Measured Beam Deformations in a Guide Made of Tubular Gas Lenses

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We discuss problems connected with the alignment of gas lenses and present experimental results showing the effects of off-axis injection of a light beam into a beam waveguide (offset $a/r \leqq 0.315$, r = radius of tubular lens) and of the introduction of various radii of curvatures ($R \geqq 500$ m) on the shape and position of the transmitted Gaussian beam. The theoretical prediction of reduced beam distortions for nonconfocal geometry was confirmed experimentally. We demonstrated low losses at small bending radii by using 12 lenses as focusing elements within a laser cavity in the bent state.

I. INTRODUCTION

Tubular gas lenses have possible use as focusing elements in an optical beam waveguide.[1,2] Theoretical analysis has shown that thermal gas lenses are not ideal; beam distortion from the cumulative effect of lens aberrations[2-6] and the beam wandering resulting from lens misalignments[7,8] limit the number of lenses that can be used in a beam waveguide. Beyond this number, corrective devices such as redirectors, refocusers, and mode filters must be used.[9,10] Redirectors sense the position of the beam and introduce deflections which tend to realign the beam with the guide axis. Refocusers sense the increase of beamwidth and tend to focus the beam back to its ideal profile. Mode filters reduce the content of unwanted higher order modes.

Previous experiments indicated difficulties with the accurate alignment of the lenses.[11] From this experience we worked out a method of alignment by which we achieved satisfactory accuracy and beam stability. Subsequently we measured the deformation of the beam transmitted off axis and around a bend and compared it with theory. We compared beam distortions for nonconfocal lens spacings with those of confocal geometry.

II. EXPERIMENTAL SETUP

Fig. 1 shows an experimental beam waveguide made of 10 gas lenses. Each lens was suspended within a 12-meter-long steel U-channel, and kept in place and aligned by two sets of screws as Fig. 2 shows. Because the lenses were not rigidly connected among themselves except through the U-channel, each could be aligned without impairing the alignment of previously-mounted lenses. An air-tight interconnection between lenses was accomplished by rubber hoses. The gas lenses used are described in Ref. 11. The actual lens elements (6.34 mm I.D., 15 cm long) were mounted within a 5.08 cm diameter waveguide tubing ($\frac{1}{2}$ meter long), which was connected rigidly to a 5.08 cm diameter, 0.5 m long spacer.

Focal length measurements were performed for a single lens as a function of gas flow rate F and temperature rise ΔT between the input gas and the heated cylindrical wall of the lens. A collimated laser beam was focused through the lens. The beam size as a function of the distance d from the geometrical center of the lens was measured (Fig. 3) and graphically extrapolated back into the lens until it intersected the half-power beamwidth of the collimated beam. The relative position of the intersection was a function of F and ΔT: for low flow rates the intersection occurred before, for higher flow rates beyond the geometrical center. For constant gas flow rate an increase in temperature shifted the intersection toward the beginning of the lens. This behavior had been predicted by theory.[3, 4] The position of the intersection was obtained with limited accuracy because it was not possible to follow the converging beam too far back into the lens. Hence, the focal length was determined from the distance d between the waist and the geometrical center of the lens. The average width

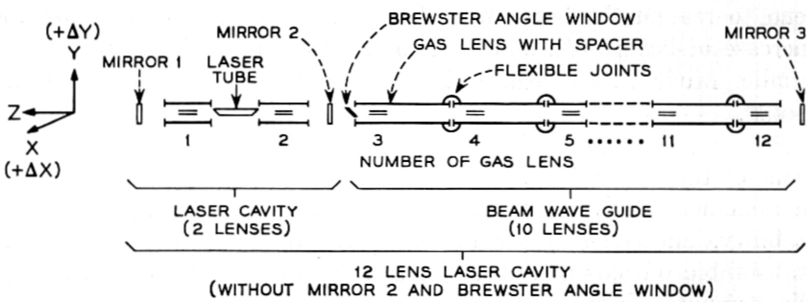

Fig. 1 — Experimental arrangement of beam waveguide.

