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HIGH ENERGY LASER OPTICS

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INTRODUCTION. -- The rapid development of lasers has introduced the need for specialized optics to exploit the capabilities of this new source of coherent radiation. Of particular interest here are the optics related to high power lasers which are necessary for high efficiency and good far field performance. Oftentimes the requirement of minimum beam divergence conflicts with the limitations introduced by the nature of high-power laser cavities and propagation phenomena. The structure of oscillator cavities to overcome these limitations, the search for optical materials, and design of mirrors and windows able to withstand the high-power densities of lasers represents formidable problems. In fact, aerodynamic windows were introduced as a method of withstanding very high laser power in wavelength regions for which there were no good optical materials available.

High power lasers are still being developed at a fast rate and in recent years the direction of these developments has tended to introduce new optical problems. For example, the high power chemical laser is one type of laser that is continually evolving and as a result has introduced unique geometrical problems of the cavity involving the flow field. Then too, saturation power densities are increasing and wavelengths are shortening, which puts additional strain on existing technology; new technologies are developing. There is considerable interest in free electron lasers as efficient high power light sources. Indications are that efficiencies greater than 30% are possible provided certain restrictive properties can be met with the electron beam and radiation field. Among the requirements are the need for extremely high radiation power densities \(10^{10}-10^{12}\) w/cm\(^2\) for electron trapping and no electric field reversals on the electron beam axis. Unusual diffraction effects are also present because of the small cross section of the gain medium. Such requirements and properties will undoubtedly affect future resonator design.

This paper will try to review some of the important aspects of optics for high energy systems and introduce some current subject material that will be of use to the symposium attendee interested in continuous high power lasers. Problems pertaining to very high pulsed power lasers such as those used in laser fusion will not be covered in this paper. Since the field has grown enormously, all aspects of the optics of high energy lasers cannot be covered in a single paper. This paper covers only two topic areas. First to be covered is the theory of unstable laser resonators as these cavities permit the efficient utilization of large mode volumes while maintaining good far field performance. Even so, propagation effects which become especially important for high power lasers can limit severely beam irradiance at a distance. Fortunately, adaptive optics is an approach which helps to circumvent this problem and this is the second topic to
be covered. By taking advantage of the coherence properties of the laser, active optics has been used to improve our ability to deliver a high irradiance beam under adverse circumstances.

RESONATORS. -- The laser cavity is not simply a microwave cavity. The microwave cavity is a closed metal structure at which only certain wavelengths resonate. Generally speaking, the dimensions of the cavity correspond to these wavelengths. Of course, this size of cavity is not useful (the exception is waveguide types which are not discussed here) for high power lasers having wavelengths on the order of microns. The high power laser cavity is large compared with wavelength and operates in a slightly different way than ordinary microwave cavities. The ordinary laser cavity does not determine the frequency of the laser so much (the cavity dimension does determine the microwave frequency) as the gain media does. Rather, it serves to discriminate among the many possible frequencies within the gain bandwidth of the molecular system. In so doing it will provide optical feedback to maintain the given oscillation permitting highly monochromatic beams and, hopefully, control the optical phase across the beam front so that low beam divergence and high focus intensities are possible.

Stable Cavities. -- As there is a large body of literature available on stable resonators, it is the purpose of this section to introduce those features of stable resonators which are helpful in understanding the requirements of high power lasers' only. Resonators can be classified as stable or unstable, depending on whether a ray is trapped between the mirrors or not. Ray optic analysis [1] shows that the stability condition is

\[ \frac{x}{d} < \left( \frac{1}{L/R_1} \right) \left( \frac{1}{L/R_2} \right) \]  

where L is the distance between the mirrors and R1, R2 refer to the radius of curvature of the mirrors 1 and 2. If the value of the product lies outside these numbers, the cavity is unstable. Because of the repeated appearance of these parameters and their importance, it is useful to define \( g_1 = \frac{1}{L/R_1} \) and \( g_2 = \frac{1}{L/R_2} \) so that the condition simply reads \( 0 < g_1 g_2 < 1 \). Any resonator can be presented as a point on a stability diagram such as shown in Fig. 1. Examples of each type of cavity are shown. The shaded region corresponds to stable cavities. Stable cavities were used first and can be used for low or high gain media.

