$, $d_m=\frac{k\omega_{m0}^2}{2}$, and $\omega_{m0}^2=\frac{\omega^2(z)}{2m+1}$.

Since damage to detectors is almost always determined by irradiance or fluence, in our analysis, we can only examine the on-axis irradiance on detecting plane for illustrating the role of limiting media in sensor protection. The on-axis irradiance on the detecting plane is

$$I_D(z,r=0,t)=I_0(t)\frac{\omega_0^2}{\omega^2(z)}e^{-\alpha L}\left|\sum_{m=0}^{\infty}\frac{(-i\Delta\varphi(z,t))^m}{m!}\frac{1}{g+i\frac{z}{d_m}}\right|^2,\tag{4}$$

where $I_0(t)$ is the on-axis irradiance at focus without the existence of nonlinear refraction. We define the normalized transmittance as $T(z,t)=\frac{I_D}{I_0\exp(-\alpha L)}$, then

$$T(x,t)=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}A_{mn}\cos\left(B_{mn}\frac{\pi}{2}-C_{mn}\right),\tag{5}$$

where $x=z/z_0$. Other parameters are expressed as follows

$$A_{mn}=\frac{[\Delta\varphi(z,t)]^{m+n}}{m!n!}\frac{x^2+1}{[1+(2m+1)^2x^2]^{1/2}[1+(2n+1)^2x^2]^{1/2}},$$

$$B_{mn}=n-m,$$

$$C_{mn}=\tan^{-1}[x(2n+1)]-\tan^{-1}[x(2m+1)].$$

Figure 2 gives the normalized transmittance $T$ as a function of $x$ for negative cubic nonlinear index. It shows that there is minimum normalized transmittance at about $x=-0.35$. Figure 3 gives the input-output characteristics of optical limiting, where $I_o=T|\Delta\varphi_0|$ represents the output irradiance since $|\Delta\varphi_0|$ is proportional to input irradiance. We can find out that the optimum geometry arrangement of optical limiting is to place nonlinear medium with a cubic nonlinearity at a position where the normalized transmittance is minimum, the po-

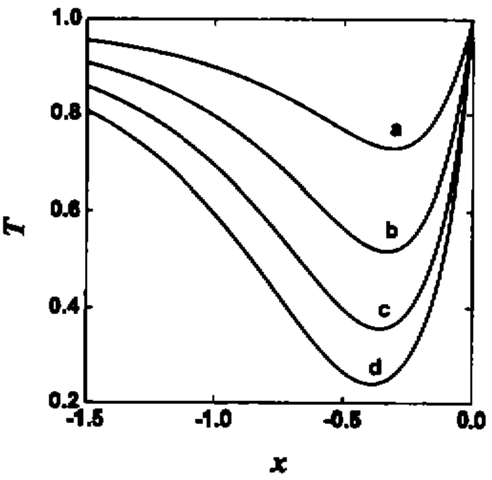


Fig. 2 The normalized transmittance $T$ as a function of $x$ for negative cubic nonlinear index in the geometry arrangement of Fig. 1(a).
(a) $\Delta\varphi_0=-0.5$, (b) $\Delta\varphi_0=-1.0$,
(c) $\Delta\varphi_0=-1.5$, (d) $\Delta\varphi_0=-2.0$.
图 2 在图 1(a)所示的光限制几何排布下，具有负非线性折射系数材料的归一化透射比 $T$ 与 $x$ 的函数关系
(a) $\Delta\varphi_0=-0.5$, (b) $\Delta\varphi_0=-1.0$,
(c) $\Delta\varphi_0=-1.5$, (d) $\Delta\varphi_0=-2.0$