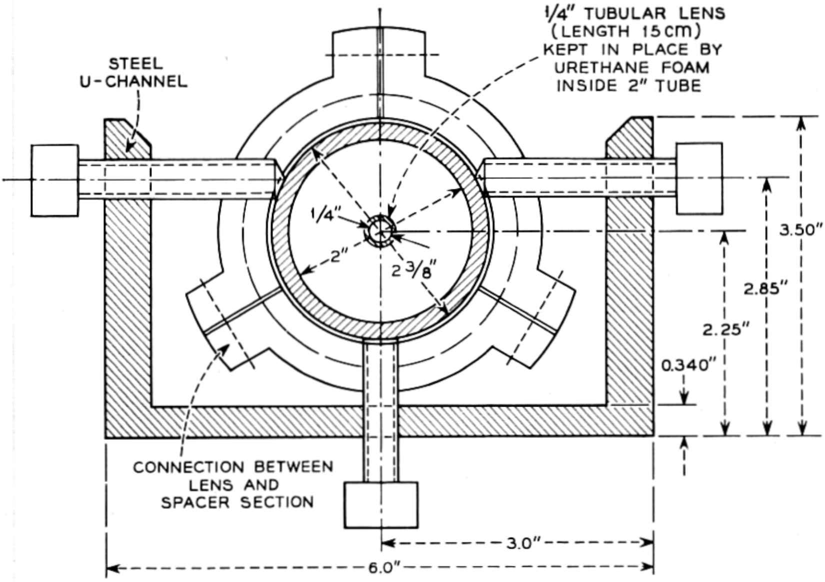

Fig. 2 — Gas lens mounted inside U channel.

of the collimated beam was w and the width of the waist w_o. From this the focal length was computed according to

$$f = \frac{d}{1 - (w_o/w)^2}.$$

Fig. 4 shows the focal length as a function of temperature rise for different gas flow rates. For $F = 1.5\ L/\text{min}$ and $\Delta T = 103°\text{C}$, the principal plane coincided with the geometrical center of the lens. We used the resulting focal length of 50 cm for the confocal operation of the beam waveguide. There was no noticeable difference between the focal lengths of the vertical and horizontal plane.

To guarantee the proper matching, we used two gas lenses as the focusing elements in the confocal laser cavity. At first the laser cavity was mounted on an optical bench, separate from the transmission line of 10 lenses. However, the change of the target spot position in time, probably caused by motion of the respective supports, was not tolerable. We achieved much better stability by mounting the launching system, together with the transmission line, into the U-channel itself.

In order to guarantee optimum alignment of the laser cavity, we

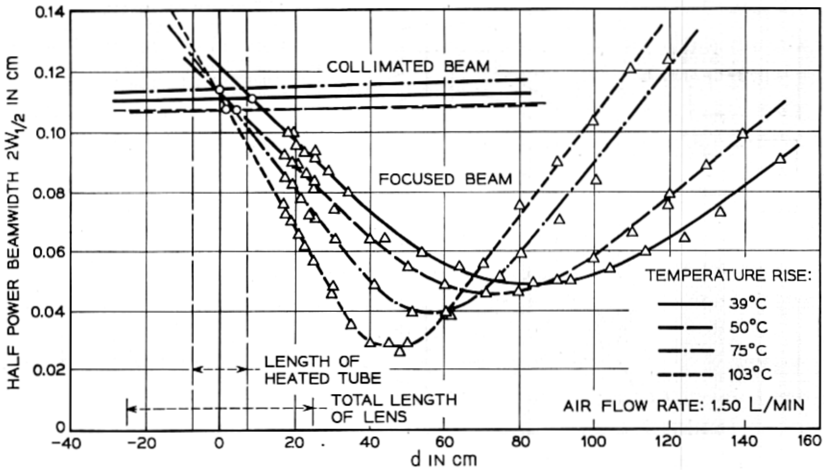

Fig. 3 — Beamwidth of collimated and focused light beam as a function of distance from a tubular gas lens.

sent a reference beam through the channel on a predetermined path and with its help the optical axes of the two gas lenses of the laser were aligned. We placed the glass tube of the laser between the lenses and adjusted for minimum scattering of the passing reference beam. We placed a plane mirror (mirror 2 in Fig. 1) at the far end from the reference laser, so that the energy was coupled back into this laser and resonance could be observed by an increase in power output. The transmittance t of this mirror was 0.95 percent. After mounting a plane parallel mirror at the other end of the laser (mirror 1 with $t = 0.20$ percent), oscillations could be obtained easily and the reference beam was shut off. As intended, the aim of the assembled laser was close to the predetermined path, and undulations of the beam within the cavity were kept to a minimum. The first gas lens of the transmission line was closed on one side with a thin glass plate mounted at the Brewster angle to block the gas flow. It did not displace the beam noticeably, a fact which was important for the eventual removal of the plate in order to form a single laser cavity out of a larger number of gas lenses.

