REVERSE-WAVE SUPPRESSOR MIRROR EFFECTS ON CW HF UNSTABLE RING LASER PERFO. (U) AEROSPACE CORP EL SEGUNDO CA AEROPHYSICS LAB J M BERNARD ET AL.

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Reverse-Wave Suppressor Mirror Effects on CW HF Unstable Ring Laser Performance

J. M. BERNARD, R. A. CHODZKO, and H. MIRELS
Aerophysics Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, CA 90245

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SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, CA 90009-2960
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Lt Scott W. Levinson/YNS was the Air Force project officer.

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SCOTT W. LEVINSON, Lt, USAF
MOIE Project Officer
SD/YNS

JOSEPH HESS, GM-15
Director, AFSTC West Coast Office
AFSTC/WCO OL-AB
The effect of a reverse-wave suppressor (RWS) mirror on the performance of a CW HF unstable ring laser has been measured in terms of forward/reverse-wave power ratio ($P_F/P_R$) and forward-wave beam quality. It was found that a well-aligned RWS mirror gave the best suppression ($P_F/P_R = 100$) and diffraction-limited beam quality. Resonator performance degraded rapidly with misalignment of the RWS mirror: a 200-μrad tilt reduced $P_F/P_R$ to 2.5 and the beam quality by a factor of 2. The forward-wave near-field pattern...
showed distinct fringes as the RWS mirror was misaligned, suggesting that a higher-order mode was causing the beam quality to degrade. A novel technique was developed to reduce the alignment sensitivity of the RWS mirror. By use of a distorted relay mirror, an aberrated ($\pm 2 \lambda$) reverse wave was fed back into the ring. The aberrated reverse-wave feedback greatly reduced the sensitivity of resonator performance to RWS mirror tilt. Diffraction-limited beam quality and good suppression ($F_0/F_R = 20$) was observed over a tilt range of 600 arcmin. It is postulated that the aberrated RWS mirror provides sufficient feedback to suppress the reverse wave over a wide angular range, yet not enough to produce higher-order transverse modes in the forward wave.
PREFACE

The authors acknowledge many helpful discussions with W. Evers, R. Wade, P. Latham, S. L. Chao, D. Dee, S. Hixson, and W. R. Warren, Jr., in defining the experimental program and interpreting the data. The experimental apparatus was maintained and operated by H. Bixler, T. Bixler, and R. Cook.
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I. INTRODUCTION

Reverse-wave suppression in ring resonators has been studied by Faxvog\(^1,2\) for stable, single-line He-Ne lasers. Suppression yielding forward-to-reverse power ratios \(P_F/P_R\) greater than 100 was reported and discussed theoretically. Experimental studies of single-line unstable ring lasers have been presented for both homogeneously broadened\(^3,4\) and inhomogeneously broadened\(^5\) gain media. Frieberg et al.\(^4\) observed that \(P_F/P_R\) is relatively insensitive to the radius of curvature or axial location of the suppressor mirror. The above authors emphasized the dependence of the forward-to-reverse power ratio on the degree of coupling between the two waves, and when a feedback mirror was used, its coupling was optimized by careful alignment. The present study includes measurements of beam quality as well as \(P_F/P_R\), and thus provides a performance parameter by which the misalignment sensitivity of various suppressor mirrors can be compared.

We have previously published a theoretical and experimental study\(^6\) demonstrating that excellent reverse-wave suppression \((P_F/P_R\) up to 92) can be obtained in a multiline, inhomogeneously broadened, multimode continuous-wave hydrogen fluoride (CW HF) unstable ring laser. In the present study, we have avoided the thermal distortion problem that limited CW HF laser beam quality to \(1/n^2 = 0.5\) in Ref. 6, and have implemented diagnostics that simultaneously record \(P_F(t), P_R(t),\) and \(n^2(t)\). [Here, \(1/n^2\) is the ratio expressing the experimental laser's power through an aperture in the far field (of Airy disc size) divided by the power for the same laser with uniform near-field phase and intensity.] We can therefore measure the effect of various types of feedback on CW HF ring laser performance.