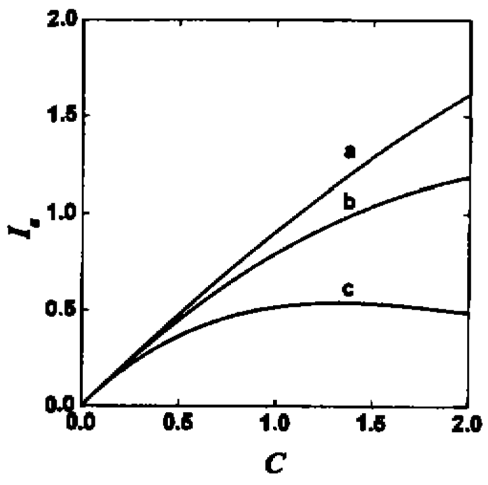


Fig. 3 The input-output characteristics of optical limiting with the geometry arrangement of Fig. 1(a), $C=|\Delta\varphi_0|$.
(a) $x=-1.5$, (b) $x=-1.0$, (c) $x=-0.35$.
图 3 在图 1(a)所示的光限制几何排布下，输入和输出的特征关系曲线，$C=|\Delta\varphi_0|$
(a) $x=-1.5$, (b) $x=-1.0$, (c) $x=-0.35$

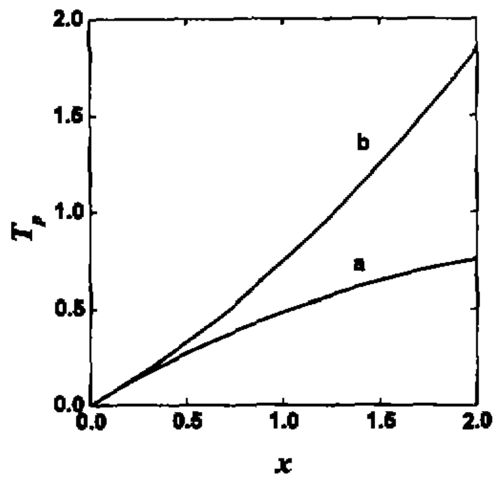


Fig. 4 Maximum normalized transmittance $T_p$ as a function of nonlinear phase shift $|\Delta\varphi_0|$ in the geometry arrangement of Fig. 1(a). Curve (a) corresponds to nonlinear media with negative nonlinear phase shift, curve (b) to nonlinear media with positive nonlinear phase shift

图 4 在图 1(a)所示的光限制几何排布下,最大归一化透射比 $T_p$ 与非线性相移 $|\Delta\varphi_0|$ 的函数关系.曲线(a)对应具有负非线性相移的介质,曲线(b)对应具有正非线性相移的介质

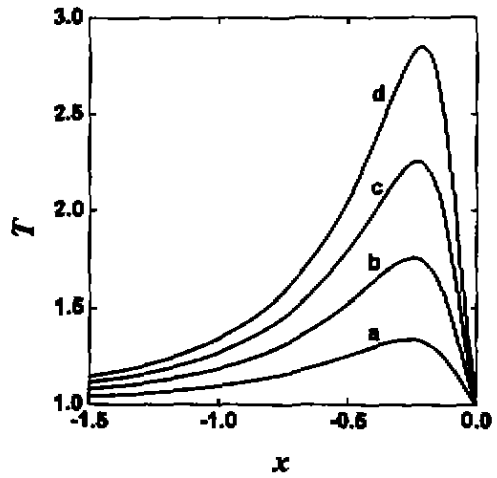


Fig. 5 The normalized transmittance $T$ as a function of $x$ for positive cubic nonlinear index in geometry arrangement of Fig. 1(a)
(a) $\Delta\varphi_0=0.5$, (b) $\Delta\varphi_0=1.0$, (c) $\Delta\varphi_0=1.5$, (d) $\Delta\varphi_0=2.0$

图 5 在图 1(a)所示的光限制几何排布下,具有正非线性折射系数材料的归一化透射比 $T$ 与 $x$ 的函数关系
(a) $\Delta\varphi_0=0.5$, (b) $\Delta\varphi_0=1.0$, (c) $\Delta\varphi_0=1.5$, (d) $\Delta\varphi_0=2.0$

sition is about $z=-0.35z_0$. Our results show that the maximum normalized transmittance change $T_p=1-T_{min}$, in which $T_{min}$ corresponds to minimum normalized transmittance, is proportional to the nonlinear phase shift $|\Delta\varphi_0|$ for small $|\Delta\varphi_0|$ limit. As shown in Fig. 4, for $|\Delta\varphi_0|\leqslant 0.5$, the following relation exists with an accuracy of $\pm5\%$,

