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Demonstration of Laser Phase Correction Using Supersonic Gas Jets

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Preliminary experiments have been carried out to demonstrate the feasibility of using active gas optics to compensate for distortions in the phase of laser beams. Two parallel supersonic gas jets, in which a simple mechanical control system varied the mean optical density of one of the jets, were placed orthogonal to the beam path. When operated with combinations of He and He-Ar mixtures, phase shifts of up to 3π have been introduced into a HeNe laser beam. The resulting far-field diffraction patterns have been shown to compare well with theoretical predictions for these phase shifts. Qualitative phase restoration has been achieved when a simply distorted laser beam is passed through the jets. Unwanted phase distortions resulting from the waves in the flow in the present nozzle design limited the Strehl ratio to a low value.

Introduction

PHASE distortions of a laser beam may be introduced as the beam propagates through the atmosphere. These phase variations limit the power density that can be delivered to a distant target. Systems of active optics[1] composed of reflective optical components whose characteristics can be varied in real time have been developed to compensate for these distortions. Typically this involves physically distorting mirrors in the transmitting optics. Research is presently being conducted on the use of gas jets as phase control devices for high power laser beams.[2] Gaseous optics should be directly applicable to high power density lasers inasmuch as aerodynamic window investigations[3] have shown that gas jets can successfully be used in place of solid optics. The system of gaseous optics would consist of an array of jets, with variable optical density, which is placed orthogonal to the beam path. A row of jets would effectively act as lenses, a linear array of phase-shifting elements changing the optical path length of the various rays of the beam as they traverse the jets. The index of refraction of a gas is given by[4]

$$n = 1 + \beta\rho \tag{1}$$

where β is the Gladstone-Dale constant of a particular gas mixture and ρ is the gas density. The optical path length of the light rays passing through a region of varying index of refraction is given by

$$L = \int_0^t n \mathrm{d}z \tag{2}$$

where z is the direction of propagation of the beam, and thereby the entire phase front of the beam is controlled by the optical density distribution $\beta\rho$ within the array of jets.

The correction concept for gas jets has been discussed in two theoretical studies[2,5] of the degree of phase compensation possible using a two-dimensional array of ideal jets (defined as jets without viscosity or entrainment present). These studies showed that substantial phase compensation could be achieved with a reasonably sized array of discrete jets. However, it is known that real jets will cause additional degradation of the laser beam quality[3] due to the presence of shear layers and waves.

The purpose of the present investigation is to study experimentally a simple double jet system in which the mean optical density of one of the jets is made variable by using a simple mechanical control system, thus providing preliminary evidence of the feasibility of active gas optics. As in aerodynamic window experiments, near- and far-field patterns were studied. The interferograms and schlieren photographs of the jets showed the presence of waves within the jets and turbulence in the shear layers. The near-field patterns thus indicated some of the causes of the power losses measured in the far field. A qualitative investigation of the far-field intensity distributions of a circular beam traversing supersonic jets was also conducted.

Principle of Operation

A simple double nozzle was designed for the experimental tests. Figure 1b shows the complete assembly of the double nozzle system with part of the brass block cut away for simplicity (A-A′ in Fig. 1a). If the two halves of the nozzle block are separated and the splitter plate is removed, the nozzles appear as shown in Figs. 1c and 1d. The left-hand nozzle is divided by a flutter valve and has two separate feed lines, making it possible for two independent streams of gas to form the free jet. The right-hand nozzle is fed by one gas to form a simple free jet. The nozzles have been scaled such that the optical interactions of the jets with a HeNe laser would approximately simulate those of a CO_2 laser system with a 10 cm aperture (i.e., λ/D is held constant, where D is the nozzle dimension). The area ratio of the split nozzle is 1.49 while that of the simple nozzle is 1.54; this variance causes a slight difference in Mach numbers. The jets are both approximately Mach 2 and each nozzle is approximately 4 mm wide and 6 mm deep. The system was operated with various combinations of He and a 62% He-38% Ar gas mixture. These gases have the same ratio of specific heats, γ, required in order to be able to match the plenum pressures while producing equal Mach number jets. Previous experimental work[6] on the interactions between laser beams and small single supersonic free jets had shown that these two gases had good optical quality potential.