In particular, we first present experimental results for a well-aligned reverse-wave feedback mirror. Forward-to-reverse power ratio, beam quality, and temporal stability are noted. The effects of suppressor mirror tilt and partial feedback are then examined. Finally, the use of an aberrated relay mirror to reduce laser sensitivity to suppressor mirror tilt is examined.
II. EXPERIMENTAL APPARATUS

A schematic diagram of the ring resonator is shown in Fig. 1. The single-pass round-trip length of this ring is 12.5 m. Mirrors \( M_3 \) and \( M_4 \) comprise a telescope of magnification 1.72. Two double-sided output scraper mirrors, with hole diameters of 10.5 and 14.3 mm, were used in these tests. This allowed us to test at two values of equivalent Fresnel number \( N_{eq} \). For a ring resonator,

\[
N_{eq} = \frac{a^2(M^2 - 1)}{2\lambda(L_1M^2 + L_2M + L_3)}
\]

where \( a \) is the scraper hole radius and \( \lambda \) is the laser wavelength. Referring to Fig. 1, \( L_1 = 3.5 \) m is the distance traveled by the forward wave from the scraper mirror to \( M_3 \), \( L_3 = 8.4 \) m is the distance from \( M_4 \) back to the scraper, and \( L_2 = 0.6 \) m is the telescope length, from \( M_3 \) to \( M_4 \). The latter mirrors have radii of curvature \(-1.72 \) m and \(+2.98 \) m, respectively. In the present case, \( N_{eq} = 0.5 \) and 0.9, respectively, for the two scrapers.

The large value of \( L_1 + L_2 + L_3 \), chosen to ensure that forward and reverse waves compete for the same gain, makes \( N_{eq} \) slightly less than unity for mode sizes on the order of the gain region size. The \( N_{eq} = 0.5 \) resonator was chosen first because the gain region uniformly fills the mode, as shown in Fig. 2. The \( N_{eq} = 0.9 \) case is the largest practical Fresnel number that we could test, since the gain slightly underfills the mode (see Fig. 2). Since no significant effect of Fresnel number on the performance parameters measured by us was found, we believe that our results are representative of resonators having even larger values of \( N_{eq} \).

These resonators are used with 2 mm and 5 mm downstream decentering of the optical axis, respectively, in order to avoid obscuration of the laser mode by the nozzle exit hardware. Note that the reverse wave reflects from a relay mirror on its way to and from the suppressor mirror.

The gain generator and gain medium properties are discussed in Ref. 7. The spatial relationship between the gain distribution for \( P_1(4) \) and
Fig. 1. Optical Schematic Diagram of the Unstable Ring Resonator. Gain region flow is in the vertically upward direction.
Fig. 2. (a) Gain Distribution as a Function of Downstream Distance for $P_1(4)$ and $P_2(3$ and $4)$, Compared to the Forward-Wave Mode Envelope Entering and Exiting the Gain Region (Station A in Fig. 1). (b) Forward-Wave Mode Envelopes, Showing the Variation of Gain Volume Height with Downstream Distance.
$P_2(3 \text{ and } 4)$ and the forward-wave mode envelope at the beginning and end of its two passes through the gain region is shown in Fig. 2 for both Fresnel numbers. In general, the $P_1(J)$ lines fill the mode volume for both passes, while the $P_2(J)$ lines do not. The large gain gradient within the mode volume on some lines explains our observation of a sensitivity of the laser output line spectrum to millimeter changes in the location of the optic axis within the gain region.

A schematic diagram of the diagnostic facilities used in these tests is given in Fig. 3. The forward-wave beam quality (BQ) is measured as $1/n^2$: the percentage of the far-field focused power transmitted through an aperture of diameter equal to that of the first null in the theoretical Airy pattern (based on a uniform-intensity and uniform-phase annulus in the near field) divided by the percentage of the total power theoretically contained within the first null. Good beam quality is considered to be $0.9 < 1/n^2 < 1.0$, while lower numbers denote worse BQ.

