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Project Report

LTP-41

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R. C. Harney

Oscillatory Beam Quality
Effects in Modular High
Energy Laser Systems

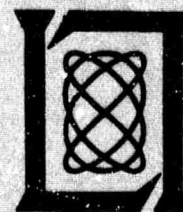
15 May 1980

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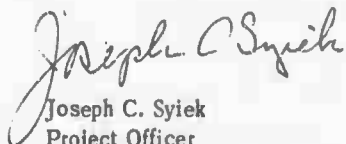
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FOR THE COMMANDER

A handwritten signature in dark ink, appearing to read "Joseph C. Syiek". The signature is fluid and cursive, with the first name "Joseph" and last name "Syiek" clearly distinguishable.

Joseph C. Syiek
Project Officer
Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

OSCILLATORY BEAM QUALITY EFFECTS IN
MODULAR HIGH ENERGY LASER SYSTEMS

R. C. HARNEY

Group 53

PROJECT REPORT LTP-41

15 MAY 1980

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ABSTRACT

The amplitude of the major phase distortions in in-line modular chemical laser systems increases linearly with the number of modules. The beam quality of a model modular linear-gain laser has been examined as a function of the amplitude of the phase distortion by propagating the distorted output beams to a distant focus using the Lincoln Laboratory laser propagation code. Oscillations are observed in both the peak intensity and the far field area containing 63% of the laser flux. The observed oscillatory behavior is not strongly dependent on the shape of the phase distortion. The implications of this behavior for modular laser design are discussed and extended to modular annular gain lasers.

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I. INTRODUCTION

Under the conditions of saturated gain which are necessary for efficient energy extraction, the output power of a CW chemical laser using an unstable resonator is proportional to the volume of the gain medium. Practical considerations limit the size of the transverse dimensions of the gain medium. Increased output power must therefore be obtained at the expense of increased length. One proposed technique for constructing long chemical laser systems is to place a number of identical laser modules end-to-end within the laser cavity. This modular approach avoids the engineering problem of building a single large device for generating the gain medium, allows for some flexibility in achieving the desired output power (by adding extra modules should efficiencies prove to be less than calculated), and makes repair of the laser easier (an entire module can be replaced more easily than a single large system can be repaired). The output beams of CW chemical lasers may be aberrated by phase distortions induced by the gain medium. These phase distortions are due to such effects as shock waves, mixing inhomogeneities, turbulence, etc. In a modular laser system the large-scale phase distortions will be identical from module to module. Since these modules are arranged such that the laser beam passes sequentially through the gain medium produced by each module, the amplitude of the phase distortion (transverse to the direction of propagation of the laser beam) from each module will add linearly to the amplitude of the transverse phase distortions of the other modules. Consequently, as the number of modules in the system is increased, the total

amplitude (but not the shape) of the phase distortion is increased.

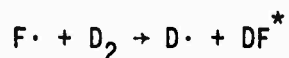
In this work we have investigated the behavior of the beam quality of a model chemical laser as a function of the amplitude of the phase distortion (or as a function of the number of modules). First, simple models are obtained for the expected large-scale phase profile of the output from a typical CW chemical laser. Next, using the Lincoln Laboratory laser propagation code the far field intensity patterns are calculated for a number of laser beams with varying amplitudes of the model phase profiles. From the far field intensity patterns, plots are obtained of both the peak intensity and the 63% flux area as functions of the amplitude of the phase distortions. For the phase profiles chosen, oscillations are observed in both of these indicators of beam quality. The dependence of this behavior on the size and shape of the phase distortions is analyzed and simple physical arguments for the existence of oscillations are presented. Finally, the implications of this oscillatory behavior for system design and utilization are discussed.

II. MODEL PHASE PROFILES

One useful form of CW chemical laser operates in the following manner. Gaseous ethylene (C_2H_4) is mixed with nitrogen trifluoride (NF_3) or fluorine gas (F_2) to produce free fluorine atoms in an incomplete combustion process



The hot reaction products are then mixed with deuterium gas (D_2) to produce excited deuterium fluoride (DF^*) in the reaction



The excited DF provides the optical gain for the laser. A schematic diagram of a "typical" laser module using this reaction sequence is shown in Figure 1. The flow field and the approximate size of the laser beam are also indicated on the figure. The expansion zones at the edges of the flow have a generally lower density (and refractive index) than the average over the portion of the gain medium encompassed by the laser beam and thus these regions tend to produce a smaller than average overall phase shift to an optical wave. The strut wakes on the other hand have a higher than average refractive index and will produce a larger than average overall phase shift. We will ignore small-scale phase perturbations and turbulence. To a reasonable approximation the phase shift profile of the gain medium is reflected in the phase profile of the output laser beam. The validity of the approximation depends on the geometry of the laser resonator. It is better for ring unstable resonators than for conventional unstable resonators. Diffraction inside the cavity may also be an important consideration. However, it is negligible when $\lambda L/a^2 \ll 1$ where L is the cavity length, λ is the wavelength, and a is the scale size of the phase distortions.

The optical gain in the phase-distorted regions may differ from that in the remainder of the laser medium. Since the laser operates in saturation

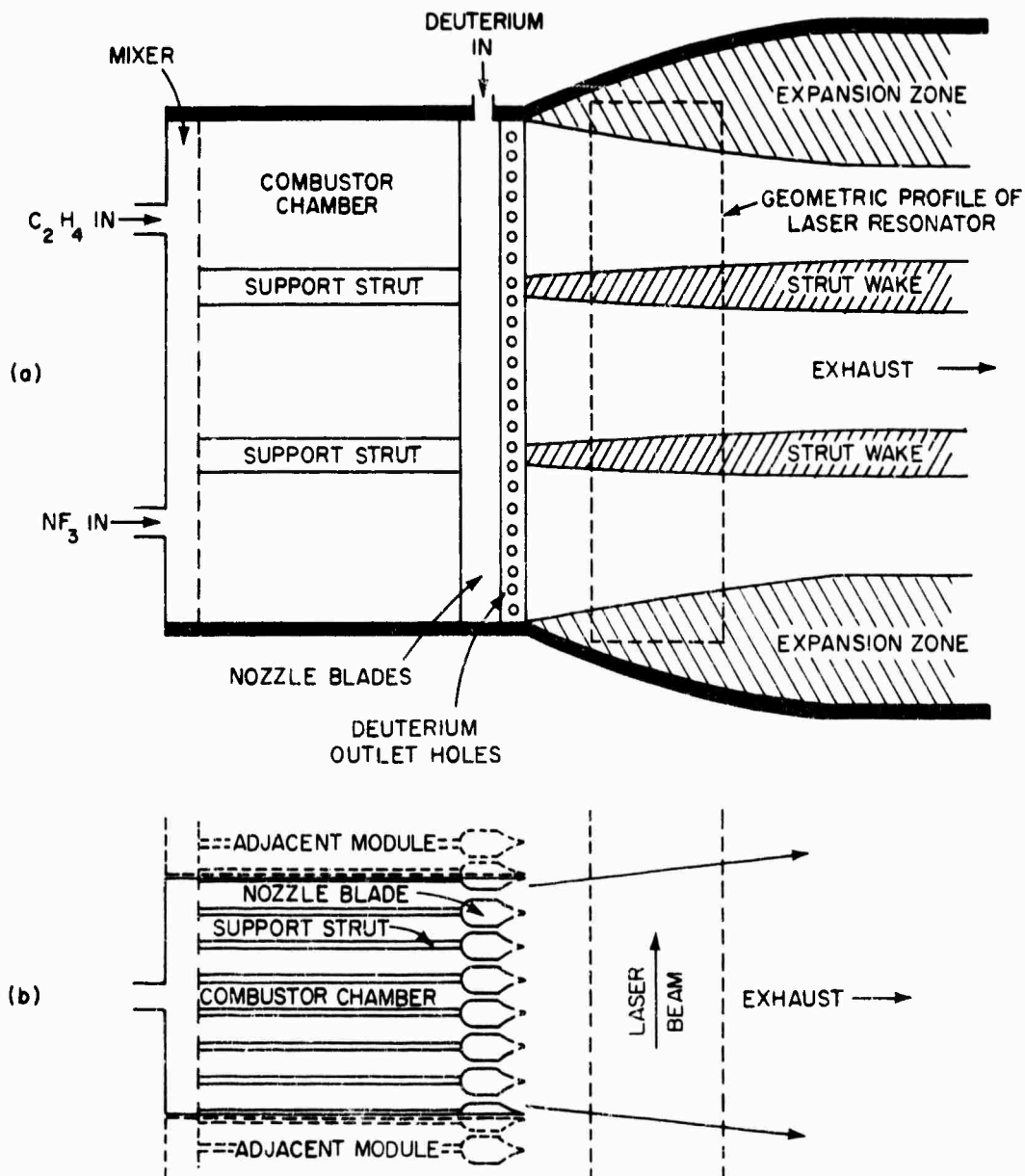


Fig. 1. Schematic diagram of a CW chemical laser module. (a) Side view. The strut wakes and expansion zones are the major phase distorting features of the gain medium. The dotted line encloses the portion of the gain medium utilized by the laser resonator. (b) Top view.

the resulting distortion in the intensity profile will also increase linearly with the number of modules. Since an intensity distortion will affect the beam quality in a manner similar to that of a phase distortion, consideration of phase distortions alone will suffice for studying the qualitative behavior of the beam quality as the number of modules is increased.