With this nozzle configuration it was possible to vary the effective optical density of the split jet. Assuming ideal jets

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with no mixing, the mean optical density of the combined jet is given by

$$\overline{\beta\rho} = \frac{1}{t}\int_0^t \beta\rho \, dz = \frac{1}{t}\left[\int_0^{t_1} \beta_1\rho_1 \, dz + \int_{t_1}^{t} \beta_2\rho_2 \, dz\right] \quad (3)$$

or

$$\overline{\beta\rho} = \frac{1}{t}\left[\beta_1\rho_1 t_1 + \beta_2\rho_2 (t - t_1)\right] \quad (4)$$

where ρ_1 and ρ_2 are the respective densities of the two jets of gas and t is the overall constant thickness of that jet. The relative thicknesses t_1 and $t - t_1$, and thereby the value of $\beta\rho$ for a given pair of gases, are determined by the positioning of the flutter valve shown in Fig. 1. A shaft which passes through the brass block is attached to the valve so that it can be controlled externally. The positioning of the valve in the throat of the split nozzle is determined by adjustment of a micrometer which rotates this shaft. The change in optical density has been assumed to be discontinuous, ignoring the mixing zone between the two jets. The optical path length is now a function of the position of the flutter valve and the gas combination and can be estimated by use of Eqs. (1), (2), and (4).

Near-Field Study

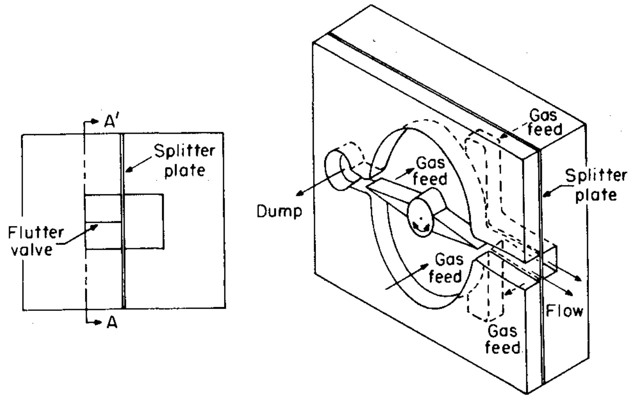
The near-field patterns of the beam as it traverses the supersonic jets are useful for studying the structure of the jets. It is important to know of any irregularities in the flow as they will cause undesirable phase distortions in the beam and alter the intensity distribution at the distant target. Long-exposure interferograms and stop-action schlieren photographs were used for this study. The interferograms in Fig. 2 are representative of those produced when a HeNe laser beam traverses the two jets just downstream of the nozzle exits. The laser beam was expanded through a telescope which produced a collimated beam considerably larger than the nozzle dimensions and the exposure time was 5 ms. The light source for the schlieren photographs was a spark gap which produced a 300 ns pulse. The optical diagnostics are the same as those described in Ref. 6. In Figs. 2a and 2b the light traverses the jets parallel to the splitter plate, this being the usual direction of viewing. In Fig. 2c the beam traverses the jets parallel to the splitter plate, thus showing the wake from the flutter valve and the two outer shear layers which the beam must traverse. The split jet was composed of part He and part 62% He-38% Ar mixture, while the single jet was purely the 62% He-38% Ar mixture. All of the experiments were conducted with this combination of gases; the only variable was the flutter valve position.

There are two obvious irregularities in the flow region. The first of these is the waves which are present. Because the jet index of refraction is very low in He, the optical density changes across the waves are nearly invisible in the He jets but they show quite clearly in the 62% He-38% Ar jets. It is apparent that the boundary layer along the splitter plate is thick enough to create strong waves at the nozzle exit. These strong waves would be undesirable in the phase control system because they cause unwanted phase errors in the beam. It would be possible to reduce the strength of these waves by reducing the boundary-layer thickness at the end of the splitter plate, perhaps by designing shorter nozzles or by applying boundary-layer suction. The waves would also be eliminated if the jets were operated at high subsonic speeds. Neither of these were attempted for this preliminary investigation.

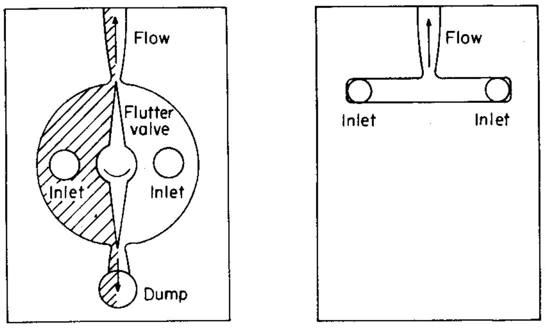
The second problem area is the turbulent shear layers. Neither the outer shear layers nor the central shear layers can be avoided in this system. It is important to understand their effects upon the beam. The schlieren photograph in Fig. 2b, taken with the knife edge horizontal, clearly shows the turbulent structures in the shear layers. It is seen in Fig. 2c that the beam must traverse at least two of these turbulent shear layers as it passes through the jets.