Three room-temperature indium-arsenide detectors provide the time-dependent laser intensity data for these experiments. They are illuminated by (1) a forward-wave beam that is transmitted through the aperture, (2) a forward-wave reference signal, and (3) a reverse-wave reference signal. Suitably amplified, the detector outputs provide waveforms that are stored on a digital oscilloscope. These waveforms can then be divided by each other to give the percent transmission (proportional to $n^{-2}$) through the aperture, and the forward-to-reverse power ratio as functions of time. These waveforms can also be analyzed to determine the rms fluctuations in the powers or BQ. Two spectrometers with detector arrays were used to document the forward- and reverse-wave spectral contents. Typically, the ring laser simultaneously outputs seven spectral lines, with most of the power on $P_1(4)$ and $P_2(5 \text{ and } 6)$. In the absence of reverse-wave suppression, the same lines appear in the forward and reverse directions, and perturbations in the forward and reverse waveforms for a given line are anticorrelated.

An intracavity shutter was used to limit the heat loading on the resonator and diagnostic mirrors. The laser on-time was limited to 30 msec.
which is comparable to the time scale that we measured for the start of beam-
quality degradation due to thermal distortion. The digital oscilloscope thus
records only data taken while the mirrors have their proper figure. With
optimized resonator and suppressor alignment, diffraction-limited operation
($n^{-2} = 1.00$) was obtained over this time scale.

Two pyroelectric energy detectors are used, with digital readouts that
display the total energy output in the forward and reverse waves during the
laser on-time. These measurements provide an accurate average $P_F/P_R$, and
calibrate their respective waveforms (as recorded on the digital oscilloscope)
to yield $P_F(t)$ and $P_R(t)$. 


III. EXPERIMENTAL RESULTS

The performance of the CW HF ring laser was first investigated for the case of an aligned reverse-wave suppressor mirror and for cases with suppressor mirror tilt. The effect of partial forward-wave feedback was then studied. Finally, the use of an aberrated reverse-wave relay mirror, to reduce suppressor mirror tilt sensitivity, was investigated. These results are noted below.

A. ALIGNED REVERSE-WAVE SUPPRESSOR MIRROR

Measurements were made to characterize laser performance by using an aligned suppressor mirror (having a spherical figure within 1/10 of the HF laser wavelength) whose +10-m curvature matched the theoretical radius of curvature of the reverse wave at the suppressor mirror location. The quantitative performance of the $N_{eq} = 0.5$ and 0.9 resonators, with and without the aligned suppressor mirror, is summarized in Table 1. Shown are the beam quality of the forward wave, forward and reverse powers, their rms fluctuation intensity $\sigma$, and the far-field centerline brightness parameter $P_F/n^2$ (which is proportional to the forward-wave power contained within the focused spot). Typical of the results of a given test series, these data display the improvement in performance obtainable by means of a well-aligned suppressor mirror. Not only is the forward power enhanced with no loss in beam quality, but the fluctuation intensity $\sigma$ has been halved. The ability of the suppressor mirror to improve temporal stability is in accord with the theoretical results of Ref. 6. The beam quality of the $N_{eq} = 0.9$ resonator is less than that for $N_{eq} = 0.5$, as a result of partial-aperture lasing in the vertical direction caused by the gain region being vertically smaller than the mode (see Fig. 2).

A two-step procedure was used to ensure that the suppressor mirror was aligned. In the first step, the suppressor mirror was adjusted so that the near-field interference fringes, in the forward wave, were axisymmetric (these fringes, discussed in the next section, could be seen to respond to suppressor tilt). The second step was to minimize the power in the reverse wave. When the suppressor mirror was near alignment, we found an extreme sensitivity of
Table 1. Performance of the Two Ring Resonators with the Mirror Out, and with a Well-Aligned RWS Mirror In. Here, $\sigma$ is the rms power fluctuation in watts.