The accurate alignment of the lens required the knowledge of the beam position inside the lens. For a null indicator we used a probe consisting of a differential detecting device with 4 photocells arranged as quarter segments of a circle as Ref. 11 describes. In this way, we avoided several difficulties such as calibration inaccuracies, dependence upon absolute intensity, and relative low sensitivity for small displacements of the beam from the probe's center. We performed the alignment as follows. We oriented the cold lens in such a way that the probe indicated null readings at each end of the tubular lens. Four external indicators marked the horizontal and vertical position of the lens within ± 1 mil. With the probe removed, we determined the position of the beam on a target 6 to 12 meters from the lens. The target was a micropositioner containing a photodiode and a metal plate with a 3-mil hole in front of it. The position of the beam maximum intensity could be defined to approximately ± 8 mils. Then we heated the lens to normal temperature. This deflected the beam downward, since the optical axis is below the geometrical axis of the tube because of the gravity effect. By means of the vertical indicators, we introduced a parallel displacement of the lens until the target spot coincided with the position before heating. By doing this, we made sure that the heating process of the lens did not deflect the beam. Henceforth, its trajectory coincided with the optical axis.

Because of symmetry, no horizontal adjustment of the lens should

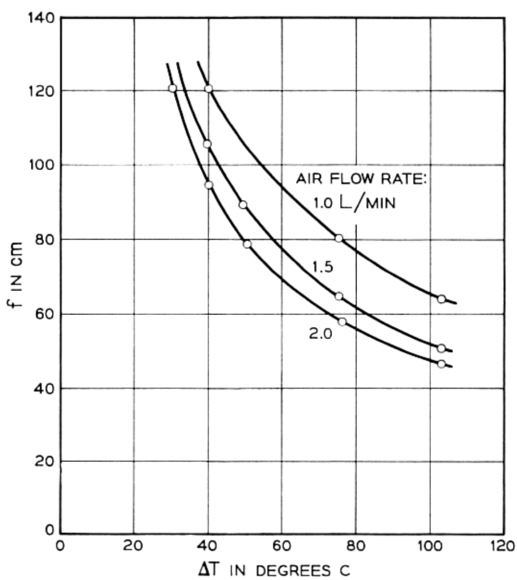

Fig. 4 — Focal length of the tubular gas lens as function of temperature rise between wall and inlet air.

have been necessary. Even though this was true for most of the lenses, a substantial horizontal displacement had to be introduced in some of them, apparently to compensate for lens inaccuracies. The vertical displacement required for the compensation of the gravity effect varied between 13 and 23 mils, with values around 17 occurring most. The horizontal displacement necessary, if all at, amounted to a few mils and only in one case reached 12 mils.

One particular difficulty arose in carrying out this procedure. By inserting the probe, a back pressure was established and the reduced air flow resulted in higher temperatures in the preceding lenses. As a consequence, the ensuing variation of the optical axes of these lenses deflected the beam from its original target spot. We could make temperature variations negligible by fast probe insertion. We neglected the beam variation caused by reduced air flow and its influence on the focal length. Air conditioning machinery vibrated the building and caused random displacements and amplitude fluctuations in the laser beam. This was particularly detrimental for the centering procedure and prevented our using a more sensitive range in the probe's differential amplifier. The fluctuations disappeared after the motors were stopped for a short period. Taking the various factors into account, we estimated the alignment accuracy of the lenses' optical center to be within ± 3 mils, which is $\frac{1}{6}$ of the theoretical $1/e$ beam halfwidth $w(= 17.75$ mils) at each lens.

III. OFF-AXIS INJECTION

We injected the light beam off axis by passing it through a tilted plane parallel glass plate 83.5 mils thick. Figs. 5 through 8 show the power profiles of the beam transmitted through the guide on axis and with different horizontal and vertical offsets. We took about 25 points for each power profile and drew a smooth curve through these points as Fig. 5 shows. The target was 6.25 meters from the center of the last lens. For a beam injected on axis, the half-power beamwidth changed from day to day. It varied between 0.13 and 0.16 inch vertically, and between 0.15 and 0.17 inch horizontally. The center of the beam on the target also moved slowly a few tens of mils as a function of time. We found no satisfactory explanation for this behavior.