The beam quality of these cavities may be measured by the divergence of the beam in the far field.

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**Fig. 1 Stability Diagram**

By application of the diffraction integral, it is known that far field patterns of laser beams are merely Fourier transforms of their near fields [2]. Generally speaking, a uniform field and phase output of a laser produces the smallest divergence and maximum intensity in the central lobe in the far field [3]. For a circular aperture the well-known Airy pattern with the angular width of 2.44 \( \lambda / d \) is a result [2]. If, however, there are amplitude and phase variations in the near field, then the divergence is larger and the central intensity is reduced. Of these, the phase distribution is the larger effect and it is this factor that must be made as uniform as possible in resonator design. Fig. 2 shows schematically the effects of amplitude and phase variations across the beam.

The solution of the wave equation will give field amplitude and phase that is necessary to predict optical beam quality. For infinite size mirrors with a uniformly passive medium, matching the solutions of the wave equation for nearly plane waves gives analytic results that predict the transverse modes and frequency of the laser [1]. These results are in the form of Hermite or Laguerre polynomials and can be found in most texts on lasers [4]. The correct solution which may correspond to a linear superposition of many of the polynomials is determined by the boundary conditions. The important thing to notice is that there is a sequence of solutions, each more complicated than its predecessor. The fundamental mode is a simple
These are the essential features of stable cavities, but, of course, to be useful some light must be extracted and one must consider the effects of finite mirror size. Mirrors of finite size lead to diffraction losses and this problem is more complicated [1]. Essentially one calculates the field by analyzing the steady state field distribution that can be sustained within an empty resonator. This amounts to calculating the field distribution at the second mirror (2) from an assumed distribution at the first mirror (1). The resulting distribution can be obtained via an integral using the scalar formulation of Huygens' principle [2,5]. This must be repeated for the reverse case, i.e., from (2) to (1) and ultimately arrive at the initial distribution. A field distribution that obeys this condition can be written as the integral equation

$$\gamma \psi(r) = \mathcal{H}\psi(r)$$

where $\psi$ is the field distribution, $\mathcal{H}$ is the propagation integral operator [2,3], and $\gamma$ is the complex eigenvalue for the given mode. More explicitly,

$$\gamma = (1-\delta)e^{i\theta},$$

where $\theta$ = phase shift and $\delta$ = round trip power loss. Therefore $\delta$ is the output coupling fraction and $\phi$ is used to determine the exact frequency of the laser. Early solutions of these oscillators was given by Fox and Li where they showed that certain type resonators and low order modes have very low diffractive losses [5]. Higher order modes have higher losses and this can be used as a means of selecting low order modes. A useful parameter in describing the diffraction effects of this problem is the Fresnel number, $N = a^2/\lambda d$, where $a$ refers to the radius of the mirrors. Figure 3 shows how the losses vary with $N$ for the lowest order modes for a cavity with circular mirrors having

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Fig. 2 Effect of Near Field Intensity and Phase Distribution on Far-Field Pattern

**Fig. 3** Diffraction Loss/Transit vs. Fresnel Number for Stable Resonators with Circular Mirrors [1]
equal diameters and curvatures. Just as expected, the losses decrease with increases in \( N \).

