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Simulation analysis of evolution of hot-images induced by coplanar multi-scatterers*

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Based on the diffraction theory model for hot-image formation, the evolution of hot-images induced by multi-scatterers located in the same plane perpendicular to the propagation axis is numerically simulated. The simulation results show that hot-images induced by coplanar multi-scatterers are also coplanar no matter whether they exist simultaneously or severally. However, if they exist simultaneously the peak intensity of the primary hot-images is weaker than if they exist severally. The unequal competition for energy between the scattered beams from the scatterers leads to the fact that part of the corresponding hot-images are relatively enhanced and the others are restrained. The results show that the hot-images of certain scatterers become stronger when any of these parameters, i.e. amplitude modulation coefficient, phase modulation coefficient and size of the surrounding scatterer, decrease.

Keywords: hot-image, small-scale self-focusing, optical damage, scatterer
PACC: 4265J

1. Introduction

The hot-image effect in high-power laser systems is a special small-scale self-focusing effect. It can damage not only nonlinear mediums in the systems, but also certain optical components, even if the systems operate at an intensity level under a typical damage threshold.[1−3] As one of the key factors restricting the performance and the output power of high-power laser systems, the hot-image effect has aroused widespread interest from the high-power laser community for a long time. A lot of research has been done on the evolution of hot-images induced by a single scatterer,[1−9] but so far little work has been done on those induced by multi-scatterers, such as contamination, dust, optical component defects, etc. The inertial confinement fusion (ICF) laser driver system is a huge and complicated system, in which there exists usually more than one scatterer. Once some kinds of conditions are satisfied, each scatterer can induce hot-images. Thus, it is even more useful to investigate hot-images induced by multi-scatterers.

In the formation of hot-images induced by multi-scatterers, it is also necessary to know whether the surrounding scatterers have an influence on the hot-image effect induced by a certain scatterer and, if so, how they exert an influence on it when some parameters of the surrounding scatterers are changed. In the present paper we numerically investigate the evolution of hot-images induced by multi-scatterers located in the same plane perpendicular to the propagation axis and the influence of the scatterer parameters on the hot-image.

2. Diffraction theory model for hot-images induced by multi-scatterers

The diffraction theory model for hot-images induced by multi-scatterers can be simply described as follows. As shown in Fig.1, if some small scatterers exist in an optical system including a nonlinear medium and are irradiated by an intense laser beam, the scattered beams induced by the scatterers will interact with the original beam in the downstream nonlinear medium and then collect energy from the original beam. Therefore the energy distribution of the laser beam will be changed after propagating through

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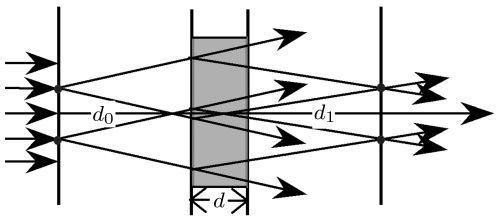


Fig.1. Formation mechanism of hot-images induced by multi-scatterers.

the nonlinear medium, and several corresponding hot-images with high intensity (several times greater than that of the original beam) will be generated in certain downstream planes. Certainly, the propagation processes of the laser beam in free space and in a nonlinear medium are different, and they can be described by

$$\nabla_{\perp}^2 E + 2\mathrm{i}k\frac{\partial E}{\partial z} = 0, \tag{1}$$

and

$$\nabla_{\perp}^2 E + 2\mathrm{i}k_0\frac{\partial E}{\partial z} = -k_0^2\frac{\gamma}{n_0}|E|^2 E + \mathrm{i}k_0(\alpha-\beta)E, \tag{2}$$

respectively, where $\nabla_{\perp}^2 = \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2}$, E is the complex amplitude of the laser beam, the z-axis is along the beam propagating direction, k is the wave number in free space, k_0 is the wave number in the nonlinear medium, n_0 is the refractive index of the nonlinear medium, γ is the nonlinear index coefficient, α is the gain coefficient and β is the loss coefficient.