$$T_p = 0.57|\Delta\varphi_0|. \tag{6}$$

This means that with the geometry arrangement we can obtain a higher measurement sensitivity than that of common Z-scan[6,7]. Our calculations also show that for nonlinear media with positive nonlinear index there does not exist a valley of normalized transmittance, but a peak exists as shown in Fig. 5. It is explained by that self-focusing in the nonlinear medium causes the focal plane to shift backward and the beam size on modified focal plane to become smaller, but the beam size on the detecting plane still becomes smaller, therefore, the normalized trasmittance still increases. It is different from the far-field case that nonliear media with both positive and negative nonlinear refraction can act as limiting media[2,8]. We think that for the geometry arrangement of Fig. 1(a), only nonlinear media with negative nonlinear refraction are suitable for limiting media. For the nonlinear medium with positive nonliear index, maximum normalized transmittance change $T_p=T_{max}-1$, in which $T_{max}$ corresponds to maximum normalized transmittance, is proportional to the nonlinear phase shift $|\Delta\varphi_0|$ for small $|\Delta\varphi_0|$. As shown in Fig. 4, for $|\Delta\varphi_0|\leqslant 0.5$, the following relation exists with an accuracy of $\pm5\%$,

$$T_p = 0.65|\Delta\varphi_0|. \tag{7}$$

For the geometry arrangement of optical limiting shown in Fig. 1(b), in which two lenses have the same focal length $f$, their separation is $2f$, and the distance from the focal plane in image space to the second lens is $f$, by $q$ transformation approach, we obtain the on-axis electric field on detecting plane that is focal plane in image space:

$$E_D(z,r=0,t) = E(z,r=0,t)e^{-\frac{\alpha L}{2}} \sum_{m=0}^{\infty}\frac{(-i\Delta\varphi(z,t))^m}{m!}\left(\frac{f}{q_{NL}}\right)^{-1} \tag{8}$$

with

$$\frac{1}{q_{NL}}=\frac{1}{R(z)}-i\frac{\lambda}{\pi\omega_{m0}^2}.$$

Thus the on-axis irradiance on the detecting plane is

$$I_D=I_0(t)\frac{z_0^2}{f^2}\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}a_{mn}\cos\left(b_{mn}\frac{\pi}{2}+c_{mn}\right), \tag{9}$$

where

$$a_{mn}=\frac{[\Delta\varphi(z,t)]^{m+n}}{m!n!}\frac{x^2+1}{[(x^2+(2m+1)^2)(x^2+(2n+1)^2)]^{\frac{1}{2}}},$$

$$b_{mn}=n-m,$$

$$c_{mn}=\tan^{-1}\left(\frac{2m+1}{x}\right)-\tan^{-1}\left(\frac{2n+1}{x}\right)$$

Let $\Delta\varphi(z,t)=0$, we have

$$I_D=I_{D l}=I_0(t)e^{-\alpha L}\frac{z_0^2}{f^2}. \tag{10}$$

where $I_{D l}$ represents the on-axis irradiance on the detecting plane without the existence of nonlinear refraction. Therefore, the normalized transmittance $T(x,t)$ can be expressed by

$$T(x,t)=\sum_{m=0}^{\infty}\sum_{n=0}^{\infty}a_{mn}\cos\left(b_{mn}\frac{\pi}{2}+c_{mn}\right) \tag{11}$$