We normalized both the vertical and horizontal beamwidths for off-axis injection with the horizontal beamwidth of the on-axis beam. We obtained this reference width at the beginning of each series of measurements. We normalized the distance between the maximum

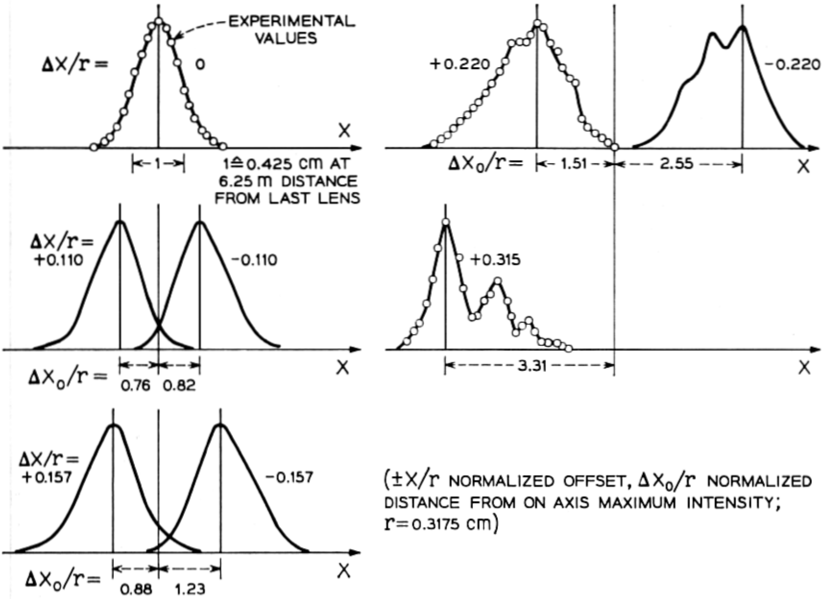

Fig. 5 — Horizontal power profile for horizontally-displaced beam.

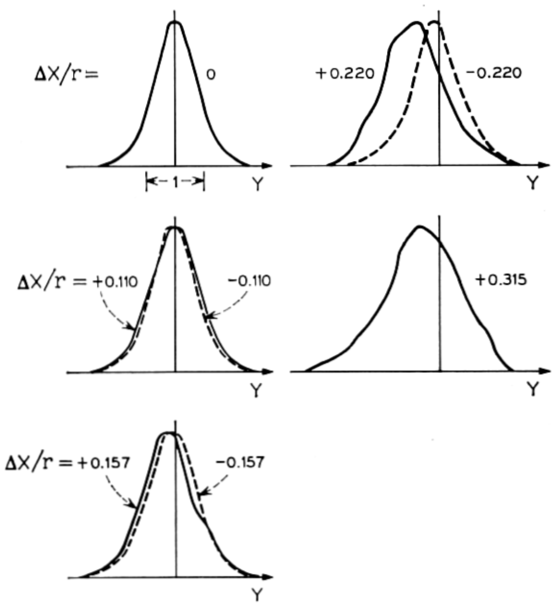

Fig. 6 — Vertical power profile for horizontally-displaced beam.

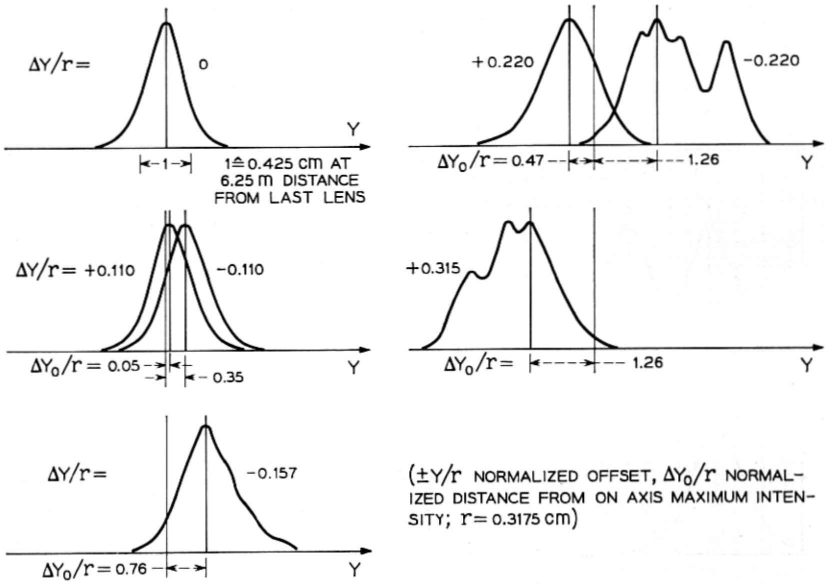

Fig. 7 — Vertical power profile for vertically-displaced beam.