<table>
<thead>
<tr>
<th>$N_{eq}$</th>
<th>Suppressor</th>
<th>$n_F^2$</th>
<th>$P_F$, W</th>
<th>$P_R$, W</th>
<th>$P_F/P_R$, W</th>
<th>$\sigma_F$, W</th>
<th>$\sigma_F/P_F$,</th>
<th>$\sigma_R$, W</th>
<th>$\sigma_R/P_R$,</th>
<th>$P_F/n_F^2$, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>Out</td>
<td>1.0</td>
<td>214</td>
<td>67</td>
<td>3.2</td>
<td>32</td>
<td>0.15</td>
<td>44</td>
<td>0.66</td>
<td>214</td>
</tr>
<tr>
<td></td>
<td>In</td>
<td>1.0</td>
<td>242</td>
<td>3.9</td>
<td>62</td>
<td>12</td>
<td>0.05</td>
<td>2.2</td>
<td>0.58</td>
<td>242</td>
</tr>
<tr>
<td>0.9</td>
<td>Out</td>
<td>1.1</td>
<td>135</td>
<td>115</td>
<td>1.2</td>
<td>16</td>
<td>0.12</td>
<td>25</td>
<td>0.22</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>In</td>
<td>1.1</td>
<td>245</td>
<td>4.2</td>
<td>58</td>
<td>13</td>
<td>0.05</td>
<td>2.0</td>
<td>0.48</td>
<td>223</td>
</tr>
</tbody>
</table>
reverse-wave power to suppressor mirror tilt. Excellent suppression
\( \frac{P_F}{P_R} = 100 \) could be obtained within 10 microradians (\( \mu \text{rad} \)) of optimum
alignment. Greater suppression \( \frac{P_F}{P_R} > 1000 \) was occasionally achievable,
with great difficulty, but was stable for only minutes. The measurements of
suppression reported in Table 1 are for an average of 20 runs, and include
examples of runs that were within \( \pm 10 \mu \text{rad} \) of optimum. Systematic measurement
of tilt sensitivity in the 10-\( \mu \text{rad} \) range requires improved room-temperature
stabilization and mirror mount adjustment.

B. EFFECT OF SUPPRESSOR MIRROR TILT

The effect of suppressor mirror tilt was evaluated by observing inter-
ference patterns in the forward-wave output beam and by measuring \( \frac{P_F}{P_R} \) and
beam quality as a function of suppressor mirror tilt. These results are dis-
cussed below.

1. INTERFERENCE PATTERNS

Typical forward-wave near- and far-field intensity patterns are noted in
Fig. 4 for the cases of no suppressor mirror, an aligned suppressor mirror,
and a tilted suppressor mirror. These patterns were observed on thermally
sensitive paper (Thermo-fax) that darkens with the application of heat. In
the case of no suppressor mirror, Fig. 4a, the near field was a nearly uniform
annulus and the far field was a diffraction-limited spot \( (n^2 = 1) \). For the
case of an aligned suppressor mirror, Fig. 4b, faint circular interference
fringes were observed in the near field. The far-field spot was again
symmetric and diffraction-limited. Figures 4c and 4d indicate that the effect
of tilt is to drive the near-field intensity in the tilt direction, here hori-
zontally upstream. High-visibility, asymmetric interference fringes are seen
in the near field. With increase in tilt, the far field elongates and
eventually appears as two spots. Thus, far-field beam quality degrades with
tilt.