**Mode Volume.** A major problem in the design of high power lasers is to obtain a large mode volume while retaining good mode control. The point about mode volume cannot be over-emphasized in dealing with high power lasers. Not completely using a fully energized cavity volume through poor mode filling is in reality a large waste of energy and a loss in system efficiency. The lowest order and most desirable mode spot size is given by

\[
w = \frac{\lambda}{\pi} = F w_0
\]

where \( w \) is the spot size. The multiplying factor \( F \) is typically of order unity for a wide range of \( g_1 \) and \( g_2 \) [6]. Typically Gaussian stable resonator modes are slender and much smaller than one would like, maybe only millimeters wide. The mode volume for this case is of order

\[
V \sim O(L \cdot w^2) = L^2 \lambda^2.
\]

For large volumes of active media this leads to very long cavities. Table 1 taken from [3] shows that lasers with volume measured in liters have cavity lengths that are very long for large \( N \) at \( \lambda = 3 \mu \). Similar results exist for other wavelengths. If we try to use a larger mode volume without increasing the length, then higher order modes develop in the presence of a gain medium [3]. Efforts to arrange the cavity geometry so that effectively \( F \) is large usually are difficult as the sensitivity to alignment becomes extreme and goes like [6]

\[
\frac{\delta w}{w} = \left( \frac{w}{w_0} \right)^4
\]

As a practical matter the requirements on mirror figure, alignment, and gain homogeneity are too large.

**Table 1. Laser-Cavity Length Requirements for Various Optical Fresnel Numbers (\( \Lambda = 3 \mu m \))**

<table>
<thead>
<tr>
<th>Resonator mode volume, liters</th>
<th>Resonator Fresnel number ( a^2/4L ), ( L ) in cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>10.3 3.3 1.0</td>
</tr>
<tr>
<td>0.010</td>
<td>32.6 10.3 3.3</td>
</tr>
<tr>
<td>0.100</td>
<td>103 32.6 10.3</td>
</tr>
<tr>
<td>1</td>
<td>326 103 32.6</td>
</tr>
<tr>
<td>10</td>
<td>1030 326 103</td>
</tr>
<tr>
<td>100</td>
<td>3257 1030 326</td>
</tr>
<tr>
<td>1000</td>
<td>10301 3257 1036</td>
</tr>
</tbody>
</table>

**Unstable Resonators.** A solution to the above problem is the unstable resonator proposed by Siegman [7]. In this case both mode control and phase coherence exist even with a large mode volume. Nearly all current high power lasers use the unstable resonator to extract power. This scheme is practical for high gain lasers only because of the large losses encountered. For high power lasers with low gain there is as yet no good solution.

A laser can be made phase coherent over the beam front only if the resonator is designed so that all parts of the laser region share an interaction through diffraction. Then the optical phases of all the emitters are locked together through the cross-coupling furnished in the cavity [3]. A low Fresnel number stable cavity impiles significant diffraction effects are present and a uniform phase cannot result. However, a high Fresnel number cavity only has the central region strongly coupled. Other optical paths with wide excursions across the cavity are not diffractively coupled and this leads to higher order modes. The situation is illustrated in Fig. 4 by the crosshatching. In an unstable...
resonator at large $N$, the lack of diffractive coupling is compensated for by providing a sort of geometrical crosscoupling. There is a central region in the unstable oscillator within which diffraction is strong and laser oscillation is in phase. The cavity simply magnifies this mode as the light bounces back and forth and escapes. This is shown as the crosshatching in the third picture in Fig. 4. It can be viewed as an oscillator in the central region and a multipass amplifier as the beam enlarges. As the magnified beam has the same phase properties of the innermost beam, good beam control is possible.

Types of Unstable Resonators.-- Figure 5 illustrates three types of common unstable resonators. In the symmetric cavity, light is coupled from both ends and so is of limited usefulness. An asymmetric cavity is used to obtain a single beam and the mirror radii can be chosen to give the desired angular divergence of the output beam. A special case is the confocal configuration where $R_1 + R_2 = 2L$. In this case the beam output is parallel in the geometric approximation. Unstable resonators are classified according to their position on the stability diagram. The positive branch of the first type (the first quadrant on the stability diagram) is used most commonly in high power lasers since it contains no intracavity focal points where nonlinear effects may occur. This branch is characterized by $g_1 g_2 > 1, g_1 > 0$.[3]

At first, it would appear that the presence of the hole in the output beam would be an undesirable feature. But except in extreme cases it was pointed out that the far field distribution depends mainly on the phase distribution and the hole fills in the far field [8]. The main feature is that the pattern has more energy in the side lobes than for the case without the hole. As long as the hole accounts for less than 50% of the beam area the far field is nearly ideal.