intensities for off-axis and on-axis beams with the radius of the tubular lens and set the maximum intensities to unity. As could be expected from theoretical considerations, the deformations in the vertical and horizontal plane were independent of each other to the first order. However, we noticed a stronger deformation of the vertical beam shape in case of larger horizontal displacements, as compared with the horizontal beam shape for large vertical displacements (see Figs. 6 and 8). The most important result shown in Figs. 5 and 7 is the increase in beamwidth for growing offsets and eventual beam deformations for large offsets. Fig. 9 shows the increase in horizontal and vertical beamwidths relative to their respective values at zero offset. Points obtained for different experimental runs and, in general, resulting in different beamwidths, fitted well into the graph, once they were related to their respective horizontal zero offset widths. The uncertainty of the result owing to limited accuracy of the measurements and ambiguity of interpolation becomes larger for increasing beamwidths and is indicated in the graphs. The growth appears to be quadratic to the first order. Whereas this dependence is approximately equal for left, right, and high injected beams, the growth is larger for the beam injected low. We found no satisfactory reason for this discrepancy.

The good symmetry in the position and the power profile of horizontally deflected beams appear to be the result of good alignment and horizontal symmetry of the lenses. The asymmetric deformations of the lenses owing to gravity apparently result in asymmetry of the position and profile for vertically-displaced beams.

For confocal geometry the normalized width w_n of a light beam which undulated with amplitude a about the axis of a sequence of n lenses is given by[10]

$$w_n = 1 + \tfrac{3}{2}\,\delta n\left(\frac{a}{w}\right)^2$$

where δ is a measure of the focal length distortion. At distance w from the center of the lens the relative increase of the focal length is δ. D. Marcuse's analysis of the tubular gas lens[4] yields a value δ of approximately 0.012 for the geometry, gas flow rate, and temperature rise being considered. The theoretical prediction for the beam size increase

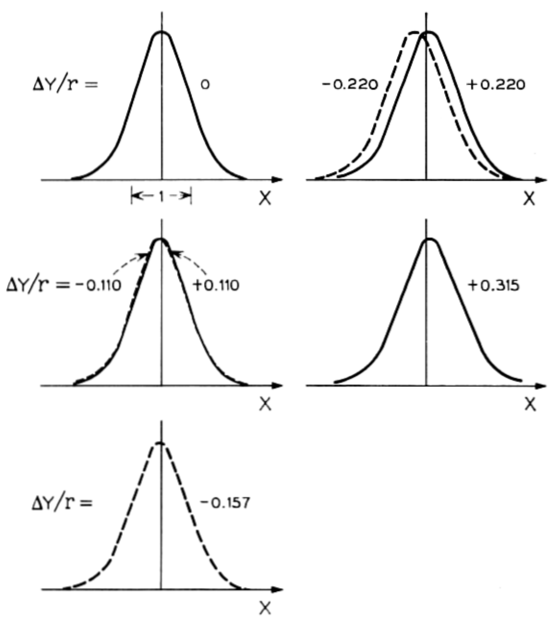

Fig. 8 — Horizontal power profile for vertically-displaced beam.

according to above equation corresponds closely to the experimental results. (See Fig. 9.) Ten per cent beam size increase occurs after 10 lenses with a beam displacement a/w of only 0.7.

IV. BENT BEAM WAVEGUIDE

Because the lenses were mounted within a U channel it was easy to put bends of varying radii into the vertical plane. We lifted the channel to calculated heights for this purpose. The curvature started at the first lens of the optical guide (third lens in Fig. 1). The laser cavity with its two gas lenses remained straight. The U-channel was sufficiently elastic to permit following the desired curvature. The light beam entered the bend on the optical axis of the first guide lens. Figures 10 and 11 show the beam profile transmitted through the line for five different radii between 2500 and 500 meters. The half-power widths are normalized with 0.425 cm. No significant change of the Gaussian beam shape occurred down to a radius of 834 meters. A small hump appeared on one side of the beam at the 625 meter radius, but we measured no noticeable power loss. At 500 meters, however, the beam showed characteristic diffraction rings and a power loss of approximately 1 dB.