According to the theory of small-scale self-focusing,[10−12] different spatial frequencies in the scattered beams correspond to different growth rates of the frequency spectrum, so different scattered beams collect different amounts of energy and form hot-images with different intensities. When several scatterers exist simultaneously in the optical system, the same spatial frequencies in different scatterers will collect energy from the original beam, so that energy competition may take place in the formation process of the hot-images. The hot-images induced by some of the scatterers are restrained because they are in the inferior position of the energy competition, while the hot-images induced by the other scatterers may be relatively strengthened.

3. Hot-images induced by two scatterers

3.1. Evolution process of hot-images

To start with, we numerically simulate the evolution process of hot-images induced by two scatterers located in the same plane perpendicular to the propagation axis. Here the beam propagation process in free space is treated by using the theory of diffraction, while that in the nonlinear medium is dealt with by means of a split-step-Fourier-transform. The area of the sampling region is taken as 2 cm × 2 cm and further divided into 1024 × 1024 pixels. The parameters of the nonlinear medium are assumed as follows: thickness d = 20 cm, refractive index n_0 = 1.528, nonlinear index coefficient $\gamma = 3.153\times10^{-16}$ cm^2/W, gain coefficient α = 0.05 cm^{-1}, loss β = 0.04 cm^{-1}. The input laser beam is assumed to be a Gaussian beam with wavelength λ = 1.053 μm, peak intensity I_0 = 4 GW/cm^2, and beam radius ω_0 = 0.3 cm. Both scatterers are considered to be translucent circular flecks each with radius r = 0.02 cm, amplitude modulation coefficient τ = 0.8, and phase modulation coefficient θ = 0.8 π. Their centre coordinates are given as (0 cm, 0.03 cm) and (0 cm, –0.03 cm), respectively. The distance between the scatterer plane and the front surface of the nonlinear medium is taken as 100 cm.

Figures 2 and 3 show the evolution process (after propagation through the back surface of the nonlinear medium) of the hot-images induced by both of the two scatterers and by one of them, respectively. Figure 4 depicts the numerical simulation results of the peak intensity of the beam at different distances from the back surface of the nonlinear medium when the two scatterers separately exist simultaneously and severally. Figure 5 and 6 reveals the intensity distributions in the primary and the second-order hot-image plane respectively. It is obvious that the hot-images (primary or second order) induced by the two scatterers also appear in the same plane no matter whether they exist simultaneously or severally. However, if the two scatterers exist simultaneously, the peak intensity of the primary hot-image is weaker than if they exist severally. The reason for this may be the fact that the two scattered beams have the same spatial frequencies, and they absorb energy from the original beam synchronously and compete with each other. So each

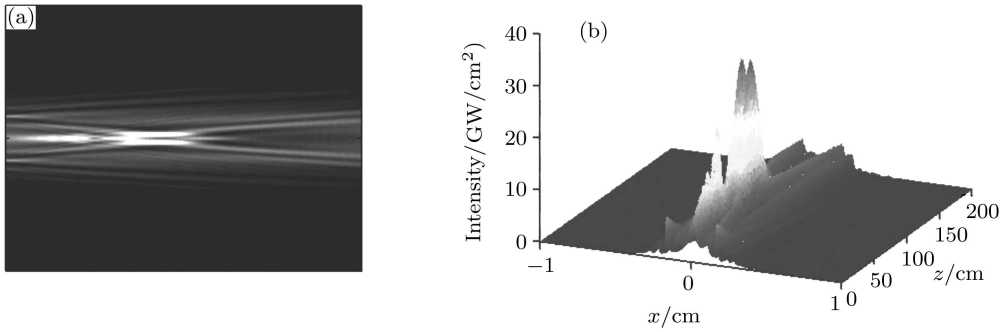


Fig.2. Evolution process of hot-images induced by two scatterers with (a) two dimensions and (b) three dimensions.

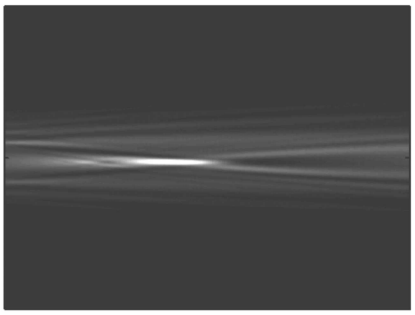


Fig.3. Evolution process of a hot-image induced by a single scatterer corresponding to one of the two scatterers.