As in stable cavity operation, the essential aspects of an unstable oscillator operation can be obtained using a geometric model [7,9]. The results of this analysis shows that the output coupling for cylindrical resonators is approximately

$$\delta = 1 - \frac{1}{M^2}$$

where $M$ is the cavity round trip magnification and is related to the $g$ parameters [9]. The geometry of the situation is illustrated in Fig. 6. Notice the amount of coupling is independent of the cavity diameter and it is simple to make the mirrors as large as required to extract energy from a given mode volume. This is true irrespective of the type of

Fig. 6. The Magnification Factor
unstable cavity. Typically, coupling values of 20% to 90% are usual. The results are also true for mirror shapes (of spherical curvature) other than circular. It is also possible to consider aspheric curvature mirrors in which M differs depending on which axis of the mirror is being described.

There is a very useful equivalence principle for unstable cavities which allows one to relate an unsymmetrical cavity with one large mirror and one small mirror (coupling from one end) to a symmetric unstable cavity with the same length. The principle is given in [10]. The round trip magnification and losses of an asymmetrical cavity with parameters $g_1$, $g_2$ and Fresnel numbers $N_1 = a_1^2/L$, $N_2 = a_2^2/L$ are the same as the one way losses and magnification of a symmetric cavity of the same length with $g$ values of each mirror given by $g = \left| 1 - 2g_1 g_2 \right|$ and a mirror Fresnel number $N = a^2/L = \left| N_1/2g_2 \right|$. This defines the mirror curvatures and diameters of the equivalent symmetric resonator. This simplifies things considerably because one can derive all the properties of one-sided resonators from the one-way results of the simple symmetric resonator. This applies not only to the simple geometric model but also in wave analysis of stable and unstable cavities. A very important parameter of the symmetric unstable resonator which by the equivalence principle applies to one-sided cavities too is the so-called equivalent Fresnel number given by $N_{eq} = N\sqrt{g_2} - T$ (or $N_{eq} = N_1^2/(g_1 g_2 - 1) \sqrt{g_2}$).

**Diffraction Effects.** -- There are diffraction effects that lead to transverse modes. To optimize the far field pattern of such a cavity, the wave nature of the cavity must be analyzed so that one can discriminate against higher order modes and obtain single mode operation. Except for special cases, no analytic solutions have been found for unstable resonator modes. One must resort to numerical solution of the integral equations of the electromagnetic field as was done for stable cavities, even if the cavity is empty. The idea follows as before but the geometry is slightly different. The equivalence principle simplifies things considerably since by symmetry we only have to propagate waves in one direction as the reverse direction is the same. Thus there is just a single integral instead of a double integral for the round trip. If one uses rectangular coordinates, the field amplitude is separable into $x$ and $y$ components [5] which are independent for an unloaded oscillator (no gain medium). A typical result from this analysis is shown in Fig. 7 along with the geometrical model results [3,11]. Whereas the geometrical model shows a loss that is independent of mirror size, the numerical wave solutions show complicated oscillatory behavior having as a limit the geometrical result for large $N$. If these results are plotted against $N_{eq}$ the oscillations peak at integral values of $N_{eq}$. Further calculations have shown that the cusps in the loss curves indicate mode crossings [12,13]. Thus in unstable resonators different modes can have lower losses at large $N_{eq}$ which is in contrast to stable resonator results. The lowest losses always exist at half integer values of $N_{eq}$ and mode crossings occur at integer values of $N_{eq}$. This has been
is sufficient so that light is directed back along the ray path to the center of the cavity, we find \( h = a/N \). So diffraction from this generally small region near the edge causes the complicated mode structure. This was recognized by Anan'ev [15,16]. By properly tapering or adjusting the reflectivity of the mirrors in this small region these diffraction effects can be eliminated and complete separation of the low order modes exist for any \( N \) as seen in Fig. 9. This ideal situation is undoubtedly hard to implement in practice. Another possible approach is to alter the shape (curvature) of a mirror to reduce edge effects [17]. Also, it is known that rectangular mirrors are not so susceptible to this mode coupling as circular ones.