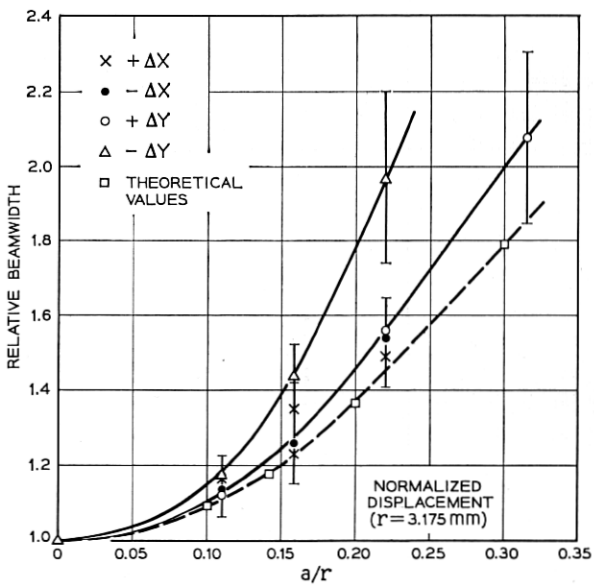

Fig. 9 — Relative increase of beam width as a function of horizontal and vertical offset.

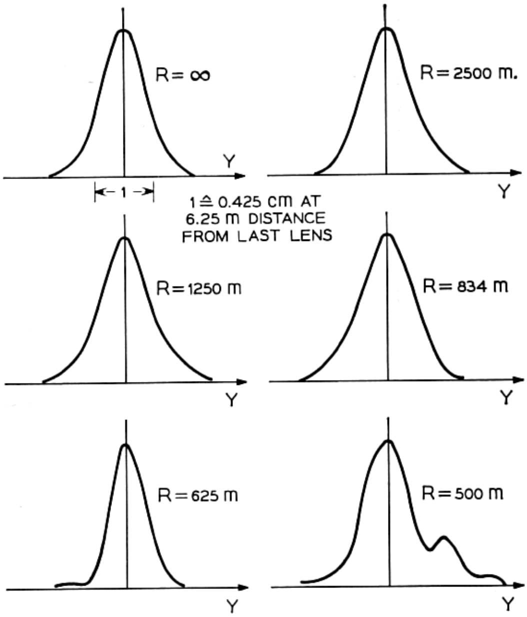

Fig. 10 — Vertical power profile as a function of radius of curvature.

According to the theory of a circular bend,[12] a beam injected off axis and with a particular tilt does not undulate, whereas on-axis injection causes undulations. We found that a small offset (without tilt) of approximately 0.35 mm for a 500-meter radius resulted in optimum transmission (power loss approximately 0.2 dB). For a parallel displacement without tilt a theoretical offset of 0.5 mm results in undulations around the ideal trajectory with minimum amplitude. As a consequence of this, the distortions are also minimized. Just as for vertical displacements, the horizontal shape did not change significantly for vertical bends.

In order to confirm the low-loss guidance properties of the 10-lens bent beam waveguide, we transformed the 2-lens laser cavity and the 10 guide lenses into a 12-lens laser, whereby the discharge tube of the 2-lens laser remained the only gain medium (see Fig. 1). Lasing was obtained at $R = 834$ meters with power output equal to that of the laser with only 2 lenses. The alignment procedure was as follows. With the 2-lens laser oscillating, we mounted a plane parallel mirror behind the 12th lens (mirror 3 in Fig. 1) and adjusted this mirror for resonance. Then we removed mirror 2 as well as the Brewster angle

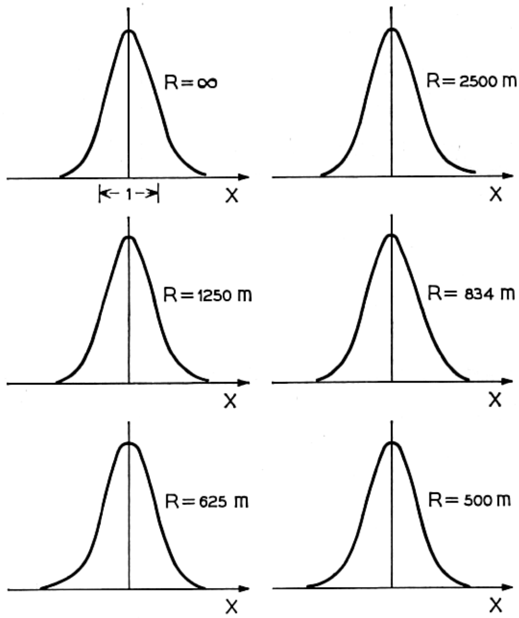

Fig. 11 — Horizontal power profile as a function of radius of curvature.

window between the laser and the guide and connected the two adjacent lenses by a hose. The 12-lens laser started lasing immediately. We replaced mirror 3 by mirror 2 in order to obtain identical operating conditions. Subsequently, the 12-lens laser was deformed into a circle with a radius of 625 meters (the first two lenses remained straight). Even though we did not obtain stable lasing, the proximity to oscillations existed, since small changes of air flow were enough to produce light flashes.

