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Coherent fiber-optic bundles offer opportunities for application of state-of-the-art electro-optic imaging techniques to the sighting and fire-control problem. However, conventional fiber-optics are limited in this application by their high attenuation coefficients (up to 2000 dB/km). Fused silica fiber with its low attenuation (1-50 dB/km), offers substantial improvement.

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20. ABSTRACT (continued)

The present work, the first phase of a two phase program, demonstrates the feasibility of fabricating coherent fiber-optic bundles from fused silica by fabricating square, 36 element, 60 micron square multifiber, the basic building block for coherent fiber-optic bundles. In addition, preform requirements for multifiber and coherent bundles were also established.

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CONTRACT REPORT BRL-CR-558

FEASIBILITY OF MAKING COHERENT FIBER-OPTIC ARRAYS FROM FUSED SILICA

Galileo Electro-Optics Corporation
Galileo Park
Sturbridge, MA 01518

July 1986

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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I. BACKGROUND

Coherent fiber-optics offer great potential for application to sighting systems. However, optical fibers currently made from mixed silicate glasses exhibit attenuation coefficients as high as 2000 dB/km or more and are subject to optical blemishes arising from imperfections in the glass-particularly at the core/clad interface. Such high attenuation practically limits coherent fiber bundles to lengths of about three or four meters. This situation restricts the application of various electro-optical imaging techniques to sighting and fire-control problems.

Fused silica offers great material improvement over conventional silicate glasses. After twenty years of development for the communications industry, optical fibers made from fused silica are available with attenuation coefficients as low as 1.0 dB/km. In addition, the (CVD) (Chemical Vapor Deposition) process used to manufacture preforms for such fiber results in near perfect, blemish-free material because CVD processes are largely immune to the limitations of conventional silicate melting technology. Although communications quality fiber is not needed for the present application, there exist intermediate quality fused silica materials which exhibit attenuation coefficients between 10 and 100 dB/km. Made with CVD technology similar to that used to make communications fiber, such material provides an ideal opportunity for facilitating the application of state-of-the-art imaging technology to sighting and fire-control problems.

Galileo has developed technology for making coherent fiber bundles from conventional silicate glasses. Cane, 1-5 mm diameter glass rods with an appropriate optical cladding, is laid up into a square array and drawn into a square multifiber. The square shape of the multifiber permits it to be laid up into a coherent bundle in which space is filled. This same technology can, in principle, be applied to fused silica. The key to developing fused silica coherent bundles is developing the ability to draw square multifiber from fused silica.

The present program is a two-phase effort to develop coherent imaging bundles from fused silica. The object of Phase I, the subject of the present report, is to demonstrate the ability to draw square, 60-micron, 6 x 6 fused silica multifiber arrays. Once demonstrated, such fiber will be used to manufacture prototype imagescopes in Phase II.

II. IMAGESCOPE MANUFACTURE

The drawing of multifiber consists of three steps: drawing cane, laying up the cane into an array, and drawing the array into multifiber. The cane is drawn from the preform down to a diameter of 1.5 mm in one meter lengths. The cane is sorted and assembled in a 6 x 6 element square array. The individual cane elements fuse together in the hot zone of the furnace during the draw to form a solid square fiber. The resulting 60-micron multifiber has 36 eight-micron optical cores held together in a matrix of low index cladding material. The secret to drawing good quality square multifiber is to find a combination of draw speed and temperature which permits consolidation of the individual elements without distortion. To assemble an imagescope, the fiber is laid on a traversing drum so that each multifiber is in intimate contact with its neighbors. Epoxy is brushed onto the multifibers to hold them together. The epoxy is cured and the ribbons of multifiber are removed from the drum. A number of ribbons are assembled vertically and pressed to form a solid block of cured epoxy holding the multifiber ribbons firmly together. The epoxied multifiber block is severed to yield a coherent assembly of optical elements.

III. FUSED SILICA MULTIFIBER

Drawing fused silica fiber is essentially the same as drawing conventional glass fiber, the primary difference being the high temperature required for fused silica.

A. Equipment

A high temperature draw tower located in a Class 100 Clean Room was used for the present work.