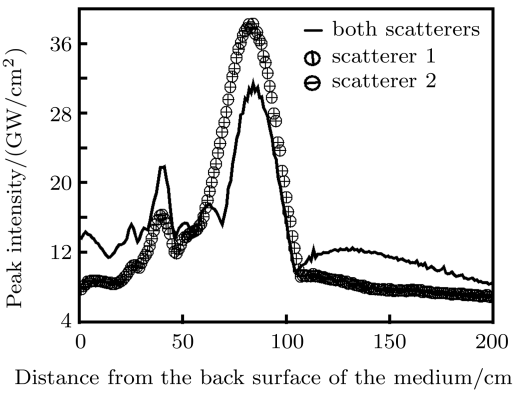


Fig.4. Peak intensities of the beam at different distances from the back surface of the nonlinear medium when the two scatterers, separately, exist simultaneously and severally.

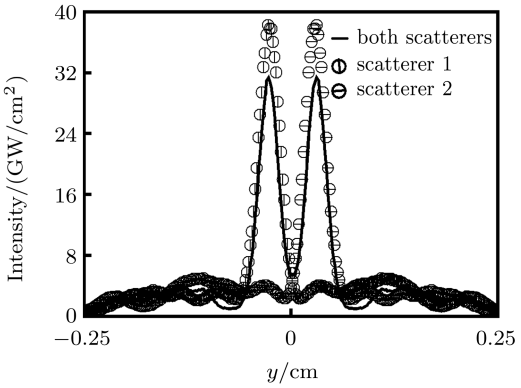


Fig.5. Intensity distributions of primary hot-images induced by two scatterers separately existing simultaneously and severally.

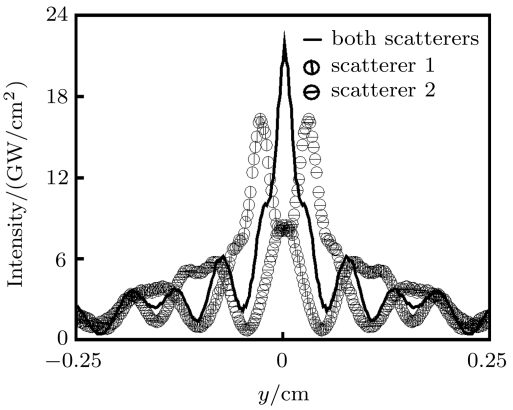


Fig.6. Intensity distributions of second-order hot-images induced by two scatterers separately existing simultaneously and severally.

spatial frequency absorbs a smaller amount of energy than when the scatterer exists severally. Finally the energy distribution of the primary hot-image induced by each scatterer is less than that when the scatterer exists severally.

3.2. Influence of scatterer parameters on hot-images

3.2.1. Phase modulation coefficients of scatterers

According to the theory of nonlinear wave coupling, energy competitions between the scattered

beams induced by the two scatterers are unequal when the phase modulation coefficients are different. In general, one of the hot-images induced by the two scatterers is relatively enhanced and the other is restrained. Figure 7 demonstrates the peak intensities of the beam at different distances from the back surface of the nonlinear medium in the case of two scatterers with different phase modulation coefficients (the other parameters of the two scatterers are kept unchanged). Figure 8 gives the corresponding intensity distributions in the primary hot-image plane. The peak intensity of the primary hot-image, which is induced by the scatterer with a phase modulation coefficient of 0.8 π, increases with the decrease of the phase modulation coefficient of the other scatterer. It proves that the scattered beam with a larger phase modulation coefficient in the region of (0, π) will stand in an advantageous point in the energy competition, and the superiority becomes more evident with the increase of the difference in phase modulation coefficient between the two scatterers. Acoording to the expression about the peak intensity of the hot-image in a laser system with a single medium in Ref.[2], $I = \exp[(\beta-\alpha)d][1+(1+\tau^2-2\tau\cos\theta)B^2+2\tau\sin\theta]A^2$, if $\tau = 0.8$, the peak intensities of the hot-images in the order of their magnitudes from small to large is in the sequence of phase modulation coefficients of 0.2 π, 0.4 π, and 0.8 π, that is to say, the scatterer with a larger phase modulation coefficient possesses a stronger competitiveness in the energy competition. So the hot-image of the scatterer with $\theta = 0.8\ \pi$ becomes weaker when the phase modulation coefficient of the surrounding scatterer becomes larger.