By changing the alignment of the mirrors, we created various paths through the 12 lenses of the laser cavity. This affected the field configuration of the fundamental mode. We observed strongly deformed beam shapes whose single mode configuration could be confirmed by placing a circular aperture into the path of the beam. We recorded no change of these shapes when the aperture was closed until laser action vanished.

V. BEAM WAVEGUIDE WITH NONCONFOCAL SPACING

Theoretical work by E. A. J. Marcatili[10] indicated that distortions of the Gaussian beam passing through a sequence of lenses are reduced if a nonconfocal geometry is chosen. To check this prediction experimentally, we aligned a beam waveguide consisting of 10 gas lenses with nonconfocal spacing (a distance-to-focal-length ratio (d/f) of 1.82). At the same time, we could make several improvements in the alignment procedure as a consequence of the experience gathered with the beam guide aligned before. We strongly reduced the influence of building vibrations by working farther away from the maintenance machinery at the far end of the waveguide corridor. The ensuing reduced fluctuations of the light beam allowed a more accurate coaxial alignment of the tubular lens with the light beam. Also, we eliminated the negative influence of the back pressure due to probe insertion on the alignment by leaving a small air gap between the lens (which was to be centered around the beam) and the preceding lens. This permitted the gas to escape. After the centering procedure we connected the two lenses air tight and then compensated for the gravity effect. Because it was a different set of gas lenses than in the experiment before, the vertical displacement to compensate for the gravity effect varied between 17.5 and 20.5 mils, but reached extremes of 15 and 26 mils.

We left the laser cavity untouched, and adjusted the temperatures of the guide lenses to yield focal lengths of 60 and 50 cm, corresponding of $d/f = 1.67$ and 2.0, respectively (Figs. 12 and 13). This did not deflect the on-axis beam in the horizontal direction. However, small deviations in the vertical position are apparently the result of the temperature dependence of the gravity effect. The horizontal and vertical beam widths of the on-axis beam for confocal geometry were virtually identical with those we measured previously. For nonconfocal operation, the horizontal beamwidth of the on-axis beam remained approximately constant, whereas the vertical width became larger for nonconfocal geometry. We recorded good symmetry of the target beam position with respect to symmetric off-axis injection of the beam in all three cases. The normalized offsets are the same as in Figs. 5 through 8. Again we measured the power profile 6.25 meters behind the last lens of the guide. However, we chose arbitrary units at this time whereby the power into the guide was held approximately constant. We could not confirm the asymmetry observed in Fig. 7 for small vertical offsets.

If you compare the power profiles of light beams passing through a sequence of lenses with different distance-to-focal-length ratios, you notice a marked increase in beam distortions as you approach confocal geometry. This is true for beams undulating horizontally as well as vertically. This behavior was predicted by theory[10] and confirms that in beam waveguides with nonconfocal spacing there is less mode conversion than in those with confocal spacing.

VI. CONCLUSION

We achieved accurate alignment of a sequence of gas lenses. We found that a beam undulating in an optical waveguide increases its beamwidth as a function of the initial offset, but maintains its Gaussian profile up to a certain maximum displacement. With 10 lenses we recorded maximum offsets of approximately 1.0 to 1.5 (normalized with the theoretical $1/e$ beamwidth $w = 0.45$ mm at the positions of the lenses). Larger offsets resulted in a change of the Gaussian beam shape and the appearance of diffraction rings. Observed symmetry in the position of the maximum intensity and the power profile for left and right horizontal displacements indicate symmetry of the lenses with respect to the vertical plane. Unsymmetrical vertical deformations are apparently the consequence of gravity aberrations.