After shaping the beam to fit a circular aperture and assuming a uniform intensity profile across that aperture, a phase profile of the form of Figure 2 is obtained for our model laser. Real unstable resonators have partially obscured apertures which further distort the output phases and the far field intensity distributions. However, ignoring this fact greatly simplifies the calculations and should not substantially alter any qualitative phenomena which may occur. Therefore, we will henceforth assume a laser beam with a uniform intensity distribution and a phase profile of the form of Figure 2. The exact shape of the phase profile was chosen (for reasons of calculational simplicity) to have one of two forms:

Gaussian

$$\phi_1(x,y) = \chi \left\{ \exp \left[- \left(y - (r/3) \right)^2 / a^2 \right] + \exp \left[- \left(y + (r/3) \right)^2 / a^2 \right] - \exp \left[- (y-r)^2 / a^2 \right] - \exp \left[- (y+r)^2 / a^2 \right] \right\}$$

Parabolic

$$\phi_2(x,y) = \chi \left\{ \left[1 - (y - (r/3))^2 / a^2 \right] + \left[1 - (y + (r/3))^2 / a^2 \right] - \left[1 - (y-r)^2 / a^2 \right] - \left[1 - (y+r)^2 / a^2 \right] \right\}$$

where χ and a are adjustable parameters and r is the radius of the aperture. In the parabolic phase profile each parabolic term $[1-F^2]$ is assumed to be zero when $|F| > 1$. The exact profiles (for $a = r/12$) are shown along the

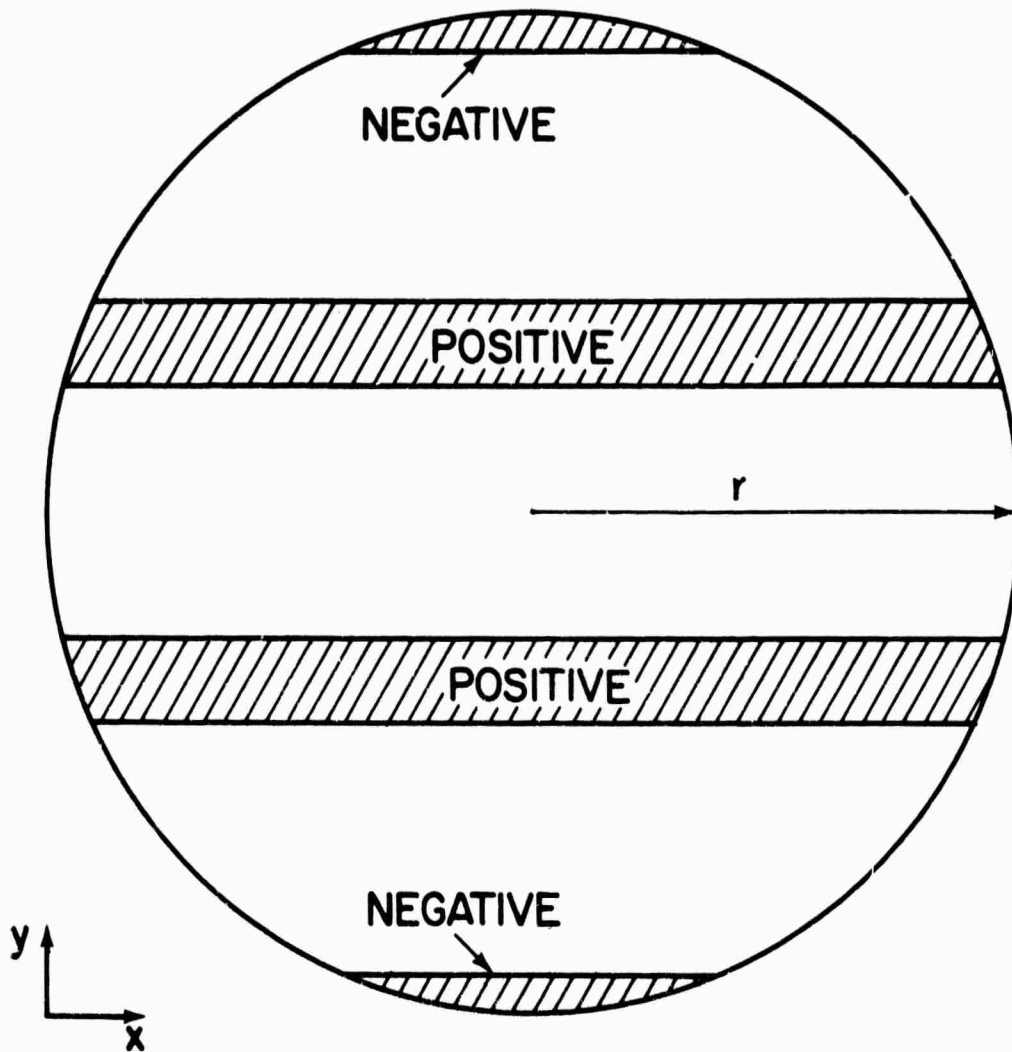


Fig. 2. Representation of the aperture of the laser beam showing the relative sizes and placement of the phase-distorted regions.

line $x = 0$ in Figures 3 and 4. The gaussian profile was chosen because it lacks sharp phase gradients and affects the phase over the whole aperture. The parabolic phase profile was chosen for the opposite reasons; it has infinite phase gradients yet is of finite extent. Thus phenomena which occur for both profiles can be assumed to occur for any profile which has the qualitative form of Figure 2.

III. COMPUTATIONAL PROCEDURES

The data presented in the next section were obtained in the following manner. First, the desired aperture phase profile is calculated from the expressions for ϕ_1 and ϕ_2 for the desired values of the phase distortion amplitude, χ , and distortion scale size, a . A uniform intensity distribution of arbitrary amplitude (but constant for all calculations) is specified within the aperture while the intensity outside the aperture is set to zero. Next, the far field intensity distribution corresponding to the aperture phase and intensity distribution is calculated using the Lincoln Laboratory laser propagation code. For linear propagation, this code calculates the far field intensity distribution using a discrete Fourier transform algorithm. The physical size of this distribution scales with the laser wavelength λ and the focal distance f , and scales inversely with the aperture diameter $2r$. For this reason all distances will be represented in units of $\lambda f/2r$. A typical far field intensity distribution calculated by the code is shown in Figure 5. The example shown is for a parabolic phase distortion with $\chi = \pi$ and $a = r/12$. Although the intensity is plotted in arbitrary units, alternate iso-intensity contours are

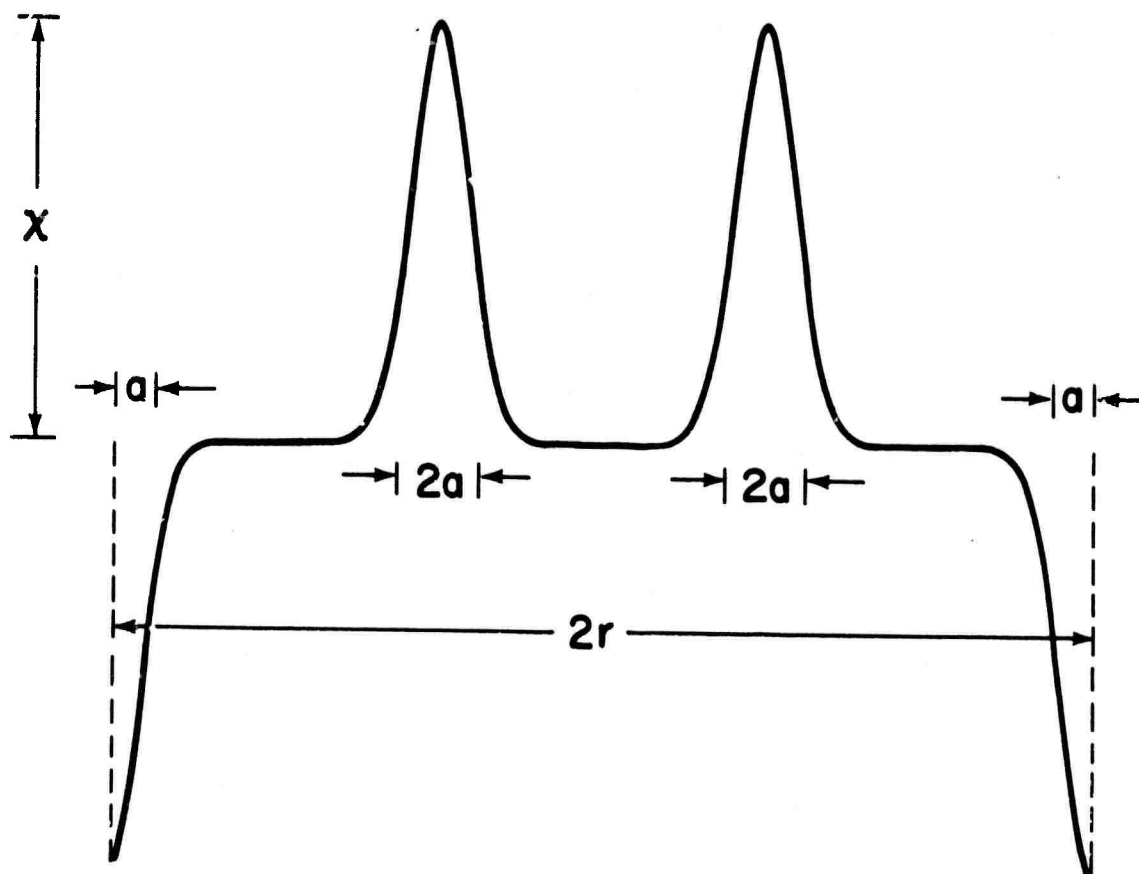


Fig. 3. Gaussian approximation to the laser phase profile. The example shown is for $a = r/12$. The amplitude x (measured in fractions of a wavelength λ/m or radians $2\pi/m$) is drawn greatly exaggerated with respect to the transverse scale length $2r$.