Far-Field Study

The diffraction patterns of a uniformly illuminated circular laser beam passing through the jets were used to study the

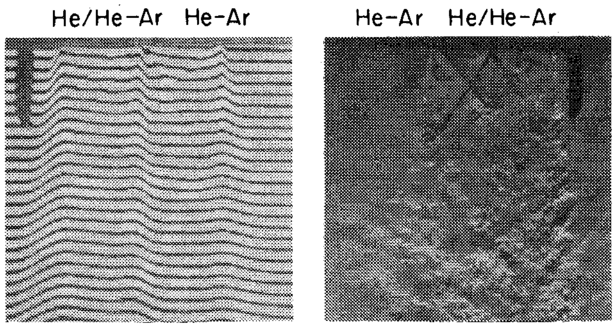


a) Exit plane b) Isometric view section A-A'

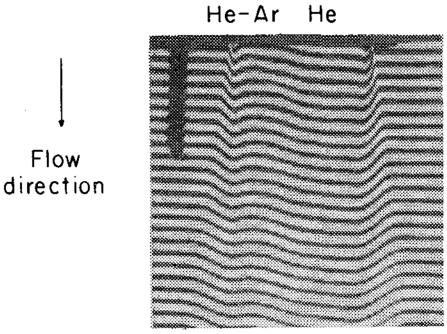


c) Split nozzle d) Simple nozzle

Fig. 1 View of the double-jet phase array.



a) b)



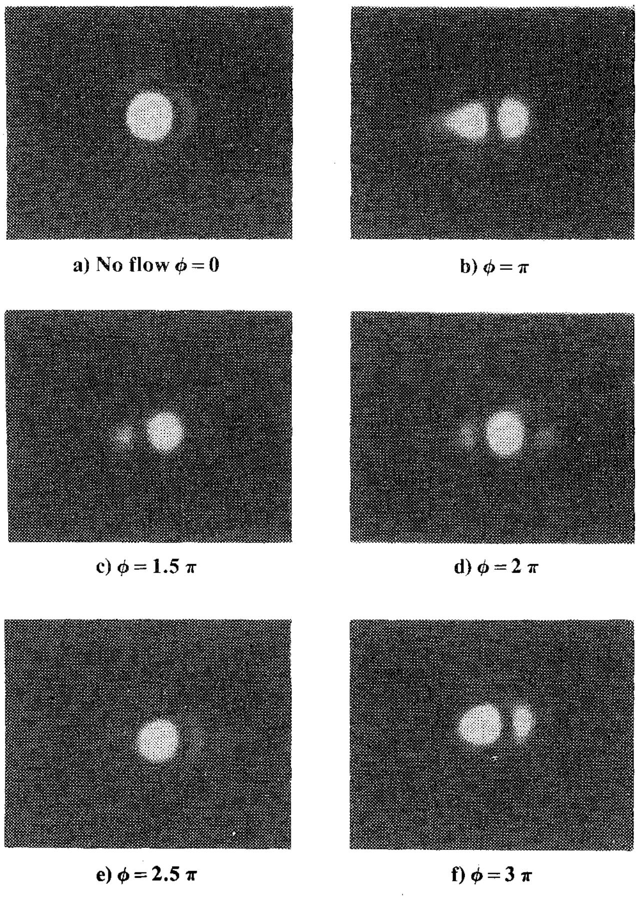
c)

Fig. 2 Interferograms and schlieren photograph of the supersonic gas jets (flow direction is down).

effects which the jets have on the far-field intensity distribution of the beam. The Fraunhofer diffraction pattern formed by an ideal beam passing through a circular aperture is well understood and serves as a good reference pattern. As shown in Fig. 3a, it consists of a bright central Airy's disk surrounded by increasingly weaker rings (Ref. 7, pp. 394-397). When the beam traverses the supersonic jets in the near field, the irregularities in the jets which were discussed in the previous section distort the diffraction pattern. A circular aperture, 5.84 mm in diameter, was placed just before the nozzle so that the circular beam traversed the jets just below the nozzle exits and inside of the side shear layers. Figure 3 shows the asymmetrical Fraunhofer patterns which resulted from a series of phase shifts starting with the reference no-flow pattern in Fig. 3a and progressing through to a 3π shift in Fig. 3f. The phase shift was varied by changing the flutter valve position and was measured on the near-field interferograms.