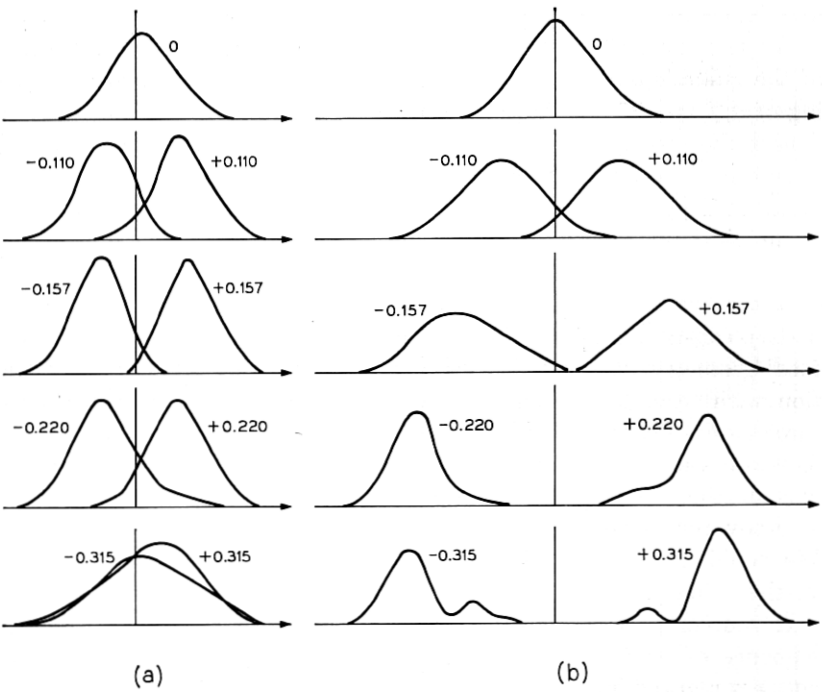

Fig. 12 — Horizontal power profile for horizontally-displaced beam (arbitrary units, offset normalized as in Fig. 5). (a) focal length: 60 cm ($d/f = 1.67$). (b) focal length: 50 cm (confocal).

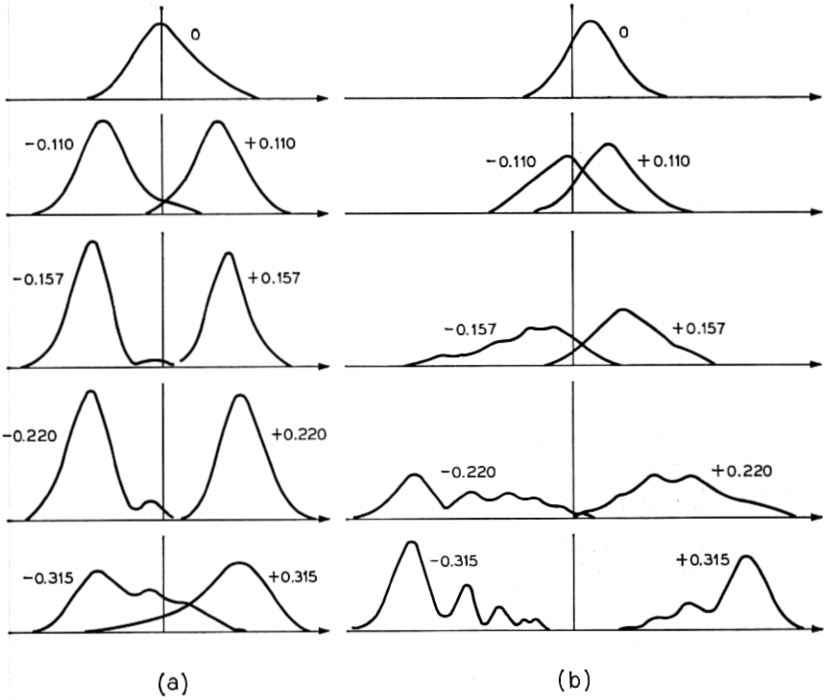

Fig. 13 — Vertical power profile for vertically-displaced beam (arbitrary units, offset normalized as in Fig. 7) (a) focal length: 60 cm ($d/f = 1.67$). (b) focal length: 50 cm (confocal).

Thus, averaged aberration properties of gas lenses can be ascertained from offset injection of a light beam into a small sequence of lenses.

We demonstrated effective guidance of a light beam around a circular bend. The minimum radius below which changes of the beam shape occurred was approximately 625 meters for 10 lenses. We confirmed the low-loss guidance properties by using 12 lenses as focusing elements within a laser cavity in the bent state.

We experimentally confirmed the theoretical prediction of reduced beam distortions for nonconfocal geometry. Thus, nonconfocal spacing of the lenses is more advantageous in optical transmission line design than confocal spacing.

VII. ACKNOWLEDGMENT

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