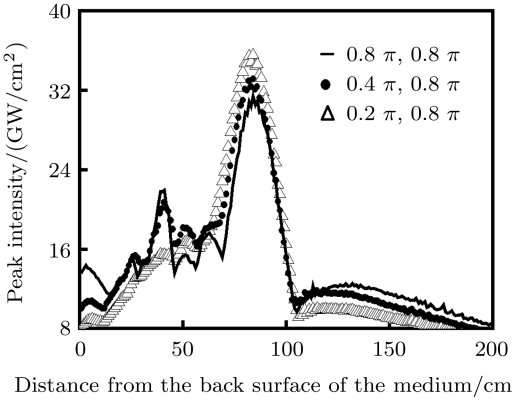


Fig.7. Peak intensities of the beam at different distances from the back surface of the nonlinear medium, induced by two scatterers with different phase modulation coefficients.

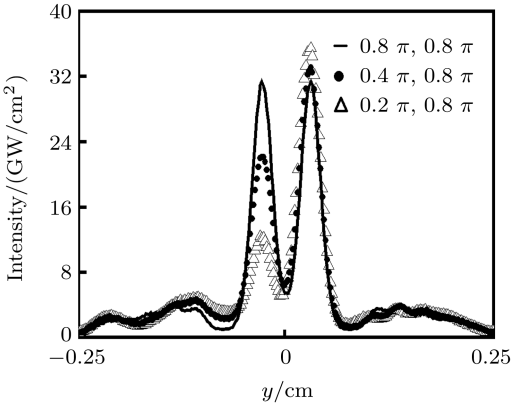


Fig.8. Intensity distributions of primary hot-images induced by two scatterers with different phase modulation coefficients.

3.2.2. Amplitude modulation coefficients of scatterers

It was also found that when the amplitude modulation coefficients of the two scatterers are different, the energy competitions between the two corresponding scattered beams are also unequal. One of the hot-images induced by the two scatterers is relatively enhanced and the other is restrained. Figure 9 shows the peak intensities of the beam at different distances from the back surface of the nonlinear medium in the case of two scatterers with different amplitude modulation coefficients (the other parameters of the two scatterers are kept unchanged). Figure 10 gives the corresponding intensity distributions in the primary hot-image plane. The peak intensity of the primary hot-image, which is induced by the scatterer with an amplitude modulation coefficient of 0.8, increases with the decrease of the amplitude modulation coefficient of the other scatterer. This proves that the scattered beam with a larger amplitude modulation coefficient will be in an advantageous position in the energy competition and the superiority becomes more evident with the increase of the difference in amplitude modulation coefficient between the two scatterers. According to the expression in Ref.[2], $I = \exp[(\beta-\alpha)d][1+(1+\tau^2-2\tau\cos\theta)B^2+2\tau\sin\theta]A^2$, when $\theta = 0.8\ \pi$, the scatterer with a larger amplitude modulation coefficient absorbs more energy from the original beam. So if the two scatterers exist simultaneously, the scatterer with a larger amplitude modulation coefficient has a stronger competitiveness in the energy competition.

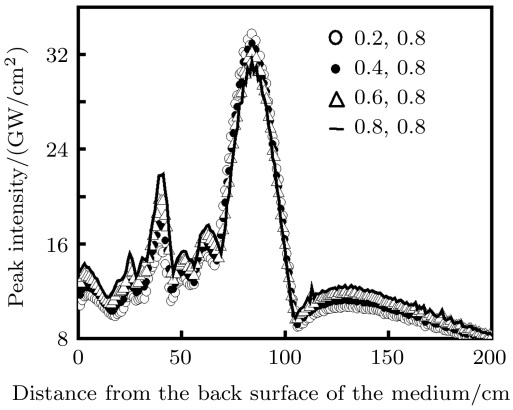


Fig.9. Peak intensities of the beam at different distances from the back surface of the nonlinear medium, induced by two scatterers with different amplitude modulation coefficients.