The high temperature furnace is equipped with an yttria-stabilized zirconia muffle tube coupled to a radio frequency generated field. Temperatures of 1400 to 2300°C are controlled by a three-mode controller using an IR temperature sensing head focused on the stabilized zirconia tube. The preform or array is fed into the furnace by an electrically driven screw assembly. The fiber is pulled from the preform by pinch wheels and spooled onto drums. Fiber size is controlled by the ratio of feed speed to draw speed at constant drawing temperature.

B. Preforms

Preforms suitable for making fused silica optical fiber are currently made in a variety of ways. A high index core with a low index cladding is required. This configuration is achieved in practice by one of two methods. In the first, the high index core is made from Ge. or P-doped fused silica, and the low index cladding is made from pure fused silcia. In the second, the high index core is made from pure fused silica while the cladding is made from B. or F-doped fused silica. Boron and fluorine are the only two dopants which will lower the refractive index of fused silica. Preforms with Fluorine-doped fused silica cladding and a pure fused silica core made by Heraeus Amersil were chosen for the present feasibility study. This choice was dictated by optical suitability (i.e., Transmission and NA) to the present application and commercial availability. Heraeus Amersil offers four choices of preform, described in Table 1.

"USS" preforms with a 1.4 OD/core ratio were originally selected for making the multifiber. Drawing the 15 mm preforms to 1.5 mm cane posed no remarkable problems. However, after laying up the cane into a 6 x 6 array, repeated attempts to draw multifiber were unsuccessful. Bubbles were observed to form at the point of contact of the individual pieces of cane, making the resulting fiber weak and distorted with low transmission. Attempts to etch and clean the cane surface had no effect. In consultation with the technical staff at Heraeus Amersil, it was determined that the fluorine exsolved from the outer layers of the "USS" preform at the high temperatures required for fiber drawing. In the multidraw, the gas became trapped between the

TABLE 1. HERAEUS AMERSIL PREFORM

Material Designation	OD/Core Ratio	Core Material	Cladding Material
USS	1.2	Fused Silica	Uniform layer of F-doped fused silica
USS	1.4	Fused Silica	Uniform layer of F-doped fused silica
SS	1.2	Fused Silica	Optical cladding layer of F-doped fused silica; Outer buffer layer of pure fused silica
SS	1.4	Fused Silica	Optical cladding layer of F-doped fused silica; Outer buffer layer of pure fused silica

contacting surface of the individual pieces of cane, forming the bubbles which rendered the fiber useless.

"SS" preforms with a 1.4 OD/core ratio were then obtained. The preforms' pure silica outer buffer forms an impermeable barrier which prevents exsolution of the fluorine. Again, drawing 1.5 mm cane from the 15 mm preform was routine, posing no remarkable problems. The 1.5 mm cane was laid up into 6 x 6 arrays which were mounted in the draw tower. As we expected, the silica buffer on the outside of the preform prevented exsolution of the fluorine and clear bubble-free fiber was produced. In successive experiments, the feed speed, the draw speed, and the furnace temperature were varied, and consolidation of the resulting fiber was monitored microscopically until a square, consolidated, undistorted, 60-micron multifiber was obtained. Five hundred meters of the fiber obtained were drawn for optical characterization.

Figure 1 is a 500X micrograph of multifiber drawn at 2032°C, showing the optical core as brighter circles surrounded by dark circles. The dark circles are the fluorine-doped optical cladding. The silica buffer layer was deformed during drawing and now filled the interstices in a continuous silica phase.

IV. OPTICAL MEASUREMENTS

Optical transmission of the fused silica fiber was accomplished through "cutback" attenuation measurements as described below.