Cylindrically Active Regions. -- An important class of resonators having a cylindrically active region [18] and using special conical or cubic reflectors [19,20] poses additional problems not handled properly in earlier theoretical papers. See, for example, Fig. 10a. In this class of resonators

![Diagram](image-url)

**Fig. 10.** A cylindrical resonator and W-Axicon Mirror

b) Geometric Polarization Scrambling Effect Produced by linearly Polarized Input Beam on a W-Axicon Mirror.
it has been shown experimentally that polarization effects are important and that mixing of the polarization state occurs due to the \(W\)-axicon (see Fig. 10b). Thus the scalar field theory described earlier is not adequate in this instance. Instead, the vector field must be analyzed. Recently Dente [21] has shown that one can write two scalar integral equations which are coupled even in the absence of a medium to describe the equivalent vector field. Thus to a large extent existing laser codes can largely be used to study the case where polarization effects are important [22]. These modifications seem to confirm experiment.

An additional problem with these resonators comes from the use of compactors, \(W\)-axicons, or inner axicons used to condense the radiation in the cavity. These axicons are subject to high radiation fields especially at the tip of the optical element [23]. This is precisely where cooling is difficult and the sharp edge and coatings may be ablated or melted away. One can imagine that damage if present in such a critical area would have an adverse impact on cavity performance.

Sensitivity to Alignment and Mirror Tolerance.-- Another important aspect of unstable resonators is their sensitivity to misalignment and mirror figure. This is of practical interest because of mechanical vibrations which may be present and figure errors in the manufacture of real mirrors. The effect of misalignment of circular mirrors was investigated by Krupke and Sooy [24]. For a small angle misalignment they predicted a change in the optical axis of angle \(\phi\) versus \(M\). Their results together with solutions [28] at finite Fresnel number are shown in Fig. 11. In the limit of large Fresnel number, it was shown that the ratio of \(\phi/x\) goes like \(2M/M-1\) for the positive branch and \(2M/M+1\) for the negative branch. This result shows that the positive branch is much more sensitive to this form of error than the less used negative branch, especially as \(M \to 1\) or as the output coupling approaches zero. These trends also apply to mirror figure tolerance as well. Other forms of errors including figure errors are currently being investigated. It is interesting to note that optical cavities using phase-conjugate mirrors (PCM) are being investigated [26,27]. The PCM has the unusual property of reflecting waves that are the complex conjugate of the incident wave. It appears that such cavities have real confined gaussian modes. The implication for high power lasers is to be determined, but this may mean that the conventional meaning of the stability of cavities is questionable.

Effect of Gain Medium & Asymmetries. -- To a large extent the theory of unstable resonators has been borne out by numerous experiments [14,24,28]. These, for the most part, have been cases where the gain medium is fairly uniform and does not alter drastically the optical properties of the cavity. However, in many high power lasers the gain varies considerably in the cavity due to natural asymmetries and saturation effects. In addition, refractive effects, whether by turbulence or imposed non-uniform flow, will cause phase errors leading to departures from the results described so far. These effects must be included and, as one might expect, only make the real problem exceedingly complex. Solutions to such cavities can only be handled by large numerical codes. Some modeling of gain distribution has been carried out by considering the effect of gain to be represented by a gain sheet [29] or sheets located in the cavity. The technique permits decoupling of the propagation from the change in energy of the wave. The method is of limited use because of the divergence of the waves in the medium and probably not so good for large \(M\).

Calculations have been made comparing the modes of an unstable resonator with gain to that with a uniform medium. The mode intensity distribution becomes more uniform in the presence of a saturable

Fig. 11. Mirror Alignment Effects
medium because the gain is lower at high intensity than at low intensity [30]. There is little effect on phase if refraction effects are excluded from the calculation. These effects together with mirror heating and deformation can be extremely important when considering the sensitivity of the cavity to alignment errors. Some continuous laser experiments have actually become pulsed with such interactions [31,32]. This is referred to as the mode media interaction problem and is unique to high power lasers.