A study was conducted using a computer code which predicted the far-field intensity distribution resulting from discontinuous phase shifts in the near field. It was shown that a phase shift of π should produce two symmetrical bright spots in the far field, each of which has a relative peak intensity or Strehl ratio (Ref. 7, pp. 460-461) equal to 0.47, as compared to the undisturbed beam, which is 1.0. The patterns between 0 and π should be mirror images of those between π and 2π (e.g., $\pi/2$, and $3\pi/2$ should be mirror images) and the entire sequence should be repetitive on 2π intervals.

As seen in Fig. 3, the experimentally observed patterns have those basic characteristics but they all have a "tail" type of structure going off to the left. This indicated that the central shear layer present in the real jets was causing an additional distortion of the intensity distribution. When a modeling of the central shear layer was added to the computer code using the actual growth rate, orientation, and virtual origin of the shear layer (obtained from the near-field interferograms), it also showed this distortion.


a) No flow $\phi = 0$

b) $\phi = \pi$

c) $\phi = 1.5\,\pi$

d) $\phi = 2\,\pi$

e) $\phi = 2.5\,\pi$

f) $\phi = 3\,\pi$

Fig. 3 Far-field diffraction patterns for various near-field phase shifts produced by the gas jets.

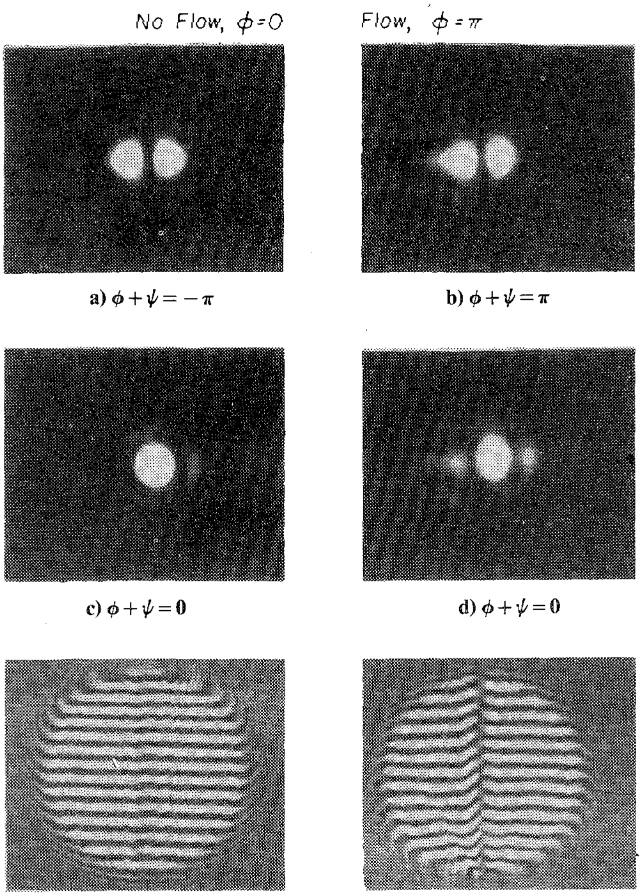
A preliminary experiment was devised to demonstrate that these gas jets can compensate for phase distortions in the input beam. The phase distortion in the beam was created by replacing one of the beam splitters of the interferometer with two rectangular mirrors mounted side by side. One of these mirrors was mounted on a piezoelectric aligner/translator. This is composed of a three-element PZT cylinder which can either translate the mirror up to 10 μm or can tilt and angularly scan the mirror up to 150 arcsec. Using this aligner/translator, it was possible to align the two mirrors perfectly and then to translate one of them slightly to produce the desired phase shift between the two halves of the beam.

The beam was positioned on the two mirrors such that the crack between them would be aligned with the shear layer between the two jets. The near-field interference fringes were used to get the two halves of the beam perfectly in phase with each other. A discontinuous shift of π was then imposed by translating one mirror with respect to the other. The resulting far-field pattern is shown in Fig. 4a and is seen to match the corresponding phase shift produced by the jets in Fig. 4b. After each run the base was rechecked to insure that the translator was not wandering. The random variation in the applied voltage was never more than 2%.