Figure 6 gives the normalized transmittance $T(x,t)$ as a function of $x$ for some nonlinear phase shift. By calculation we obtain the following relations:

$$\Delta T_{p-v}\approx 0.406|\Delta\varphi_0|,\quad |\Delta\varphi_0|\leqslant\pi \tag{12}$$

$$\Delta Z_{p-v}\approx 1.7z_0, \tag{13}$$

where $\Delta T_{p-v}$ is the peak-valley transmittance change, and $\Delta Z_{p-v}$ is the peak-valley separation of normalized transmittance. The relations in Eqs. (12) and (13) are the same as those in the conventional Z-scan which uses one lens[6]. The input-output characteristics of optical limiting are given in Fig. 7 at different positions of nonlinear media. The optimum positions of limiting media with positive and negative cubic nonlinearities are about $-0.85\,z_0$ and about $0.85z_0$ respectively. At these optimum positions the transmitted on-axis irradiance decreases by about $0.203|\Delta\varphi_0|$. It is shown obviously by Figs. 3 and 7 that the limiting effect with the geometry arrangement of Fig. 1(a) is more effective than that of Fig. 1(b) for the same nonlinear medium at their optimum geometry arrangements.

## 2 Summary

We discuss the effect of geometry arrange-

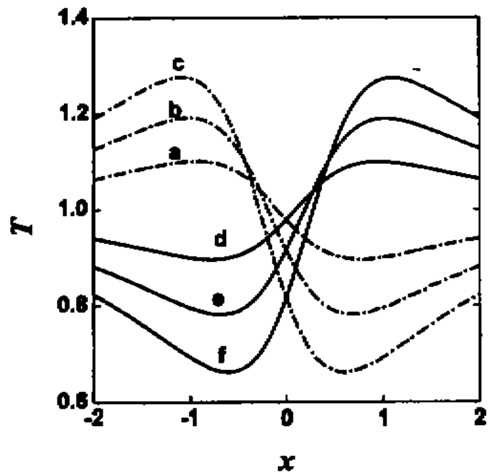


Fig. 6 The normalized transmittance $T$ as a function of $x$ for different nonlinear phase shift in the geometry arrangement of Fig. 1(b)

(a) $\Delta\varphi_0=0.5$, (b) $\Delta\varphi_0=1.0$, (c) $\Delta\varphi_0=1.5$, (d) $\Delta\varphi_0=-0.5$, (e) $\Delta\varphi_0=-1.0$, (f) $\Delta\varphi_0=-1.5$

图 6 在图 1(b)所示的光限制几何排布下，在不同相移时归一化透射比 $T$ 与 $x$ 的函数关系

(a) $\Delta\varphi_0=0.5$, (b) $\Delta\varphi_0=1.0$, (c) $\Delta\varphi_0=1.5$, (d) $\Delta\varphi_0=-0.5$, (e) $\Delta\varphi_0=-1.0$, (f) $\Delta\varphi_0=-1.5$.

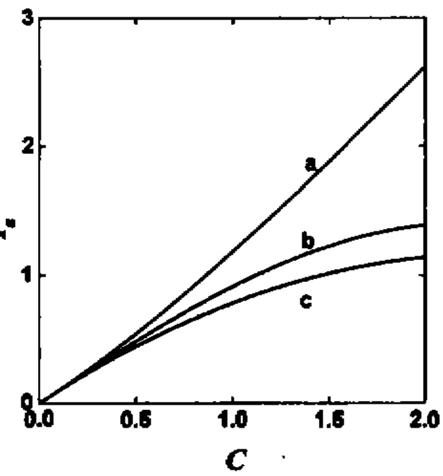


Fig. 7 The input-output characteristics of optical limiting with the geometry arrangement of Fig. 1(b) for positive cubic nonlinearity index, $C=|\Delta\varphi_0|$

(a) $x=-0.85$, (b) $x=0$, (c) $x=0.85$.

图 7 在图 1(b)所示的光限制几何排布下，具有正非线性折射系数的输入和输出的特征关系曲线，$C=|\Delta\varphi_0|$

(a) $x=-0.85$, (b) $x=0$, (c) $x=0.85$

ments of optical-limiting media with cubic nonlinearities in infrared focused optical-detecting systems on optical limiting. The optimum geometry arrangements in these systems are discussed. It is noted that in the geometry arrangement depicted in Fig. 1(a) the nonlinear media with positive nonlinear index can not be employed as optical-limiting media, which is different from previous suggestions for the far-field geometry arrangements. The geometry arrangements discussed in this paper can also be employed for measurements of nonlinear refraction with a higher sensitivity than that of common Z-scan.

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