Of course, simple idealized models don't approach the real situations many times and more complicated codes must be used. For example, the BLAZER computer code is used for wave analysis supplemented with RESALE codes for chemical processes if present [3]. The solutions are far too involved to treat in any analytic fashion and vary from device to device. This is especially true if multiple spectral lines are involved as in the case of an HF laser. In the final scenario the only sure way to analyze real cavity behavior is by diagnostic experiments for beam power and energy [3].

ADAPTIVE OPTICS.--Through design errors or unavoidable beam propagation problems, the ideal amplitude and phase distribution across a laser beam may be less than desired giving rise to poor far field performance. Optical components whose characteristics can be altered are now being investigated and used as a means to improve this performance. The term active optics refers to an adaptive optical system that operates in real time in order to control wavefronts. Here we briefly discuss the role of adaptive optics in high power laser operation.

The integral solution of the wave equation in a weakly refractive medium shows that the intensity at a point P in the far field is approximately [33]

$$I(P) = \left| \frac{1}{\lambda S_0} \iint_{(4\pi)^2} E(r)^2 k ds dr \right|^2$$

where $s$ represents the ray path from the source to $P$, $E$ is the amplitude distribution of the source, $\phi$ is the initial phase distribution, and $n$ represents the index of refraction along the ray path. Three things besides the overall laser power level affect the intensity at $P$ and should be noted in this formula. Two of these were mentioned in the previous section. The first is $\phi$ which is affected by the presence of many transverse modes, figure errors of the mirrors in the cavity and other sources of phase error. The second is $E(r)$ which, if not uniform, affects $I(P)$ in a deleterious way by increasing the energy in the side lobes. Nonuniform amplitude is typical with large N laser cavities (Fig. 8). Finally, there is the integral which is the optical path length. This integral is affected by index of refraction variations caused either by turbulence or thermal blooming (i.e., a change in the medium by heating action of the beam itself). Fortunately, $n$ is almost one for many problems of interest. The value of $n-1$ may be written as $\beta_0$ where the value of $\beta$ is $0(3x10^{-4})$ typically and the density, $\rho$, is measured in amagats. Thus the integral of $\beta(n-1)ds$ represents phase changes due to $\rho$ variations. If $\rho$ is constant, there will be no effect on $I(P)$, but a spatial variation in $\beta(r)$ gives a spatial phase variation which contributes to a degradation in far field performance. It should be noted that adaptive optics attempts to modify phase errors by interjecting a compensating optical element in the wave train. Appreciable success has already been achieved [34]. As yet, to the author's knowledge there is no known way to correct for amplitude variations once they occur. Fortunately, the phase corrections are the most important as they affect the beam most.

Suppose that $\beta(n-1)ds$ is zero, that the amplitude of the field is constant, and that the initial phase distribution over the laser beam is nonzero and small. Then the reduction in peak light intensity relative to the beam is given by [35]

$$I/I_0 = 1 - \frac{\Delta \phi}{\phi_0}^2 = 1 - \Delta \phi^2$$

where $I_0$ is the intensity for an unaberrated beam and $\Delta \phi^2$ is the mean square error of phase over the beam cross section (after subtraction of tilt and focus). This figure of merit is known as the Strehl ratio [36]. The result shows that this ratio is independent of the nature of the aberration and demonstrates the extreme sensitivity of the image peak intensity to phase error.

Aberrations are wavefront deviations from a spherical reference sphere. In a classical sense these aberrations are described in terms of a set of characteristic functions depending on the wavefront modification and then labeled as tilt, astigmatism, coma, spherical aberrations, etc. [35]. The simplest active systems are those that control tilt or focus of a beam. In the former, this is just a flat mirror whereas the latter is usually done by adjusting the separation distance of two focusing elements.
as in a Cassegranian telescope. Most active optical systems are directed toward removal of the more complicated aberrations of wave fronts such as astigmatism and coma and this is where the research currently lies for laser application.