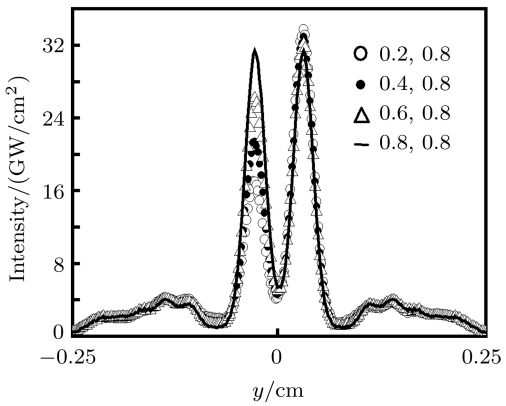


Fig.10. Intensity distributions of the primary hot-images induced by two scatterers with different amplitude modulation coefficients.

3.2.3. Sizes of scatterers

If the sizes of the two scatterers are different, the energy competitions between the scattered beams are also unequal. One of the hot-images induced by the two scatterers is relatively strengthened and the other is restrained. Figure 11 shows the peak intensities of the beam at different distances from the back surface of the nonlinear medium in the case of two scatterers with different sizes (the other parameters of the two scatterers are kept unchanged). Figure 12 gives the corresponding intensity distributions in the primary hot-image plane. The peak intensity of the primary hot-image, which is induced by the scatterer with a size of 0.02 cm, increases with the decrease of the size of the other scatterer. This shows that the scattered beam from the scatterer with a large size will be in an advantageous position in the energy competition and the superiority becomes more obvious with the increase of difference in size between the two scatterers. According to the theory of small-scale self-focusing,[10−12] the larger scatterer results in a more serious modulation of the beam and leads to a stronger hot-image effect. That means that the competitiveness of the surrounding scatterers (corresponding to the scatterer with a size of 0.02 cm) is stronger in the energy competition when their sizes become larger, and therefore the hot-image of the scatterer with a size of 0.02 cm decreases correspondingly.

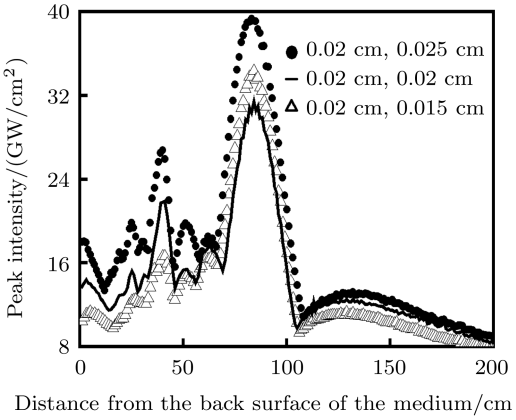


Fig.11. Peak intensities of the beam at different distances from the back surface of the nonlinear medium in the case of two scatterers with different sizes.

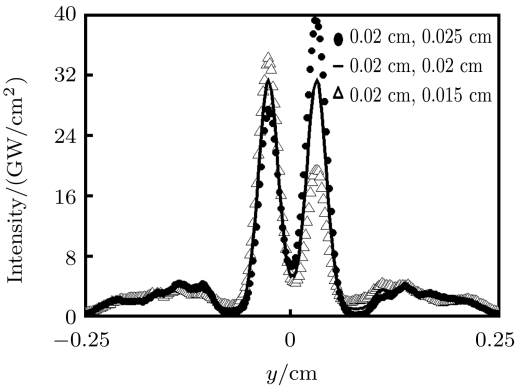


Fig.12. Intensity distributions of the primary hot-images induced by two scatterers with different sizes.

4. Hot-images induced by multi-scatterers

We have also simulated the evolution process of hot-images induced by more than two coplanar scatterers. It is shown that when several scatterers located in the same plane perpendicular to the propagation axis exist simultaneously, the corresponding

hot-images will be also coplanar and appear simultaneously, but the peak intensity of the primary hot-images is weaker than that of the hot-images induced by the scatterers existing severally. Figure 13 shows the front projections of the intensity distributions of the primary hot-images induced by three coplanar scatterers. Figure 14 indicates the corresponding intensity distributions in the primary hot-image plane. Figure 15 gives the front projections of the intensity distributions of the primary hot-images induced by five coplanar but noncollinear scatterers. Here the hot-image effect induced by the scatterer in the centre is restrained to a certain degree. Figure 16 displays the front projections of the intensity distributions of the primary hot-image induced by five coplanar and collinear scatterers. It is shown that only four bright spots can be seen because one of the scatterers is in a disadvantageous position in the energy competition, so that the evident hot-image cannot be seen clearly in the corresponding positions.