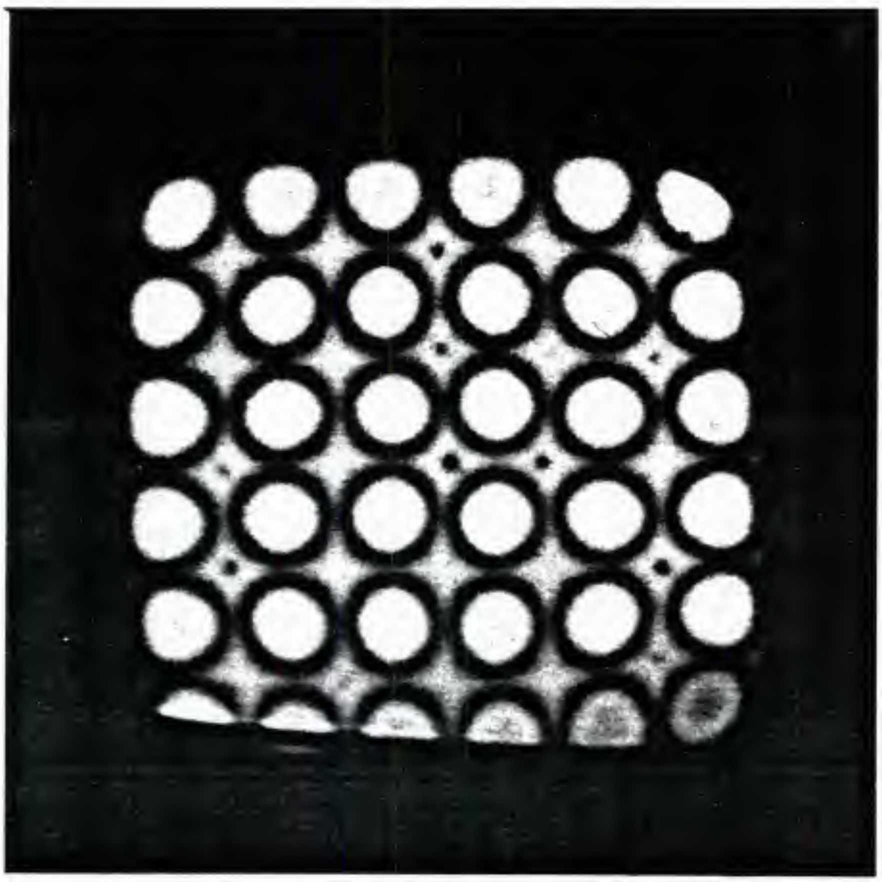

Figure 1. 500X Micrograph of Multifiber Drawn at 2032°C

Collimated light from a tungsten-halogen (visible to near IR) or a deuterium (UV) source was passed through a narrow bandpass filter and then through an optical chopper. A lock-in amplifier was used to correlate the rotation frequency of the chopper to the modulated detector signal to discriminate against background radiation. To insure that the acceptance cone of the fiber was completely filled, the quasi-monochromatic light was focused into the cleaved fiber with a .30 NA microscope objective (for visible and IR wavelengths) or with a suprasil lens (for UV wavelengths).

The input end fiber was mounted on a three-axis stage which permits positioning for optimum coupling of power. The opposite end of the fiber was held in front of a silicon detector by a vacuum chuck which permits precise repositioning of different fibers so that the same portion of the detector surface was illuminated.

Attenuation was determined by measuring the detector response at each wavelength for a given length of fiber, then cutting the fiber back and making a similar measurement for successively shorter lengths of the same fiber. The logarithm of the detector response was plotted vs. fiber length, and a linear least squares line was fit to the data. The attenuation coefficent, $k = \{-10 \log (T)\}/DX$ (dB/M), is given by the slope of the line.

The attenuation coefficient of 100 micron monofiber made from the 1.4 OD/core, "SS" preform was first measured and the results plotted in Figure 2. This fiber exhibits attenuation through the visible and near IR of about 20-40 dB/km. Multifiber made from this material normally would be expected to exhibit similar attenuation. However, results of measurements on the multifiber array indicate the square multifiber exhibits losses ten times those of the 100-micron monofiber and a long wavelength cutoff of about 650 nm. (In Figure 3 the data are plotted as % T for 10 meter length vs. λ in order to show the cutoff).