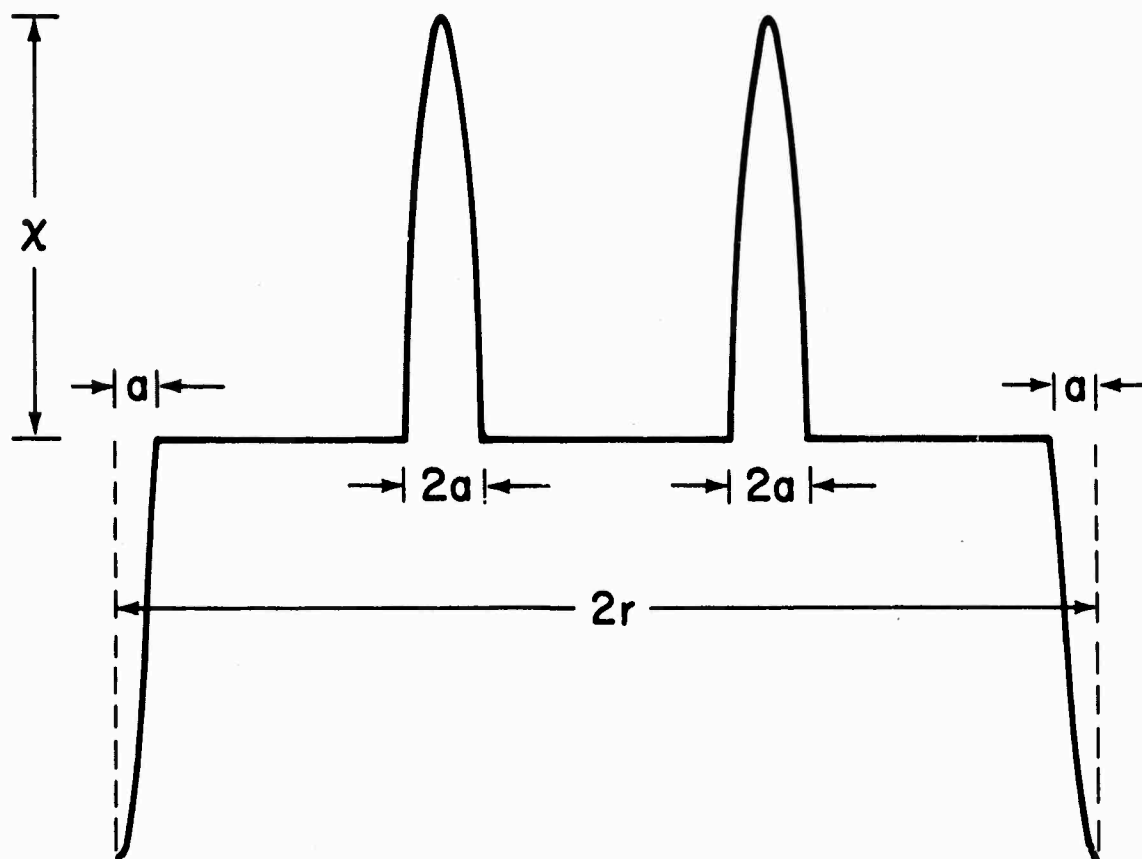


Fig. 4. Parabolic approximation to the laser phase profile. The example shown is for $a = r/12$. The amplitude χ (measured in fractions of a wavelength λ/m or radians $2\pi/m$) is drawn greatly exaggerated with respect to the transverse scale length $2r$.

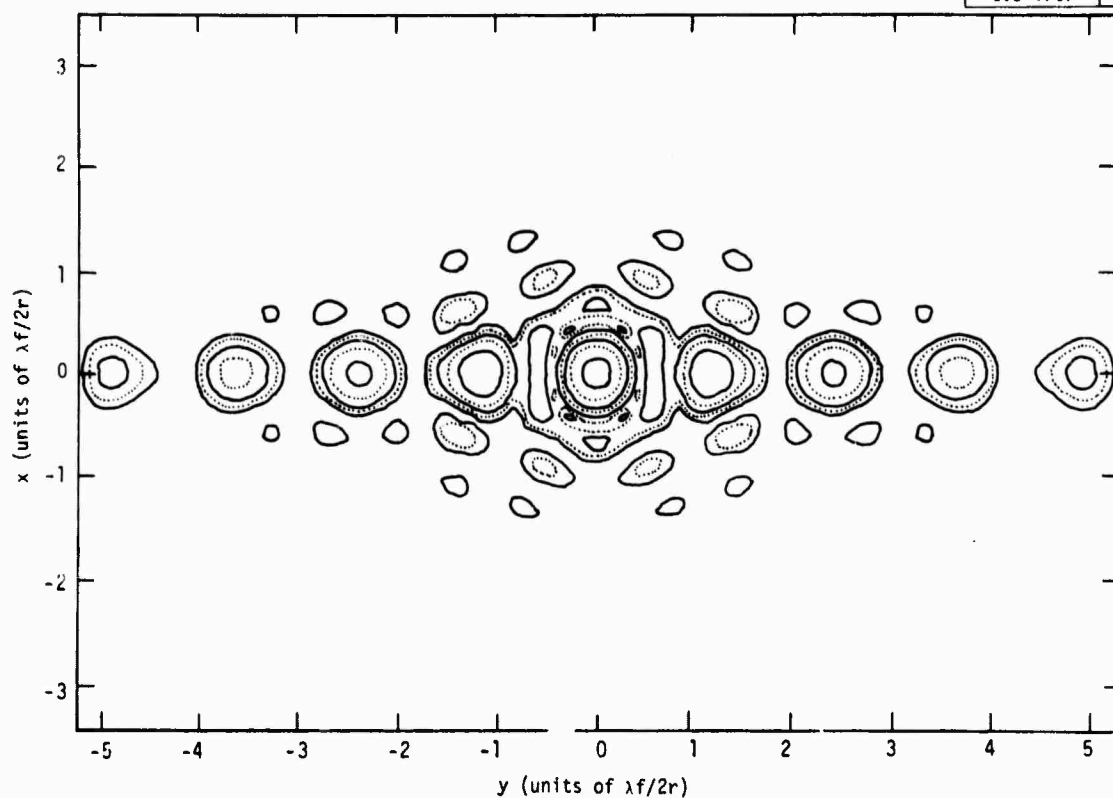


Fig. 5. Far field intensity distribution of the parabolic phase profile with $\chi = \pi$ and $a = r/12$. The transverse dimensions x and y are in units of $\lambda f/2r$. The intensity is plotted in arbitrary units, however, alternate iso-intensity contours are separated by 4 dB.

separated by 4 dB. From the far field intensity distribution the code next calculates flux-in-a-bucket curves through point-by-point integration. Both circular flux buckets and buckets whose shape follows the iso-intensity contours are used. The curves obtained for the example of Figure 5 are shown in Figure 6.

Two different parameters were chosen as indicators of the laser beam quality: the peak focused intensity and the focused spot size. The peak focused intensity I_{MAX} is obtained directly from the far field intensity distribution. The focused spot size, on the other hand, is obtained from the flux-in-a-bucket curves. The focused spot size A is assumed to be equal to πR^2 where R is the equivalent radius of the flux bucket which contains 63% of the total laser power. Because the effective average intensity of the focused laser beam is better approximated by $P/A_{contour}$ than by $P/A_{circular}$ (P is the total laser power) for a distorted beam, all areas used in the next section will be those calculated using contour flux buckets.

IV. RESULTS AND DISCUSSION

Using the procedures described in the preceding section, the peak intensity and the focused spot size were calculated for values of χ between 0 and 4π (increments of $\pi/4$) for the following cases:

- 1) gaussian phase distortion with $a = r/24$
- 2) gaussian phase distortion with $a = r/12$
- 3) parabolic phase distortion with $a = r/24$
- 4) parabolic phase distortion with $a = r/12$