The patterns in the near field may be viewed as the interference of two
(or more) phase-related forward-wave modes. One of these is the fundamental
(low-loss) forward-wave mode associated with the well-aligned resonator. The
second wave may be viewed as a higher-order (high-loss) forward-wave mode that
Fig. 4. Qualitative Near- and Far-Field Intensity Distributions of the Forward Wave for the $N_{eq} = 0.5$ Resonator. (a) Without suppression, (b) with aligned suppressor, (c) with suppressor tilted 300 μrad, and (d) with suppressor tilted 600 μrad. Suppressor mirror tilt is horizontal and drives the near field in an upstream direction. (Patterns are observed on thermal paper.)
is initiated and maintained by the injection of the reverse wave into the resonator by the suppressor mirror. The reinjected reverse wave also partly supports the fundamental low-loss forward wave, thereby partly suppressing the corresponding fundamental low-loss reverse wave. When the suppressor mirror is aligned, the reinjected reverse wave is weak and supports a low-loss symmetric mode similar to the fundamental forward-wave mode. Hence there is no loss in beam quality and the interference fringes are weak. With increase in tilt, the reverse-wave power is increased, leading to increased power in the higher-order modes, increased near-field fringe visibility, and poorer beam quality.

The presence of the fringes indicates that the two modes are phase-related. This is in accord with ring resonator theory, which indicates that when a suppressor mirror is used the forward and reverse waves are phase-locked during stable operation.

The present discussion represents a first attempt to explain the interference patterns associated with a tilted reverse-wave suppressor mirror. Current physical optics studies of the coupled forward- and reverse-wave modes will lead to a more comprehensive understanding of these patterns.

2. LASER PERFORMANCE

The effect of suppressor mirror tilt on forward-to-reverse power ratio and beam quality for the $N_{eq} = 0.5$ resonator is given in Fig. 5. This figure is an average of many tests. As expected, both $P_F/P_R$ and $1/n^2$ decrease with increasing tilt, with at most a 10-μrad tilt tolerance for optimum $P_F/P_R$, and a 50-μrad tilt tolerance for beam quality.

As previously noted, far-field centerline brightness is proportional to $P_F/n^2$. This quantity, for the data in Fig. 5, is included in Fig. 6 as the dashed line denoted "conventional relay mirror." The far-field brightness is relatively insensitive to $P_F/P_R$, for $P_F/P_R > 0(10)$, and therefore depends primarily on beam quality. Hence the brightness curve in Fig. 6 is similar to the curve for $1/n^2$ in Fig. 5. The limit of very large suppressor mirror tilt ultimately corresponds to that for the case of no suppressor mirror. In this
Fig. 5. Measured Dependence of the Forward-to-Reverse-Wave Power Ratio and Beam Quality on Horizontal Tilt of the Suppressor Mirror for the $N_{eq} = 0.5$ Resonator
Fig. 6. Effect of Suppressor Mirror Tilt on Forward-Wave Far-Field Brightness for Cases of Conventional and Aberrated Relay Mirrors for the $N_{eq} = 0.5$ Resonator
limit, \( P_F/P_R + 1, 1/n^2 + 1 \), and \( P_F/n^2 \) approaches half of the value for zero tilt, as noted in Fig. 6.

C. PARTIAL FEEDBACK

The effect of partial suppressor mirror feedback is examined analytically and experimentally in this section. We consider the case where the ring resonator length is adjusted so that the forward and reverse waves compete for the same gain medium. In this limit, \( ^6 \)

\[
P_F/P_R = \sqrt{R^-/R^+} \tag{1a}
\]

\[
\equiv \sqrt{(R^-_M + R^-_b)/(R^+_M + R^+_b)} \tag{1b}
\]

where \( R^+ \) denotes the net reflection coefficient for reflection of the forward wave into the reverse direction. Also, \( R^+ \equiv R^+_M + R^+_b \), where \( R^+_M \) is the contribution of a forward-wave suppressor mirror (if present) and \( R^+_b \) is the contribution of diffractive and surface-particle backscatter. A similar definition applies for \( R^- \). In general, \( R^+_b/R^-_b = 0(1) \).