Upon comparing Figs. 4c and 4d, it is apparent that these jets can indeed compensate for a phase distortion within the beam itself. The reconstructed pattern of Fig. 4d, however, is not a perfect Airy's pattern. The near-field interferograms of Figs. 4e and 4f can be used to identify the sources of the remaining distortions. The small secondary lobe in Fig. 4c is clearly caused by the nonuniformity in the center of the fringe pattern of Fig. 4e, produced by the butted edges of the two rectangular mirrors. This is an artifact of the system used to create the phase distortion in the beam and would obviously not be present in the real system. Likewise, the disturbance in the center of Fig. 4f, which is a combination of the shear layer in the jets and the discontinuous phase shift between the two mirrors, is responsible for the two symmetrical, secondary lobes seen in Fig. 4d.

As previously mentioned, unwanted phase errors caused by the jets must be minimized so that the laser power density is not severely reduced on the target. A cursory measurement of the Strehl ratio was carried out for one small phase shift in order to estimate the beam degradation due to these effects in this double-nozzle system. For this measurement a relative phase shift of $\pi/6$ ($\pm\pi/10$) was used, obtained by operating both nozzles with the 62% He-38% Ar mixture. This measured shift results from the small (~3%) area ratio difference between the two nozzles discussed earlier. This small shift was used to avoid the double-peaked far-field pattern associated with larger phase shifts (see Fig. 3). The far-field sampling aperture was 1.14 mm in diameter, corresponding to a subtended half angle of the beam, $\theta_{1/2} = 0.258\ \lambda/D$, where D is the transformed diameter of the beam after the 5.84 mm circular beam has passed through a reducing telescope. By taking the ratio of the fraction transmitted with flow to that without flow for this small sampling aperture and correcting for induced tilting caused by the flowfield, the Strehl ratio is approximately measured. For this case a value of 0.50 was obtained for the Strehl ratio at the peak intensity point.

The predicted Strehl ratio for a phase shift of $\pi/6$ ($\pm\pi/10$), including modeling of the phase shift within the shear layer, is in the range 0.99-0.94. Taking into account possible errors in experimentally locating the peak intensity point and the effect of the finite aperture size reduces the predicted signal by as much as an additional 0.03 or to 0.99-0.91. The difference between these values and the measured Strehl ratio of 0.50 is due to unwanted flow irregularities which were identified in the near-field study. Referring to the photographs of Fig. 2,



a) $\phi+\psi=-\pi$ b) $\phi+\psi=\pi$

c) $\phi+\psi=0$ d) $\phi+\psi=0$

e) $\phi+\psi=0$ f) $\phi+\psi=0$

Fig. 4 Phase compensation by gas jets (ϕ = phase shift caused by jets, ψ = phase shift caused by the split mirror).

four problem areas are apparent: outer shear layers normal to the beams, central shear layer width and turbulence, wake from the flutter valve, and waves and other losses within the core flow. The degradation caused by the outer shear layers and the waves of a single supersonic jet of the He-Ar mixture has been measured to be 0.07.[6] When the double nozzle is operated with only one gas, interferograms taken perpendicular to the splitter plate show no measurable wake from the flutter valve, although there may be scattering losses. The reduction in Strehl ratio caused by the turbulence of the central shear layer has been estimated to be 0.02-0.20, where the upper bound represents a complete loss of that portion of the field traversing this layer. (The fractional area occupied by the layer was measured to be 12%.) Assuming that the losses may be superimposed, the peak intensity degradation due to the particularly strong waves in this double nozzle configuration and other unidentified losses are 0.40-0.14. While it is impractical to reduce these losses in the current device, the waves might be completely eliminated by redesigning the jets to operate at high subsonic speeds. Alternatively, shortening the nozzle and splitter plate or applying boundary-layer suction should substantially weaken the waves and also narrow the shear layers in the jets. These design improvements are being investigated.

Conclusion

This experimental investigation has demonstrated that phase control of laser beams by an array of gas jets with controllable optical densities is feasible. Phase shifts which range from π to 3π have been introduced into the HeNe beam by the gas jets and compensation for a phase shift of π within the beam has been achieved. The effects which the near-field phase shifts have on the far-field diffraction patterns have been shown to agree qualitatively with the theoretical predictions.

The near-field interferograms, however, have indicated that there are irregularities in the flow region, particularly strong waves from the splitter plate, which are produced by the present double nozzle configuration. Because of these unwanted flow disturbances, the measured Strehl ratio for a relative phase shift of $\pi/6$ was significantly lower than that for ideal jets. Improvements in the nozzle design and lowering of the Mach number should improve the Strehl ratio substantially.

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