Explanation of the discrepancy in optical performance between the two types of fiber is apparent on examining the structure of the multifiber. The photograph in Figure 1 shows eight-micron optical conducting cores in a square array on 10 micron centers. Normally the two-micron spacing would be occupied by low index cladding material. This effective optical cladding thickness of two microns is sufficient to maintain the optical integrity of the cores. In the present case, however, the preform's outer silica buffer forms a continuous high-index phase interspersed in the cladding material between the optical elements. This continuous silica phase forms an extraneous waveguide in the fiber structure. The optical cladding, the dark rings in Figure 1, separating the cores from the continuous silica phase is much less than the wavelength of light, and frustrated total internal reflection occurs between the optical core and the continuous silica phase. This manifests itself as cross talk or leakage of the evanescent wave from one medium to the other. This phenomenon is wavelength-dependent, i.e., the higher wavelengths are more likely to tunnel through the optical cladding, resulting in long wavelength cutoff. This wavelength dependence can be readily observed in Figures 4, 5, and 6. The photographs show the number of elements illuminated at the output end of the fiber when the outermost row of elements is illuminated at the input. When the input light is only 450 nm, (Figure 4) the outermost elements are illuminated. As the wavelength of the input light is increased to 550 nm (Figure 5), more elements are illuminated at the output. When red light (650