Fig.13. Front projections of the intensity distributions of primary hot-images induced by three coplanar scatterers.

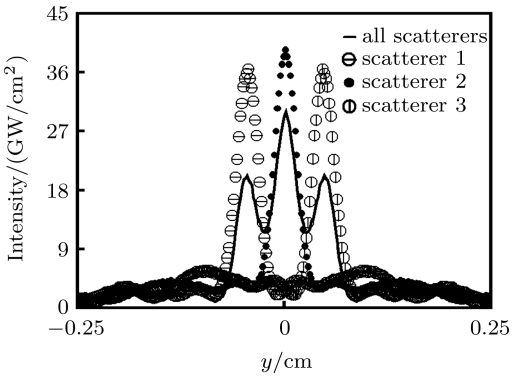


Fig.14. Intensity distributions of primary hot-images induced by three coplanar scatterers separately existing simultaneously and severally.

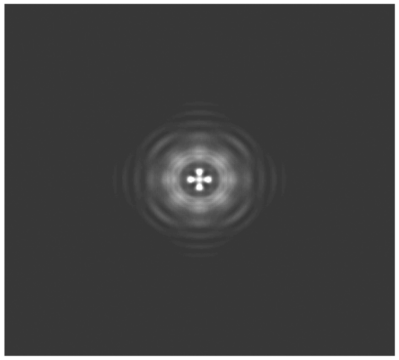


Fig.15. Front projections of the intensity distributions of primary hot-images induced by five coplanar but noncollinear scatterers.



Fig.16. Front projections of intensity distributions of primary hot-images induced by five coplanar and collinear scatterers.

5. Conclusions

We have numerically analysed the evolution of hot-images induced by multi-scatterers located in the same plane perpendicular to the propagation axis and the influence of the scatterer parameters on the hot-image effects. The numerical simulation results show that hot-images induced by coplanar multi-scatterers appear in the same plane no matter whether the scatterers exist simultaneously or severally. However, if they exist simultaneously, the peak intensity of the corresponding primary hot-images is weaker than when they exist severally. Moreover, the energy competitions between the scattered beams are unequal due to the different parameters of the scatterers. As a result, part of the hot-images are relatively enhanced and others restrained. The results indicate that the competitiveness of the surrounding scatterers decreases in the energy competition when

any of these parameters, i.e. amplitude modulation coefficient, phase modulation coefficient and size of them, become smaller with other parameters kept unchanged. As a result, the hot-images of certain scatterers become stronger correspondingly.

References

[1] Hunt J T, Manes K R and Renard P A 1993 *Appl. Opt.* **32** 5973

[2] Xie L P, Jing F, Zhao J L, Su J Q, Wang W Y and Peng H S 2004 *Opt. Commun.* **236** 343

[3] Francois Y G, Feit M D, Kozlowski M R, Rubenchik A M, Salleo A and Yoshiyama J 2000 *Appl. Opt.* **39** 3654

[4] Widmayer C C, Milam D and de Szoeke S P 1997 *Appl. Opt.* **36** 9342

[5] Xie L P, Zhao J L and Jing F 2005 *Appl. Opt.* **44** 2553

[6] Xie L P, Zhao J L, Su J Q, Jing F, Wang W Y and Peng H S 2004 *Acta Phys. Sin.* **53** 2175 (in Chinese)

[7] Peng T, Zhao J L, Xie L P, Ye Z J, Li Q and Su J Q 2007 *Acta Phys. Sin.* **56** 3255 (in Chinese)

[8] Wang Y W, Hu Y H, Wen S C, You K M and Fu X Q 2007 *Acta Phys. Sin.* **56** 5855 (in Chinese)

[9] Peng T, Zhao J L, Xie L P, Ye Z J, Wei H H, Su J Q and Zhao J P 2007 *Appl. Opt.* **46** 3205

[10] Bespalov V I and Talanov V I 1966 *JETP Lett.* **3** 307

[11] Campillo A J, Shapiro S L and Suydam B R 1973 *Appl. Phys. Lett.* **13** 628

[12] Fleck J A, Morris J R and Bliss E S 1978 *IEEE J. Quantum Electron.* **14** 353