Basic Active Optics Systems for Laser Transmission. -- Usually the active optical system is designed to optimize a property of the system such as the energy density at a specific location. Three basic components are required [36]: a wavefront modifying device; a measuring device which accepts laser light and provides an output related to the property being optimized; and an information processing device which through appropriate algorithms converts the measured data into control signals for the wavefront modifying device. Two basic systems which are used in laser transmission are shown in Fig. 12. Such systems normally operate on a single wavelength using the radiation generated by the laser. If more than one spectral line is involved such as in the chemical laser, considerable additional complication is involved in order to phase lock the various spectral lines [37]. Simpler systems would be advantageous.

In Fig. 12a, the phase conjugation approach, the beam reaching the target gives rise to reflection from small areas producing glints which generate spherical waves. These reflected waves traverse the same propagation path in a reverse direction and are spatially modified by the same optical disturbance as the transmitted beam. The received wave is compared to a local reference wave and the required correction, which is the phase conjugate of the measured wavefront distortion, is generated.

The second system (Fig. 12b) is a multidither or aperture tagging approach in which small perturbations in phase, \( \phi \ll \pi \), are made on each small segmented area on the outgoing beam. The optical power returned from a glint is analyzed to determine which part of the aperture is to be adjusted. These perturbations are always added to the wavefront so that there is always some residual error, but this is small. In this approach the return signals do not have to propagate along the same optical path as the transmitted beam.

Depending on the physical situation or tracking mode one method may have an advantage over the other. Both approaches are being pursued for active laser beam control. It appears that the phase conjugate system can operate quite fast \( (0\text{msec}) \) if convergence of the loop has been obtained. Loop convergence times will be long \( (0\text{sec}) \), however, at low signal to noise ratios which occur at large ranges. In the case of the multidither system the convergence time can be short even at rather large ranges [36]. Either frequencies (sinusoidal perturbations) can be quite high. In the case of one experiment [38] these frequencies range from 8-32 kHz with a spacing of 1.4 kHz and gave an overall convergence time of 1.5 to 3 msec.

Wavefront Modifying Devices. -- Both reflective and refractive wavefront modifying devices are possible in principle. At the present time reflective devices (mirrors) are the most successfully used correctors and this is what is described here. The regimes in which active mirrors operate may be separated in terms of wavefront correction range and frequency response and are shown in Fig. 13. For large mirrors with large deflections the frequency response is poor and their function is primarily for figure control of a system. Curve B shows the operating range for mirrors that require high frequency response but not necessarily large deflection as for atmospheric correction. Lastly the small rectangular area is required for aperture tagging the mirrors.

To meet these needs four basic types of active mirrors have been developed and are shown in Fig. 14. Of these, only the first two seem to be useful for high power application. The piston type mirrors use piezoelectric position actuators which under the right circumstances can be driven to frequencies on the order of 10 kHz and tend to be small. From the optical point of view, the use of segments having both piston and tilt capability is preferable as
fewer segments are required to match a given wavefront. Somewhat larger mirrors tend to be made as a deformable thin-plate. This type has reached a high stage of development and is more easily cooled than others.

Another possible approach which is just being investigated is a refractive type device using free gas jets. This idea developed from our understanding of the aerodynamic window as an optical element. It may be possible to improve the optical quality of a high power laser beam by inducing phase changes in the aerodynamic window itself. But this possibility has not yet been proven in the laboratory.

Applications. -- Turbulence: Much interest in adaptive optics centers on turbulence compensation at the IR wavelengths and the question naturally arises as to how much compensation is possible. To a large extent this depends on the turbulent scale dimension and the required frequency response. Fortunately, in the case of atmospheric turbulence the required bandwidth is only several hundred hertz which, although difficult to implement, is not an impossibly high bandwidth. It is extremely difficult to get a system with a bandwidth greater than 1 kHz. Intense turbulence and smaller scale turbulence requires increasing the number of degrees of freedom of the system sensibly. In fact, small scale turbulence that exists in boundary layers in laser cavities or on aircraft probably can't be corrected for.