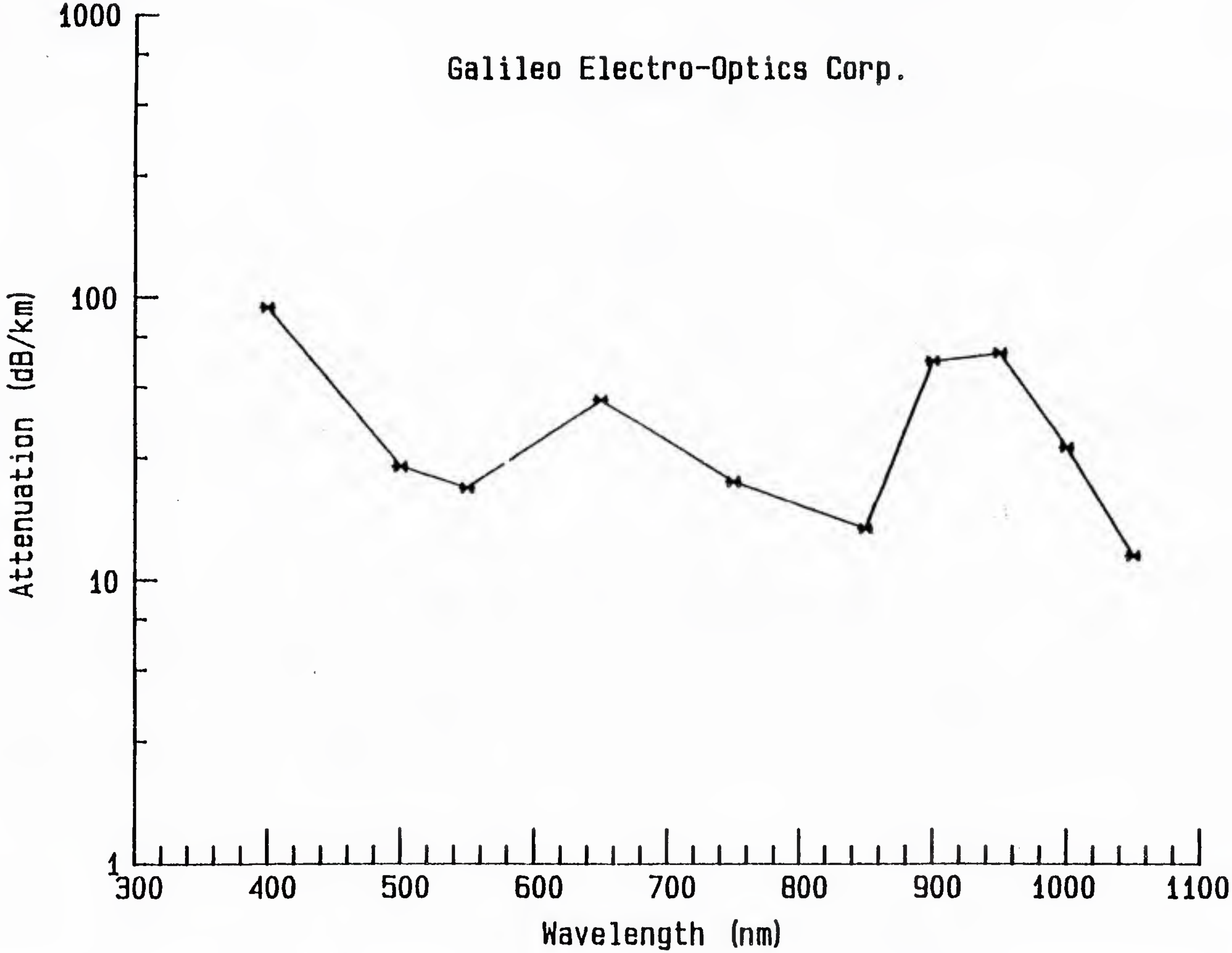

Figure 2. Attenuation vs. Wavelength for 100-micron Fused Silica Monofiber

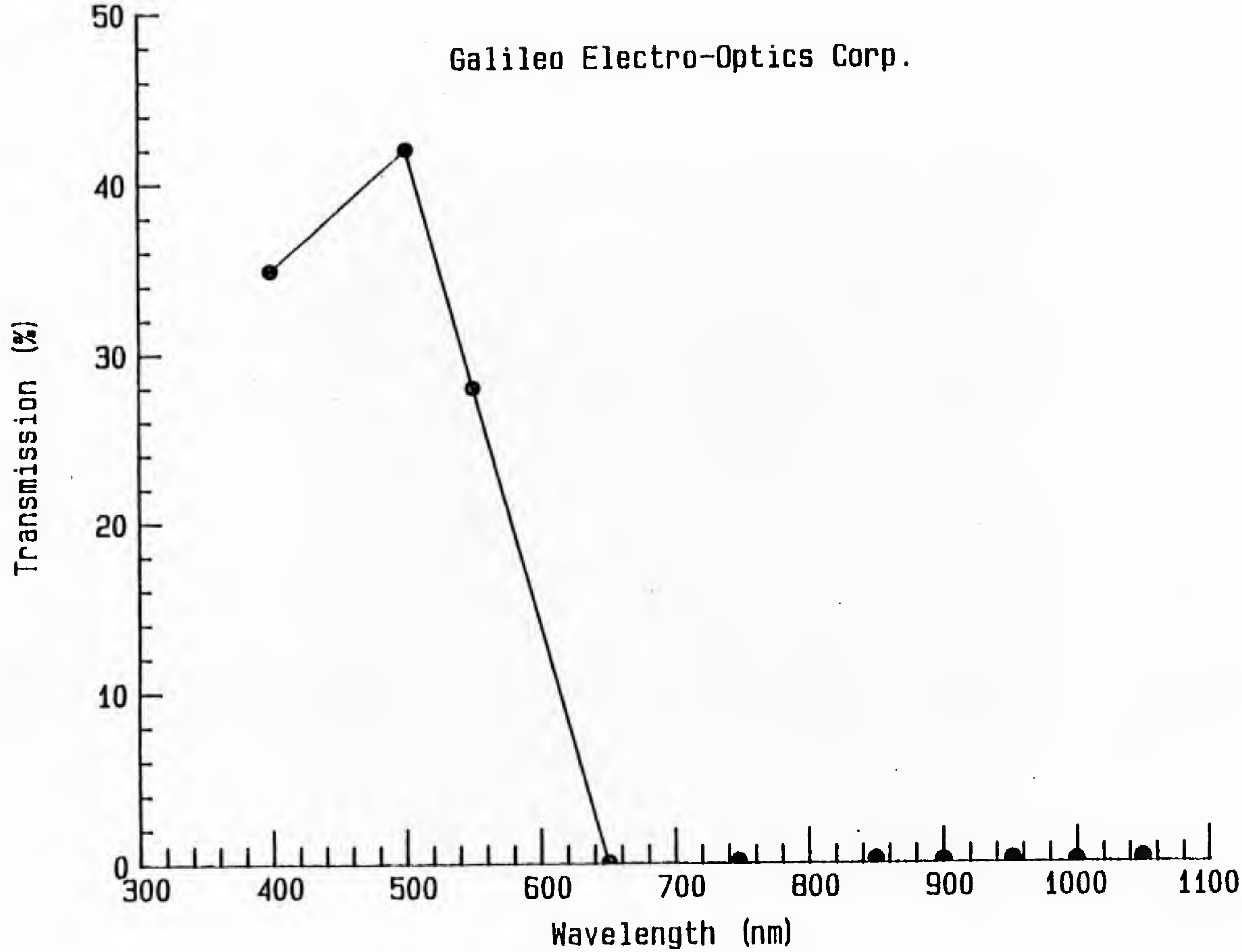

Figure 3. Transmission vs. Wavelength for 60-micron 6x6 Multifiber

Figure 4. Multifiber Illuminated at 450 nm

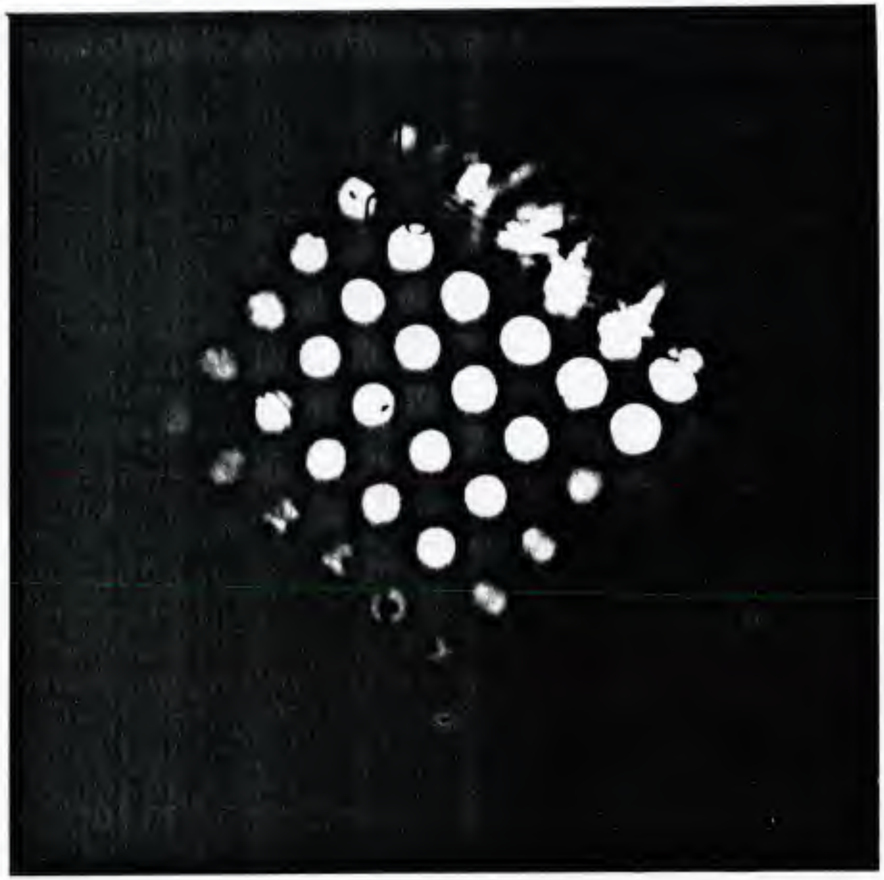

Figure 5. Multifiber Illuminated at 550 nm

Figure 6. Multifiber Illuminated at 650 nm

nm) is input (Figure 6), light is dispersed among all the elements. When the fiber is put in a mode stripper (a refractive index-matching medium which extracts unguided modes from the cladding), no light is transmitted above 650 nm.

V. CONCLUSION

The ability to draw a square, 6 x 6 array of 60-micron fused silica multifiber was successfully demonstrated. The mechanics of the draw were shown to be a straightforward extension of the technology previously developed at Galileo for mixed silicate glasses. Further, the preform requirements for both mechanical and optical performance of the multifiber were identified. The preferred preform is a Ge-doped fused silica core with a pure fused silica optical cladding and an OD/core ratio greater than 1.4.

Negotiations for such preforms from a commercial vendor are in progress in preparation for the execution of Phase II of this program: fabrication of a 1-meter, 4 x 4 mm format fused silica imagescope.

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