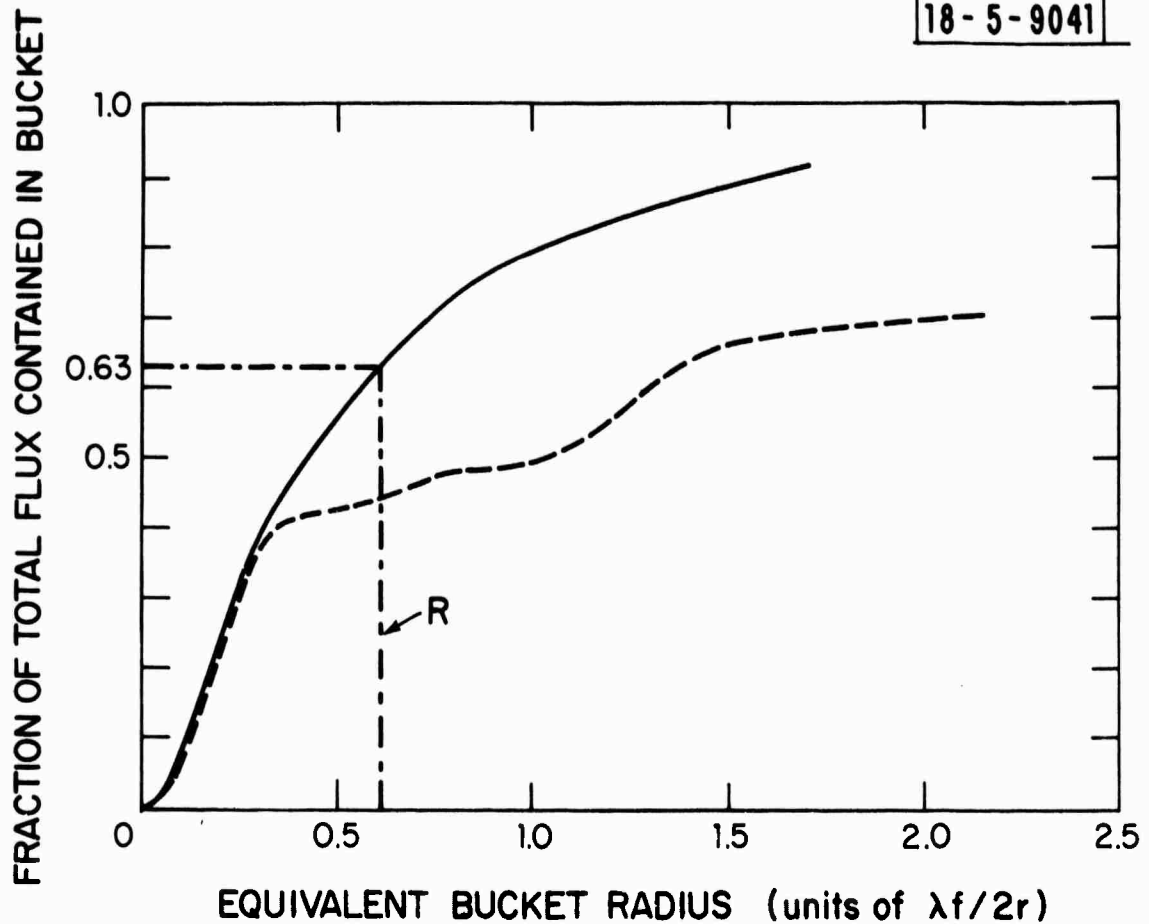


Fig. 6. Flux-in-a-bucket curves for the parabolic phase profile with $\chi = \pi$ and $a = r/12$. The dotted curve represents the result obtained with circular flux buckets; the solid curve represents the result obtained with contour flux buckets.² The area containing 63% of the total focused laser flux is given by πR^2 .

The results are plotted as smoothed curves in Figures 7-10. As expected the decrease in beam quality (as evidenced by either the peak intensity decrease or the increase in spot size relative to that of a beam with no phase distortion) for $a = r/12$ is larger than that for $a = r/24$ at all values of χ . What is, at first, unexpected is the appearance of substantial oscillations in the beam quality as the amplitude of the phase distortion is varied. The oscillations are real and not artifacts of the calculation because they persist even when the mesh size used for the discrete Fourier transform is varied.

Naive arguments favor a monotonic decrease in beam quality as χ is increased. However, the following simple physical arguments show why the oscillations should occur. Consider a one-dimensional aperture divided into two halves. For uniform illumination the Fourier transform of the electric field in each subaperture has the form $\sin x/x$. The far field intensity distribution is given by the square of the sum of the Fourier transforms from the two subapertures. If a phase shift which is linear with position is applied to one subaperture (but not to the other) the position of its $\sin x/x$ Fourier transform will be shifted with respect to the $\sin x/x$ transform of the second subaperture. The magnitude of the position shift is proportional to the slope of the linear phase shift. Because $\sin x/x$ changes sign in an oscillatory manner as x increases, the sum of the two Fourier transforms (and hence the intensity distribution) will radically change shape as the relative separation between the two transforms is increased. That is, the oscillation in peak intensity arises

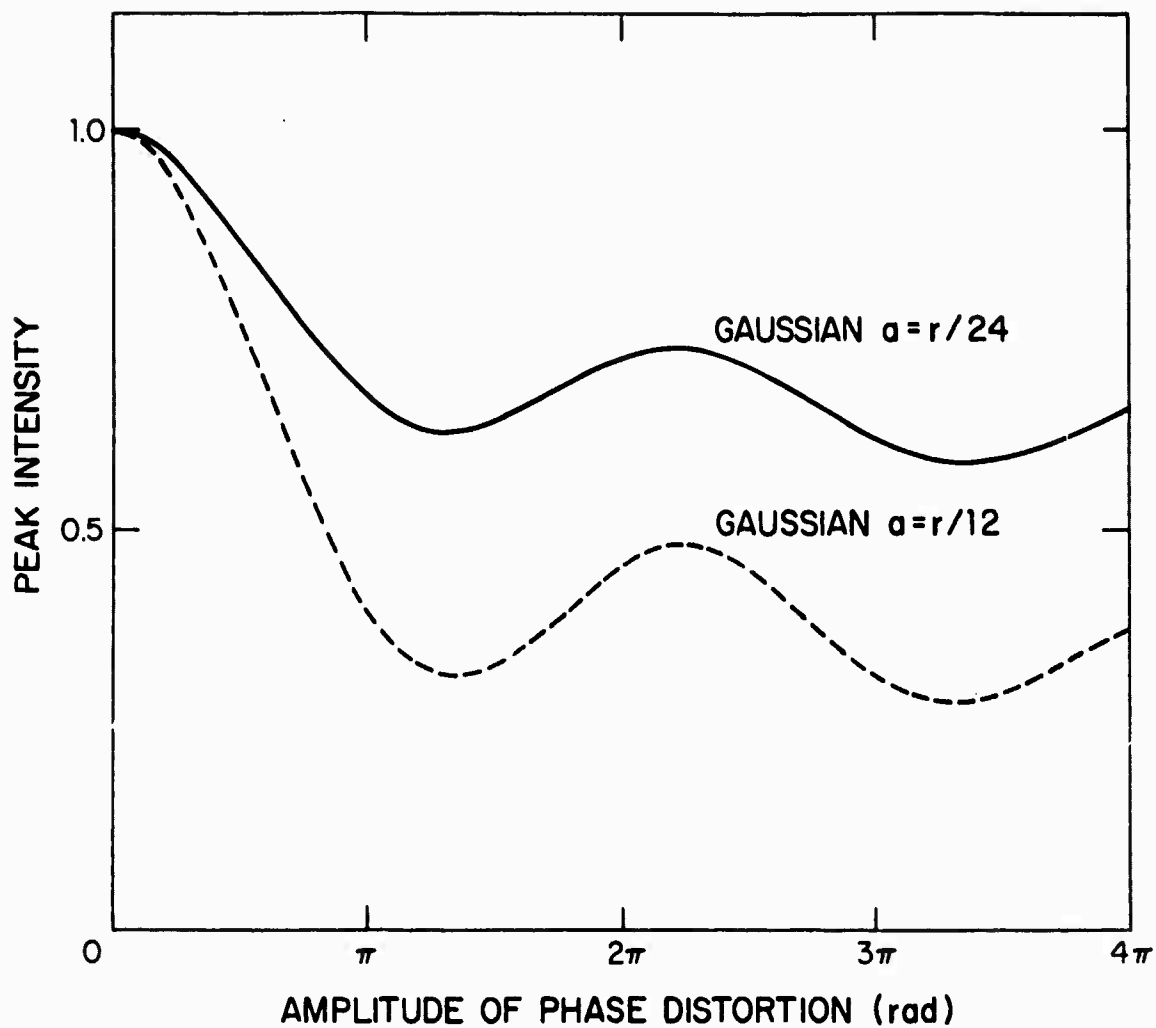


Fig. 7. Peak intensity (in arbitrary units) at the focal plane as a function of the amplitude of the phase distortion for gaussian phase profiles with $a = r/24$ (solid line) and $a = r/12$ (dashed line).