An experiment was conducted to evaluate \( R^+_b \) and to validate Eq. (1). The \( N_{eq} = 0.9 \) resonator was used. For convenience, the forward wave was suppressed and reverse-wave power and beam quality were measured. Various percentages of forward-to-reverse feedback were used. In this case, \( R^-_M = 0 \), \( R^+_M \neq 0 \), and Eq. (1) becomes

\[
P_F/P_R = \sqrt{R^-_b/R^+_M} \left[ 1 + O(R^+_b/R^+_M) \right] \tag{2}
\]

A schematic diagram of this experiment is shown in Fig. 7. A flat feedback mirror provided 92% return, and two filters transmitting 50% were inserted sequentially to obtain 23% and 6% feedback of the forward wave into the reverse direction; the latter corresponds to \( R^+_M \). These tests are
Fig. 7. Schematic Diagram of the Forward-Wave Feedback Tests
summarized in Table 2. Substitution of the values of $P_F/P_R$ from this table for $R^+_M = 0.06, 0.23, \text{ and } 0.92$ into Eq. (2) yields $R_b \times 10^4 = 1.98, 1.49, \text{ and } 1.68$, respectively. The approximate constancy of the values for $R_b$ tends to validate Eq. (1) and thereby the theory of Ref. 6. It is seen that for the present resonator, $R^-_b = O(10^{-4})$. It may be assumed that $R^+_b$ is of the same order so that the approximation in Eq. (2) is valid. Finally, it is seen that, for a well-aligned suppressor mirror, only a small percentage of feedback is needed to achieve significant suppression. Thus an aligned reverse-wave suppressor mirror with $R^+_M = 0.01 \text{ will result in } P_F/P_R = 10$, no loss in forward-wave beam quality, and a forward-wave far-field brightness within 10% of the value for $R^-_M = 1.00$. This result suggests the use of an aberrated relay mirror to reduce ring resonator performance sensitivity to tilt, as discussed in the next section.

D. ABERRATED REVERSE-WAVE RELAY MIRROR

The extreme sensitivity of a conventional ring laser to suppressor mirror tilt, and the substantial suppression obtained by partial feedback, suggested that a suppressor mirror that spread its feedback over a wide angular range may provide suppression with reduced tilt sensitivity. This can be achieved by the use of an aberrated reverse-wave relay mirror. The effect of such a mirror on beam quality could not be predicted, but it was hoped to be minimal; if the feedback that reinforces the forward-wave fundamental mode is comparable to the feedback that tends to reinforce higher-order modes, the fundamental mode will have the lowest loss and should dominate.

An aluminum substrate was prepared as a reverse-wave relay mirror using conventional machine-shop polishing techniques, with no regard to surface figure. A photograph and an interferogram (taken with 633-nm light, at +18.5-m radius of curvature) of this mirror appear in Fig. 8. The interferogram shows that the mirror surface has random undulations of +3 microns at spatial frequencies of $5 \text{ cm}^{-1}$ and less. The reflectance as a function of angle along several meridians (spaced by $30^\circ$) of this mirror is compared to an optical quality (less than 150 nm surface misfigure at less than $1 \text{ cm}^{-1}$
Table 2. Performance of the $N_{eq} = 0.9$ Resonator with Varying Percentages of Forward-Wave Feedback

<table>
<thead>
<tr>
<th>% FW</th>
<th>$n_F^2$</th>
<th>$P_F$, W</th>
<th>$P_R$, W</th>
<th>$P_R/P_F$</th>
<th>$\sigma_F/P_F$</th>
<th>$\sigma_R/P_R$</th>
<th>$R_b^{-} \times 10^{-4}$</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>1.1</td>
<td>122</td>
<td>97</td>
<td>0.81</td>
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<td>0.148</td>
<td>62</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>19</td>
<td>331</td>
<td>17.4</td>
<td>10</td>
<td>0.526</td>
<td>25</td>
</tr>
<tr>
<td>23</td>
<td>1.1</td>
<td>8</td>
<td>320</td>
<td>39.3</td>
<td>8</td>
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<tr>
<td>92</td>
<td>-</td>
<td>6</td>
<td>442</td>
<td>74</td>
<td>4.4</td>
<td>0.733</td>
<td>36</td>
</tr>
</tbody>
</table>
Fig. 8. (a) Photograph and (b) Interferogram of the Aberrated Relay Mirror
spatial frequency) flat mirror in Fig. 9. The ordinate in this figure is the power transmitted through a fixed aperture (of Airy disc size) at the nominal reflected-wave focal point. The aberrated mirror provides a focal spot of roughly ten times the angular extent of a conventional mirror. Polishing scratches perpendicular to the 60° meridian are responsible for the large angular spread of scattered light in that direction.