Atmospheric turbulence is a distortion which is not a function of laser power and is referred to as a linear interaction. As such, it is relatively easy to improve the Strehl ratio (provided the scale length is not too small). Improvements with a multiplexer system are detailed in [41,42].

Thermal blooming: Another and more difficult type of disturbance is that of thermal blooming. This is a nonlinear interaction caused by the inevitable heating of the atmosphere by the laser and creates an undesirable lensing action and defocusing of the beam. It is distinctly a high power laser phenomenon and depends critically on the laser power. The lensing action takes place all along the beam path and so the effective lens is thick. Preliminary work on compensation for thermal blooming has been considerably less successful than for turbulent compensation. Simply altering the phase profile and thus the projected far field pattern just shifts the problem to another region of the beam in the case of blooming. In some simple cases there is no solution in principle [43]. In any case there is little or no improvement, whereas for turbulence the
improvement is as good as one makes the wavefront corrector. Real time compensation for thermal blooming has been demonstrated in the laboratory [44] using a tagged aperture approach. The results for this experiment are shown in Fig. 15 wherein it is seen that the intensity on target was increased 2.5 times over that without using active optics. A sensible improvement, but one which is clearly limited. One other promising approach is the use of predictive phase compensation [45]. Here the optimum phase distribution can be worked out in advance and applied with only minor feedback corrections. Other algorithms are being investigated too.

In many cases thermal blooming exists in the presence of a relative wind, either due to an actual wind, a movement of the transmitter, or an apparent wind caused by the tracking of some moving target. In some ways the latter is an easier problem as the lensing action is then strongest near the transmitter, affording a better opportunity to improve the far field pattern. Thermal blooming with wind produces crescent shaped far field patterns which move (tilt) into the wind. Figure 16 shows calculated results for the change in peak flux as a function of nondimensional slew rate $N_W$ (relative wind) and distortion number $N_D$ (beam power). One sees that increasing the wind reduces the effects of thermal blooming and so does the use of active optics. For fixed slew rate we can increase the irradiance on target by 2.5 again.

Herrmann [43] has shown that the phase conjugate method leads to nearly complete compensation of atmospheric turbulence. Partial compensation for cases with moderate blooming with and without turbulence are possible if the effective thermal lenses is near the transmitter as for slewed beams. For cases with substantial blooming, the method only gives limited improvement.

Adaptive Optics in Resonators: Recently there have been studies concerning the use of adaptive optics in resonators because of their known sensitivity to alignment. Computer studies [46] have shown that azimuthal mirror misfigures in cylindrical resonators as small as $\lambda/20$ can lead to severe degradation in the Strehl ratio. However, it was shown that this error can be substantially compensated by using an adaptive optical element for the outer axicon as the results in Table II show. This element is operated in a static mode but the actuators are

Table II. Computer Results for Distorsions of the Form $(\lambda/N) \cos 2a$ Applied to the Rear Cone [46]

<table>
<thead>
<tr>
<th>Misfigure</th>
<th>Strehl Ratio Without Compensation</th>
<th>Strehl Ratio With Compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda/120 \cos 2$</td>
<td>0.9010</td>
<td>0.9996</td>
</tr>
<tr>
<td>$\lambda/40 \cos 2$</td>
<td>0.6016</td>
<td>0.9916</td>
</tr>
<tr>
<td>$\lambda/20 \cos 2$</td>
<td>0.4012</td>
<td>0.9916</td>
</tr>
<tr>
<td>$\lambda/10 \cos 2$</td>
<td>0.1056</td>
<td>0.9911</td>
</tr>
</tbody>
</table>
adjusted (in the computation) to maximize the Strehl ratio. The improvement with the proper actuator setting is excellent. Other trial cases using distortions on other conical elements showed similar improvements. While these calculations were carried out without a gain medium, the basic compensation method is likely to be successful under gain conditions including the possibility of including an active feedback system for slowly varying resonator properties.

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References.