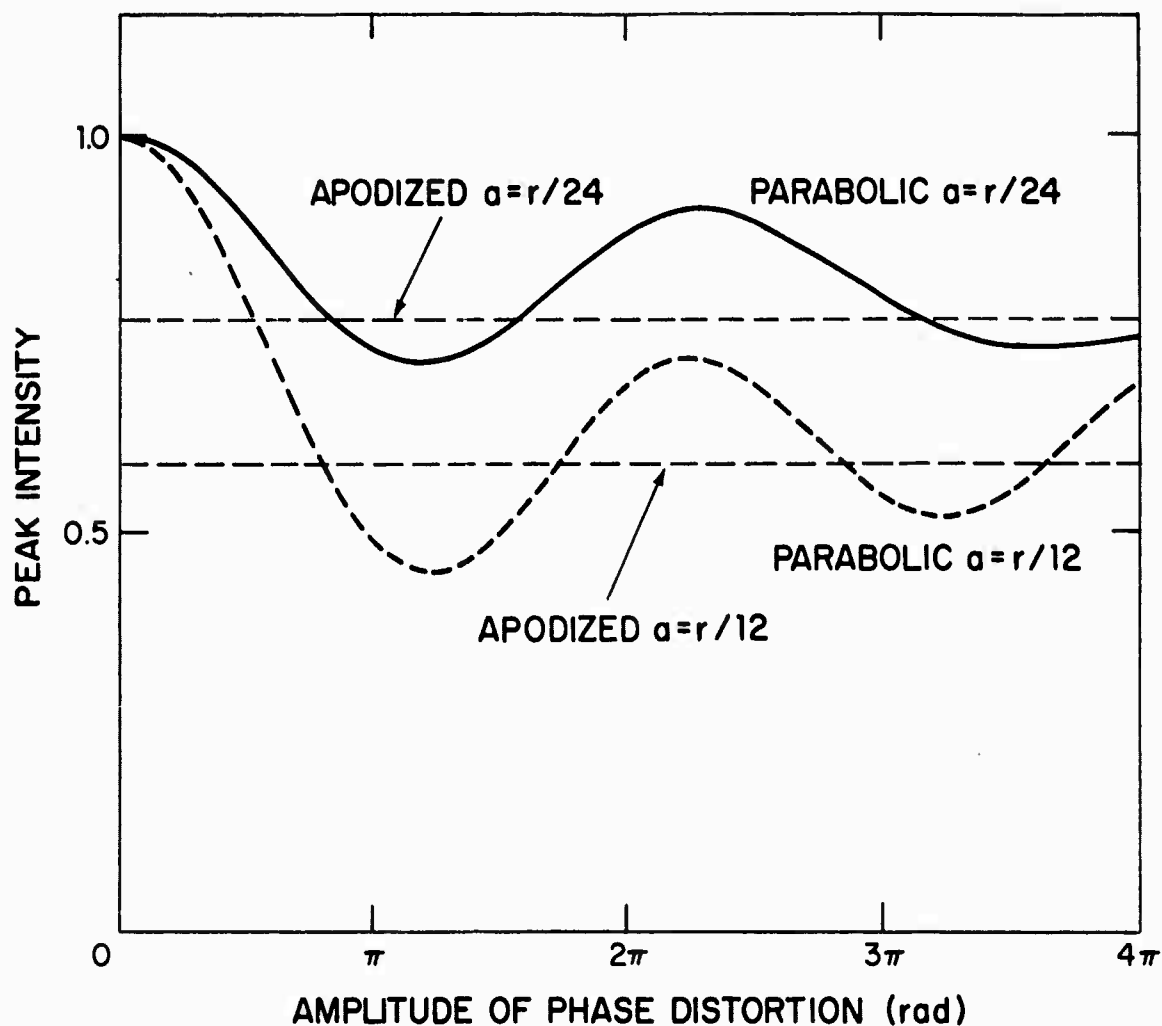


Fig. 8. Peak intensity (in arbitrary units) at the focal plane as a function of the amplitude of the phase distortion for parabolic phase profiles with $a = r/24$ (solid line) and $a = r/12$ (dashed line). The dotted lines show the results obtained by apodizing the parabolic phase profiles.

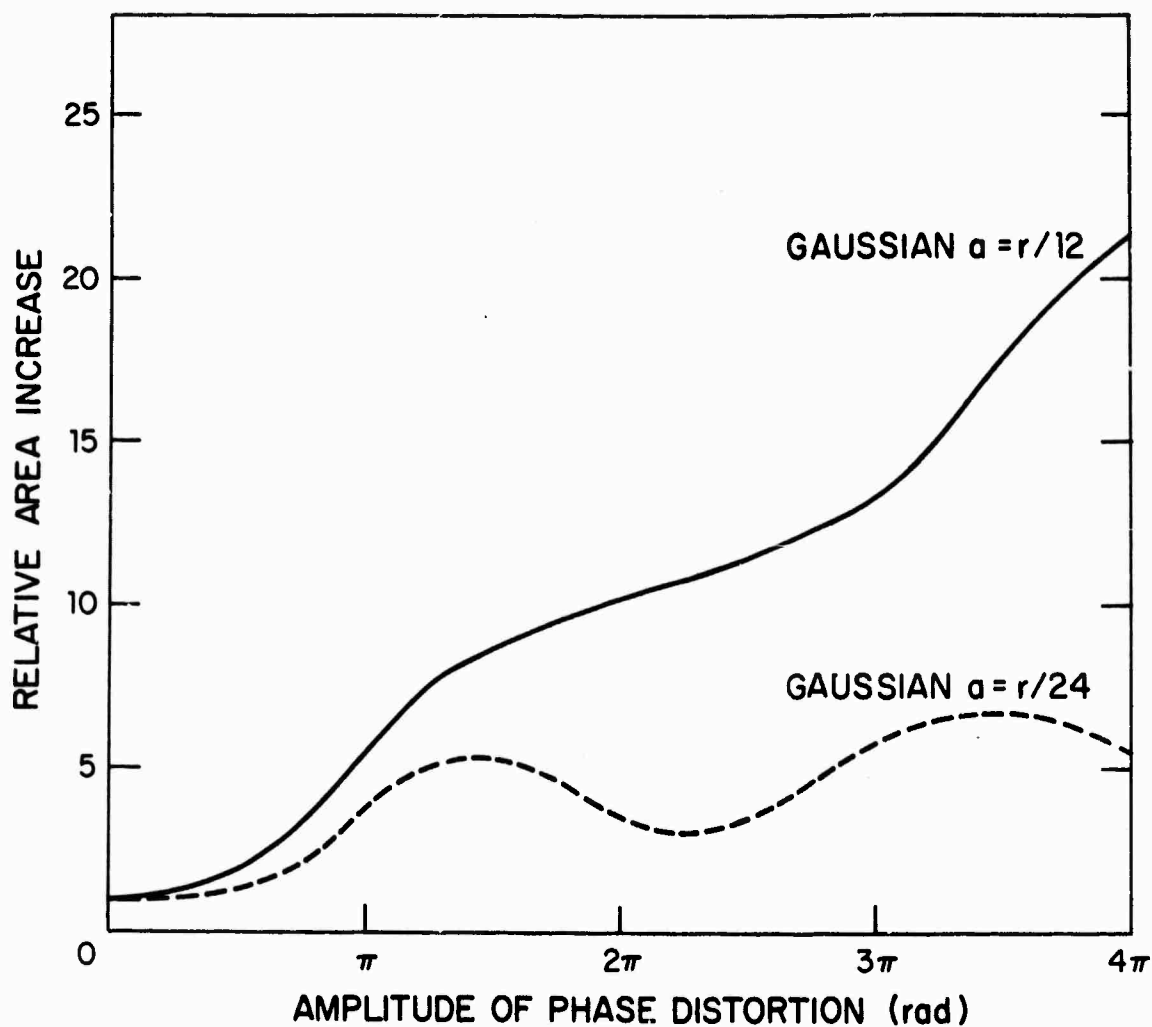


Fig. 9. Relative area increase of the focused beam as a function of the amplitude of the phase distortion for gaussian phase profiles with $a = r/24$ (dashed line) and $a = r/12$ (solid line).

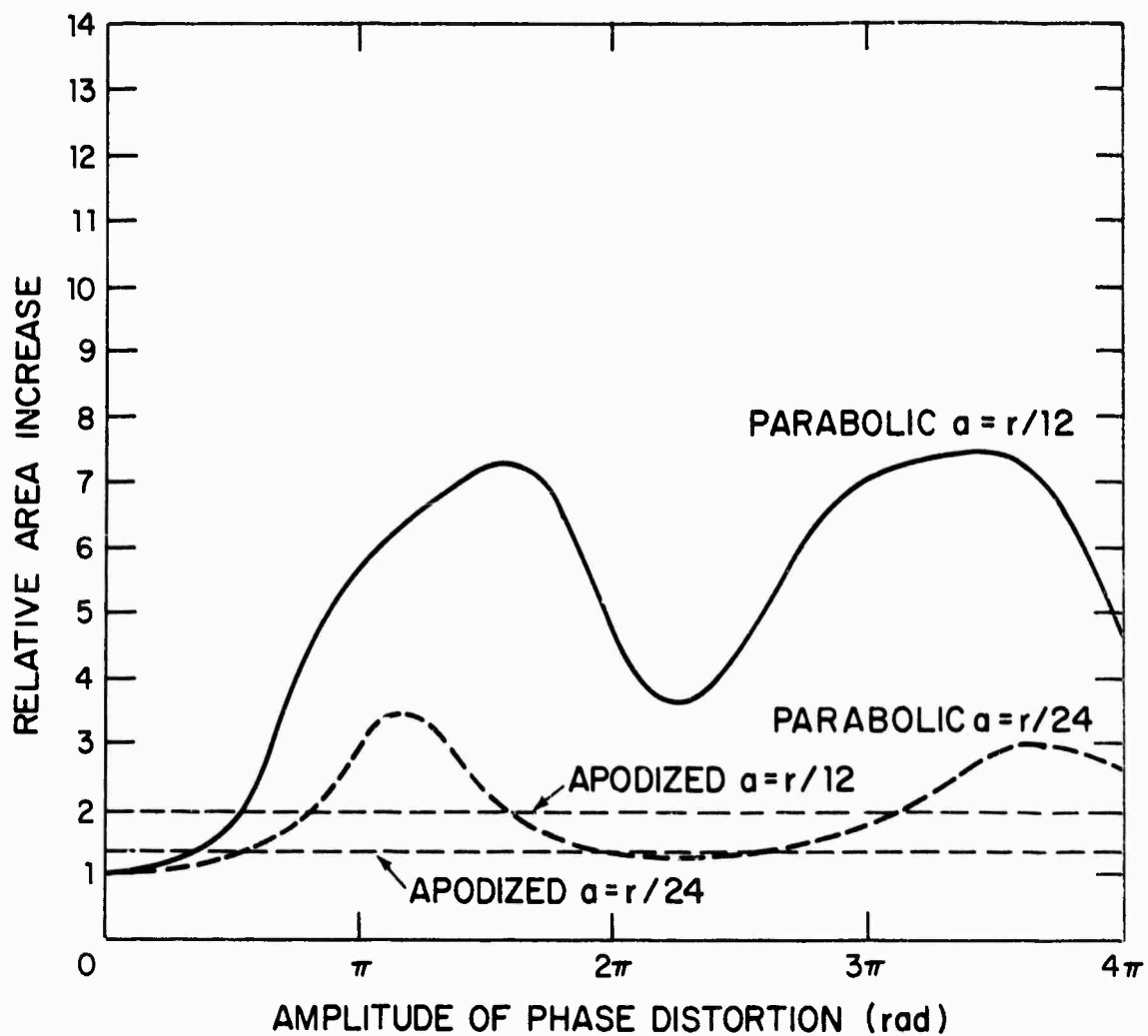


Fig. 10. Relative area increase of the focused beam as a function of the amplitude of the phase distortion for parabolic phase profiles with $a = r/24$ (dashed line) and $a = r/12$ (solid line). The dotted lines show the results obtained by apodizing the parabolic phase profiles.

as the principal maximum of one Fourier transform undergoes successive construction and destruction interferences with the positive and negative maxima of the second Fourier transform. The argument above can be easily generalized to show that oscillations should occur for any phase distribution which does not have a constant phase gradient over the aperture.