The performance of the $N_{eq} = 0.5$ resonator was investigated by using the aberrated relay mirror in the reverse-wave feedback path. Because of relay mirror aberration, the zero-tilt alignment position of the suppressor mirror was uncertain to within ±200 μrad. A nominal zero-tilt position was chosen and the suppressor mirror tilt was systematically increased to a value of 600 μrad. The resulting variation of $P_F/P_R$ and $1/n^2$ with tilt is given in Fig. 10 and the corresponding variation of $P_F/n^2$ is given in Fig. 6. Figure 10 indicates a slight deterioration in beam quality from the value $n^2 = 1.0$, and values of $P_F/P_R$ in the range of 10 to 25. No systematic variation of these quantities with suppressor mirror tilt is observed. This result may be contrasted with the severe degradation of $P_F/P_R$ and beam quality with suppressor mirror tilt noted in Fig. 5 for a conventional relay mirror. The effect of tilt on far-field brightness for the two relay mirrors is indicated in Fig. 6. The value of $P_F/n^2$ for the aberrated relay mirror is seen to be insensitive to suppressor mirror tilt for the entire tilt range under investigation. Moreover, $P_F/n^2$ is within 10% of the value for an aligned suppressor mirror with a conventional relay mirror. In the present case, the aberrated mirror provides superior far-field brightness when suppressor mirror tilt exceeds 100 μrad.

In the case of the aberrated relay mirror, the insensitivity of $P_F/P_R$ to tilt is a consequence of the large angular spread of the feedback, as shown in Fig. 9. The insensitivity of beam quality to tilt is a result of the fact that the amount of reverse-wave power fed back into individual higher-order forward-wave resonator modes is inadequate to compensate for the higher losses in these modes compared with the fundamental. Hence the fundamental (high beam quality) mode dominates. An aberrated relay mirror is expected to be useful in cases where suppressor mirror tilt and/or figure control is difficult or costly.
Fig. 9. Reflectance of the Aberrated Relay Mirror as a Function of Angle, along Three Meridians 30° Apart, Compared with the Same Measurement Taken on an Optically Flat Mirror
Fig. 10. Measured Sensitivity of Forward-to-Reverse-Wave Power Ratio and Beam Quality to Horizontal Tilt of the Suppressor Mirror, Using an Aberrated Relay Mirror. $N_{eq} = 0.5$. 

$P_F / P_R$ vs. SUPPRESSOR TILT, microradians
IV. CONCLUSIONS

The effect of suppressor mirror reflectivity and tilt on CW HF unstable ring laser performance has been evaluated in terms of $P_F/P_R$, $1/n^2$, and $P_F/n^2$. A systematic variation of suppressor mirror reflectivity yielded results that tend to validate Eq. (1) and the theory of Ref. 6, and indicate an intrinsic backscatter reflectivity of the order $R^0 = 0(10^{-4})$ for the present resonators. A conventional reverse-wave suppressor mirror system yielded the best resonator performance, but was sensitive to suppressor mirror tilt. An aberrated relay mirror was found to provide uniform far-field brightness over a 600-μrad tilt range.
REFERENCES


LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military space systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the nation's rapidly developing space systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

**Aerophysics Laboratory:** Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

**Chemistry and Physics Laboratory:** Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and infrared detectors, atomic frequency standards, and environmental chemistry.

**Computer Science Laboratory:** Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence, microelectronics applications, communication protocols, and computer security.

**Electronics Research Laboratory:** Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, RF systems, electromagnetic propagation phenomena, space communication systems.

**Materials Sciences Laboratory:** Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; non-destructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

**Space Sciences Laboratory:** Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.