Figure 7-10 indicate that the amplitude of the beam quality oscillations is a function of the scale size, a , of the phase distortion. To further investigate this behavior we calculated the peak intensity and focused spot size at a fixed $\chi (= \pi)$ for values of a between $0.75 \cdot (r/24)$ and $3 \cdot (r/24)$ in increments of $0.25 \cdot (r/24)$. These results are plotted as smoothed curves in Figures 11 and 12. The peak intensity shows a monotonic (and almost linear) decrease with increasing scale size (over the region plotted) for both gaussian and parabolic phase distortions. The relative area increase on the other hand exhibits a sigmoidal behavior for both types of distortion. This behavior probably results from the following cause. As a increases from zero the phase distorted regions affect more and more of the aperture leading to a rapidly rising relative area increase. As a increases further the regions of high phase distortion (near $x = 0$ in the $\exp(-x^2/a^2)$ or $1-(x^2/a^2)$ factors) become flatter (i.e., have shallower phase gradients) and become physically larger as well. Thus the regions of steep phase gradients first become relatively more important and then relatively less important as the magnitude of a continues to increase. This would result in a sigmoidal behavior. The steep slope of the curve between $a = r/24$ and $a = r/12$ may be of practical interest. By designing a system to have

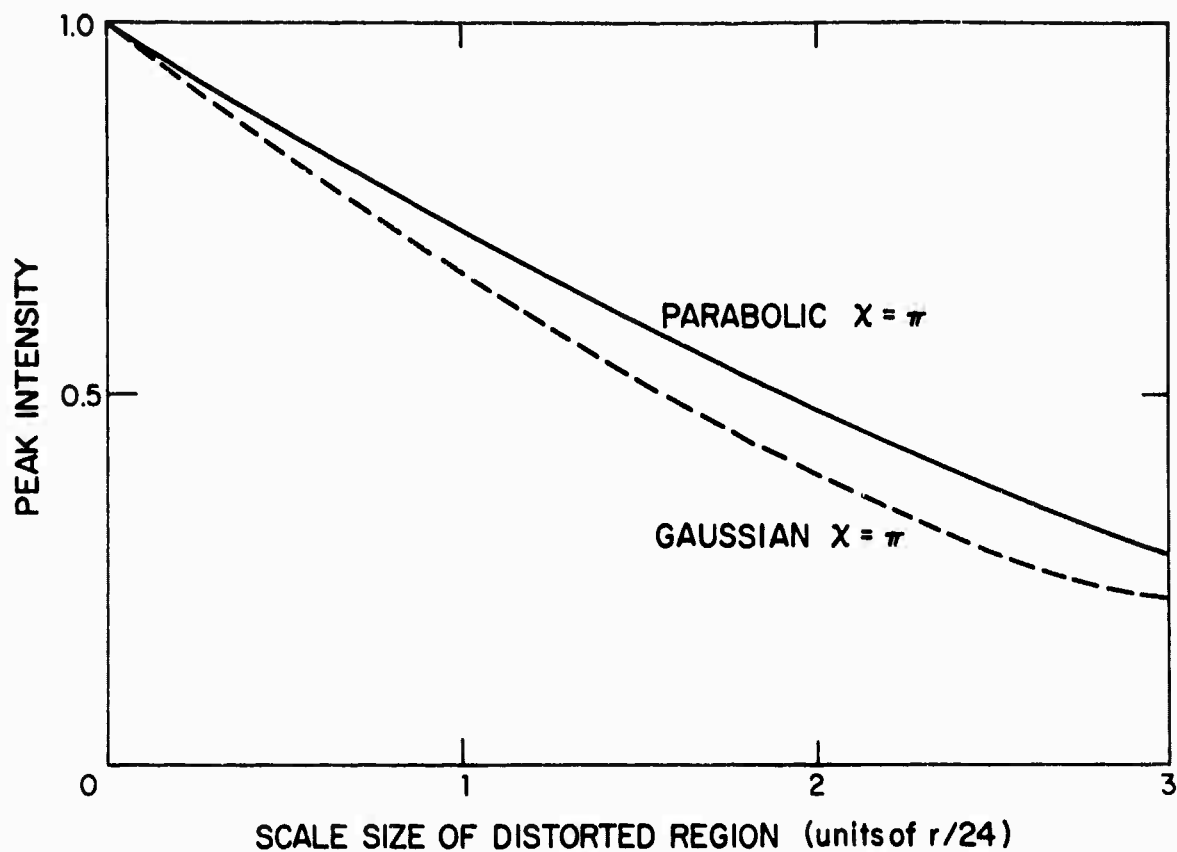


Fig. 11. Peak intensity (in arbitrary units) at the focal plane as a function of the scale size of the distorted region (in units of $r/24$) for gaussian (dashed line) and parabolic (solid line) phase profiles with $\chi = \pi$.

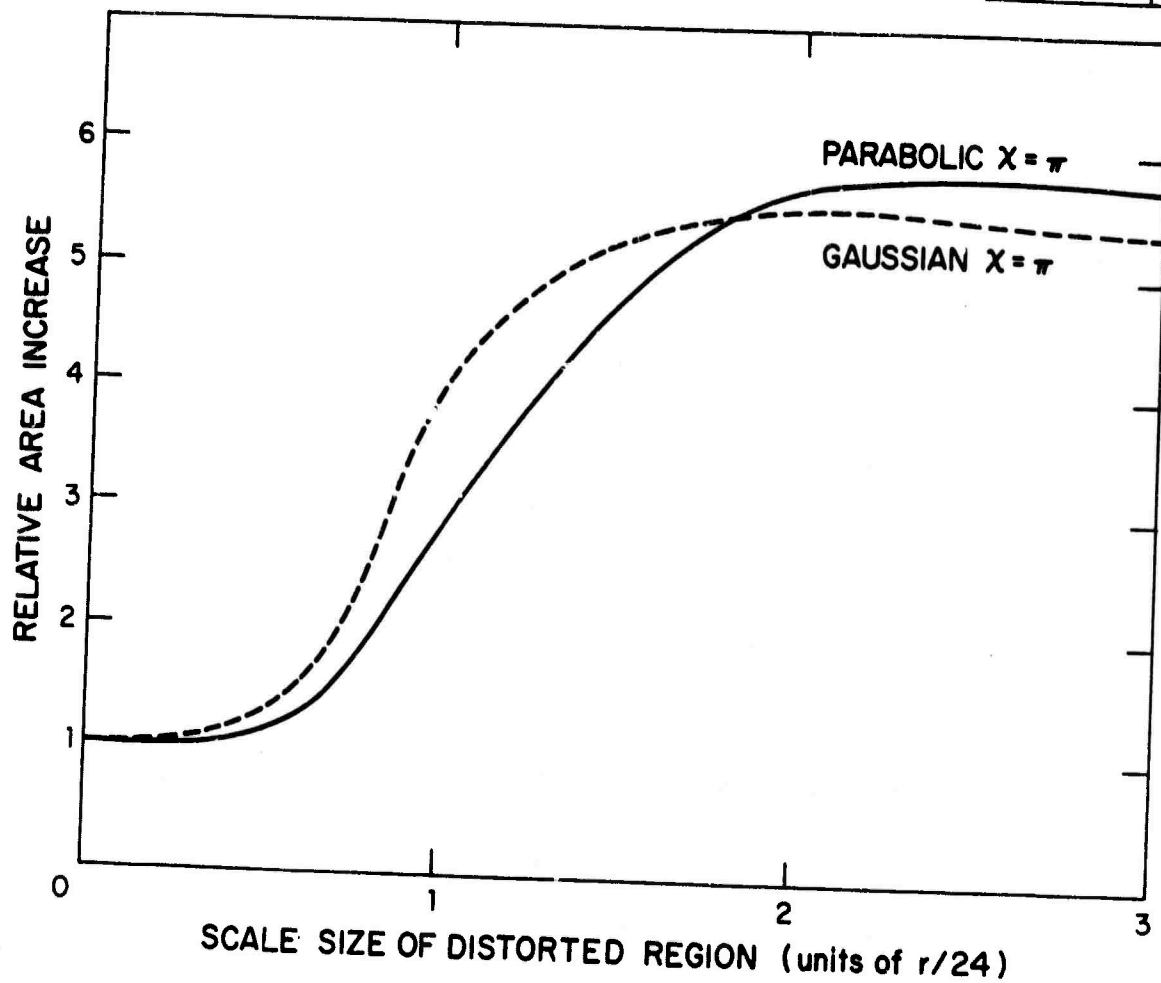


Fig. 12. Relative area increase of the focused beam as a function of the scale size of the distorted region (in units of $r/24$) for gaussian (dashed line) and parabolic (solid line) phase profiles with $\chi = \pi$.

relatively more area free of strut wakes and other large scale phase structures, the relative magnitude of a would be decreased, which might then result in a substantial improvement in beam quality.

Figures 13 and 14 compare the beam quality oscillations obtained for the gaussian and parabolic phase profiles (with $a = r/24$). In all instances the degradation is larger for the gaussian profile. This is to be expected as the gaussian profile affects the whole aperture to some extent, while the parabolic profile affects only part of the aperture.

If the phase distortion is confined to a small fraction of the aperture, it may be possible to improve the beam quality by eliminating the intensity in the distorted regions. We have analyzed the possible effects of this "apodization" procedure in the following manner. After calculating the phase and specifying a uniform intensity over the whole aperture, the phase at each mesh point was examined and at every point at which the phase differs from zero by more than $\epsilon(10^{-8})$ the intensity was set to zero. The small value of ϵ insures that the results of the apodization procedure will be independent of the value of χ chosen. The modified phase and intensity distribution is then handled as before. The peak intensity and relative area increase were calculated for apodized parabolic profiles with $a = r/12$ and $a = r/24$. The results are included in Figures 8 and 10 for comparison. The peak intensity oscillates about the apodized value. Thus, at some values of χ , apodization increases the peak intensity, while at others, apodization substantially decreases the peak intensity. The unapodized relative area increase on the other hand is larger than the apodized value

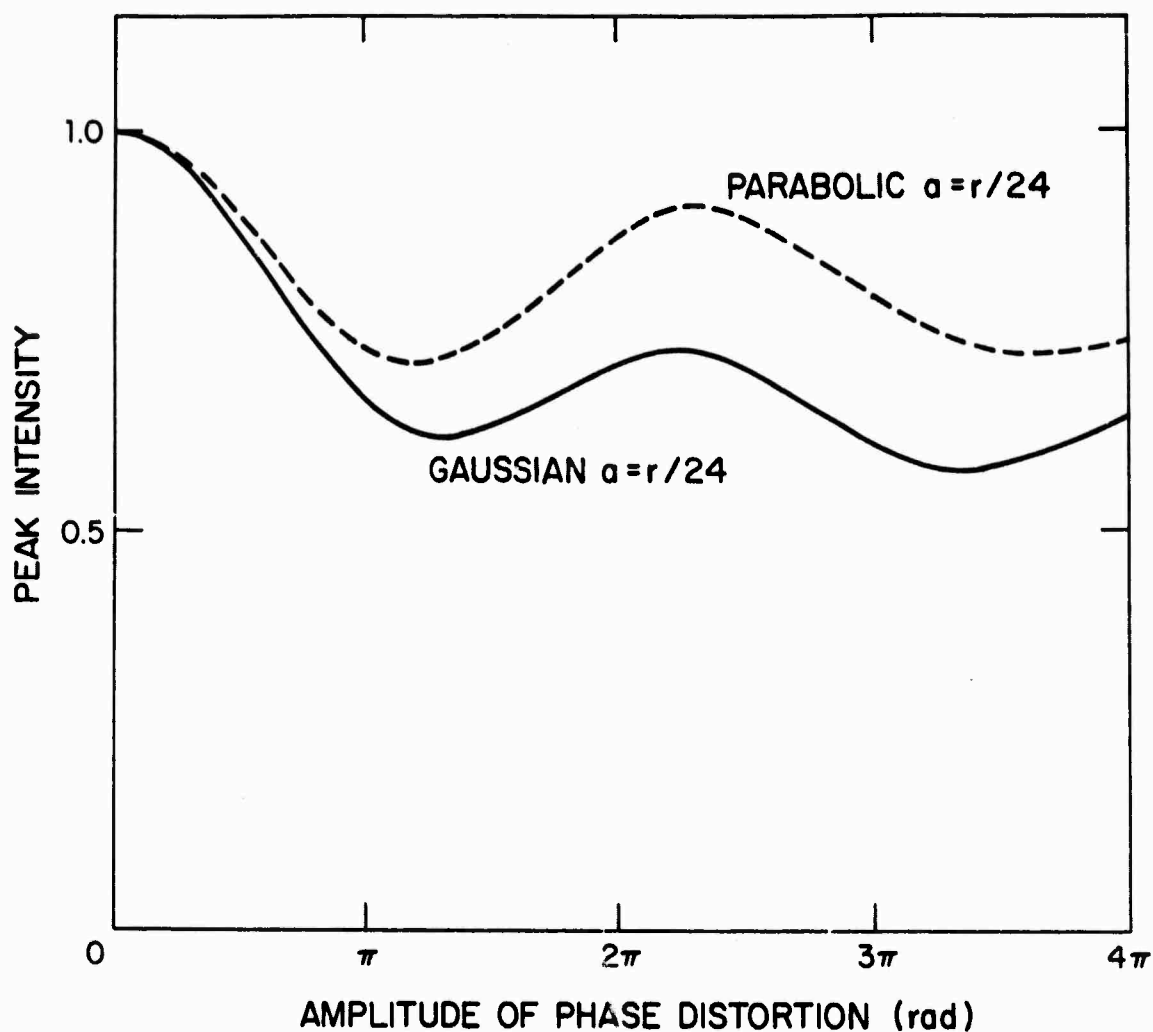


Fig. 13. Comparison of the peak intensity (in arbitrary units) at the focal plane as a function of the amplitude of the phase distortion for gaussian (solid line) and parabolic (dashed line) phase profiles with $a = r/24$.

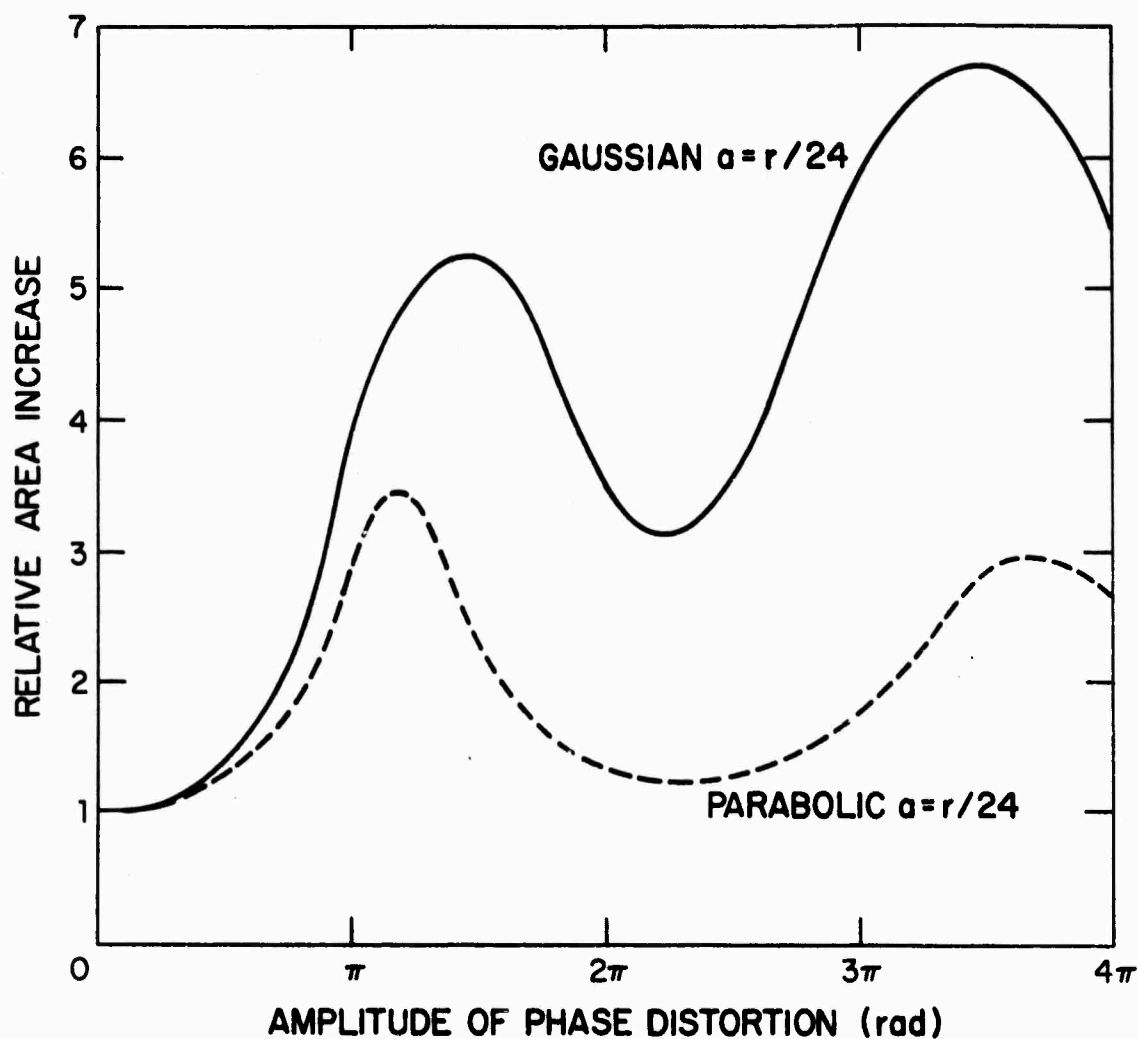


Fig. 14. Comparison of the relative area increase of the focused beam as a function of the amplitude of the phase distortion for gaussian (solid line) and parabolic (dashed line) phase profiles with $a = r/24$.

for most values of χ . Thus except for small amplitudes of the phase distortion, apodization decreases the focused spot size.

Adaptive optics may also be useful in controlling beam quality oscillations. Because the oscillatory behavior results from the large-scale phase distortions, reflecting the beam off a deformable mirror with a reasonable number of actuators (placed either inside or outside the laser cavity) should yield a substantial reduction in the amplitude of the phase distortions, with a resulting significant improvement in beam quality. By varying the amplitude of the mirror deformation changes in the number of modules could be readily compensated.

The preceding results have all been cast in terms of the amplitude of the phase distortion. However, in the Introduction it was noted that for modular laser systems, both the output power and the amplitude of the phase distortion increase linearly as the number of modules is increased. To see how the oscillatory beam quality effects impact on modular laser performance we have used the preceding results to calculate the peak intensity and the average intensity (laser power divided by the focused spot size) as a function of laser output power. These results are plotted in Figures 15 and 16 where we have assumed that an output power of 1 (in arbitrary units) corresponds to a phase distortion amplitude $\chi = \pi$. The peak intensity exhibits mild oscillations but always increases with increasing output power. The average intensity, on the other hand, undergoes severe oscillations having deep local minima. For example, increasing the output

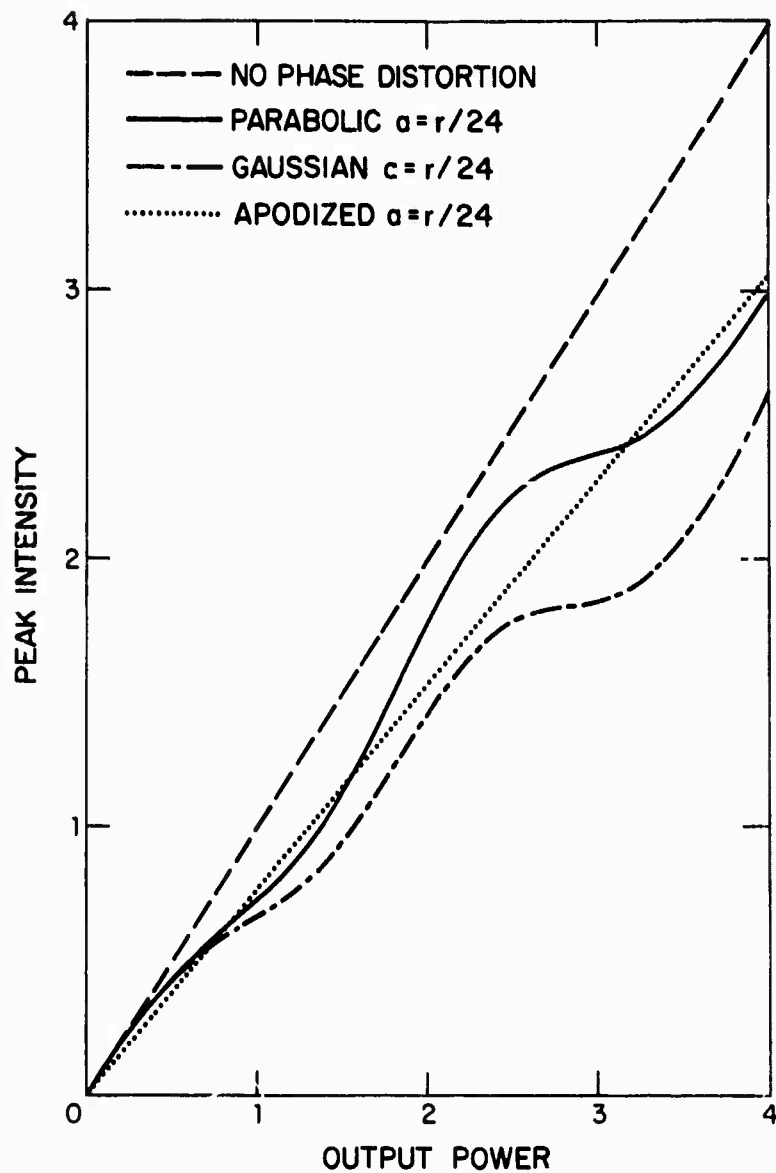


Fig. 15. Comparison of the peak intensity (in arbitrary units) at the focal plane as a function of the output power (also in arbitrary units) of a modular laser with no phase distortion (dashed line) and gaussian (dot-dash line), parabolic (solid line), and apodized (dotted line) phase distortions with $a = r/24$. An output power of 1 is chosen to correspond to $\chi = \pi$.

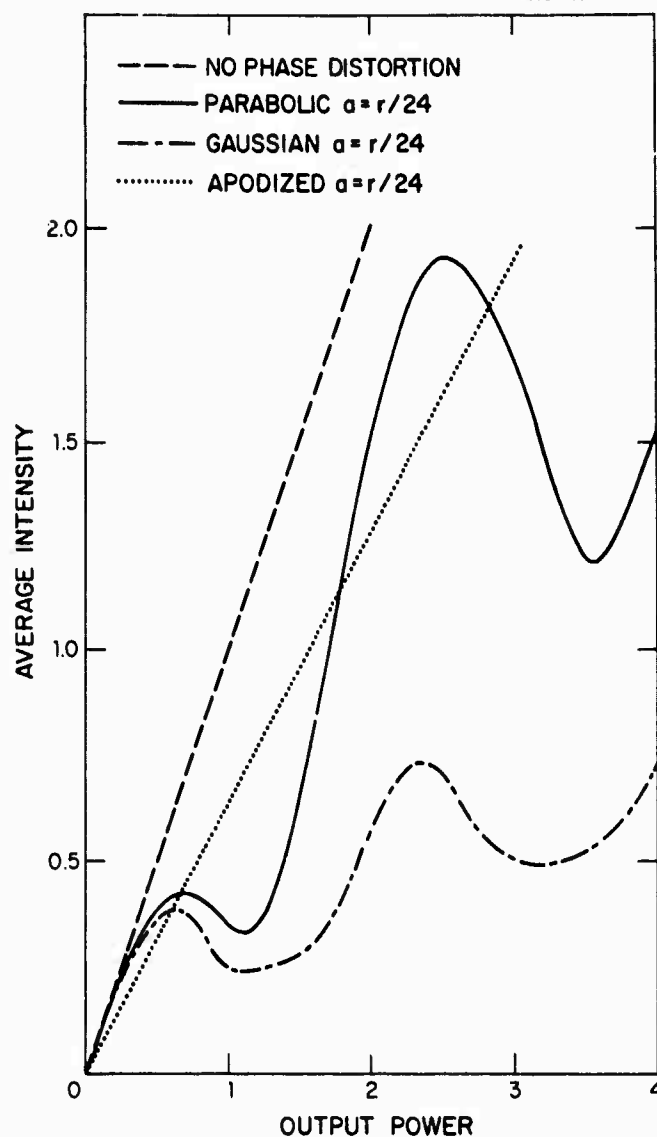


Fig. 16. Comparison of the average intensity (in arbitrary units) at the focal plane as a function of the output power (also in arbitrary units) of a modular laser with no phase distortion (dashed line) and gaussian (dot-dash line), parabolic (solid line), and apodized (dotted line) phase distortions with $a = r/24$. An output power of 1 is chosen to correspond to $\chi = \pi$.

from 0.5 ($\chi = \pi/2$) to 1.0 ($\chi = \pi$) by doubling the number of modules results in a 30% decrease in average intensity for the gaussian phase profile. Typically, laser designers attempt to keep the maximum phase distortion below $\pi/2$ (one-quarter wavelength) in order to maintain a high beam quality. However, in a modular laser it may be necessary to exceed this upper limit in order to achieve the desired output power levels, and, as shown by these calculations, this is just the regime in which the first minimum occurs. Thus, the oscillatory beam quality effects observed here may have a significant impact on the design of modular laser systems.

V. CONCLUSIONS

A simple model has been developed for the output phase profile of a typical modular linear CW chemical laser. The output beam quality of this laser was investigated as a function of the amplitude and scale size of the model phase distortions using the Lincoln Laboratory laser propagation code. Oscillations were observed in the beam quality (as measured by both the peak intensity decrease and the focal spot size increase) as the amplitude χ of the phase distortion was increased, although the oscillatory behavior does not become apparent until χ becomes of the order of π . The oscillations become more pronounced as more of the aperture is affected by the phase distortions. Simple physical arguments indicate that beam quality oscillations should occur in any system with a large scale phase distortion which does not change shape as its amplitude is increased. Thus oscillations should be expected to occur in any modular laser system (chemical or otherwise) and in laser amplifier systems consisting of a chain of many identical

amplifier units or units scaled in size and coupled by beam-expanding telescopes.

Since the amplitude of the phase distortion as well as the output power increases linearly with the number of modules in a modular linear laser system, the oscillatory behavior observed here may have significant impact on modular laser design. For example, using fewer modules might result in a higher average intensity at the focus. Apodization of the phase distortion regions can be effective in substantially improving beam quality in some instances, although in others it can be deleterious. The use of adaptive optics (either inside the resonator or in the output beam) might be capable of suppressing the oscillatory behavior entirely.

An alternate approach to modular laser construction involves the use of an annular gain medium. Increased gain volume can be achieved by increasing the length of the gain medium or increasing the radius of the annulus. The former can be accomplished by adding additional identical modules end-to-end while the latter necessitates a change in module dimensions as the radius changes (unless the annulus is formed as a regular polygon approximation to a circle). If the length of the gain medium is increased by adding additional modules, the same oscillatory effects as observed in in-line modular systems will occur. If, however, the radius of the gain medium is increased by adding more modules azimuthally, the rms phase distortion will not be significantly affected and no oscillatory behavior is expected to occur.

In conclusion, the existence of oscillatory beam quality effects should

be considered in the design of modular laser systems. These effects suggest that annular lasers are superior to in-line lasers in terms of their power scalability if it is the radius of the gain annulus which is scaled rather than the length of the gain annulus.

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