SAND93-2144C
Conf-931054--1

Kinoform/lens system for injecting a high power laser beam into an optical fiber

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Second draft, October 21, 1993

1. ABSTRACT

A method for injecting a high peak power multimode YAG laser beam into an optical fiber has been developed. The design minimizes the peak irradiance on the fiber's entrance face and reduces its dependence on the laser's mode structure and the system alignment. A simple lens and a specially designed kinoform (or binary optics element) operate together to transform a 5 mm diameter laser beam into two concentric ring foci that fit on the 400 μm diameter fiber face.

2. INTRODUCTION

As lasers become more powerful and less expensive, there is an increasing number of applications which use lasers primarily as an energy source. In many of these applications, the output of a pulsed, high power laser is coupled into a multi-mode fiber. The fiber is used as a light pipe and delivers the optical energy to a desired location. Applications which fall in this category include high-power optical fiber sensors, industrial laser machining, micromachining, marking of parts, ablation of biological tissue (e.g., corneal sculpting and arterial plaque removal), catalysis of chemical reactions and initiation of high explosives.

In many of these applications, the source may be a Q-switched laser with pulsewidths of 10-20 ns and pulse energies of 10-100 mJ, resulting in peak powers ranging from 1-10 MW. The fiber injector must couple these pulses into a multimode fiber which is typically silica on silica with a diameter of 100-400 μm. Typical fluxes on the face of the fiber ~~are then in the~~ 10 GW/cm^2. ~~regime~~ The primary purpose of the fiber injector is to evenly distribute the energy over the fiber face, thus keeping the peak fluence on the fiber face below the damage threshold. In addition, the fiber injector must also smooth out the beam both in front of the fiber in order to avoid air breakdown and also inside the fiber to avoid fiber breakdown. In particular, the fiber injector must not produce a focus at any point.

As a secondary goal, the fiber injector should also make the overall system insensitive to any variations. For example, since energy delivery is the goal of this type of application, it would be advantageous to use all of the modes supported by the laser cavity rather than using only the lower order modes in order to get a predictable beam shape. In addition, environmental effects can misalign the laser cavity, thereby changing both the mode structure and divergence of the laser. Both of these effects can be mitigated by a fiber injector which is insensitive to variations in the mode structure and the divergence of the laser. As another example, mechanical tolerances can result in significant translation and tilt of the laser beam. A fiber injector which is insensitive to these variations can eliminate the need for an active alignment system.

For our design, we assumed the following typical numbers: a 5-6 mm diameter laser beam with a divergence of 2-5 mrad and a 400 μm diameter fiber with a numerical aperture of 0.22. Tilt and decentration errors are estimated to be about 2 mrad and 0.5 mm, respectively

3. THE SYSTEM

Our system is similar in operation to a lens/axicon combination [1], [2], as depicted in figure 1. By itself, a lens would create a focal spot at the center of the fiber, as shown in figure 1a. However, in combination with an axicon it creates a ring focus as in figure 1b. In our system, we replace the axicon with a binary optics element (or kinoform) [3] that diffracts the focusing beam into two concentric rings as shown in figure 1c. These rings have 150 μm and 300 μm diameters so the pattern fits on the 400 μm diameter fiber for any ring width less than 100 μm. The 7 mm diameter lens and axicon have apertures larger than the beam in order to accommodate beam decentration. We have chosen the shortest focal length possible for the lens, thereby minimizing the movement of the two-ring pattern on the fiber face when there are pointing errors and

Figure 1: Operation of a lens/kinoform system a) Lens alone produces a focal spot at the fiber center b) Lens/refractive axicon produces a ring focus at the fiber c) Lens/kinoform produces multiple ring foci.

also matching the incoming beam to the numerical aperture of the fiber. The focal length of 17 mm combined with the 7 mm aperture create a beam with a maximum numerical aperture of .20, which is a bit smaller than that of the fiber, which has a numerical aperture of .22. Shorter focal lengths, when coupled with the possible system variations, could potentially exceed the numerical aperture of the fiber. We would like to match the numerical aperture of the fiber (as opposed to underfilling the fiber) since we feel that filling more of the fiber's modes makes the intensity more uniform.

So what can we expect from this system? The most important point is that the peak intensity is minimized because the beam footprint on the fiber face is large. Furthermore, the footprint area is roughly equal to the sum of the two ring lengths multiplied by the ring width. Thus, it is proportional to the laser divergence, and not to the square of the divergence as would be the case with a conventional lens system. For the laser divergences given, the ratio between the peak intensity and the average intensity over the fiber face is in the range of $1.6 < I_{peak}/I_{average} < 3.7$. At first glance, one wonders why a long focal length lens could not be used for the fiber injection. This is a workable

Figure 2: The kinoform behaves simultaneously as refractive axicons of different powers, with each diffraction order corresponding to a specific axicon

approach in the lab where the divergence of the laser can be measured and compensated. However, for an operational system, the focal length of the lens would have to be chosen to accommodate the greatest divergence, which is 5 mrad. Furthermore, the 2 mrad pointing tolerance would have to be included, along with a small assembly tolerance. The intensity ratio is therefore in the range $2.25 < I_{peak}/I_{average} < 9$. We feel that the lower peak intensities of the lens/kinoform system justifies the added complexity.

4. THE KINOFORM

The kinoform is a diffractive axicon. Referring to the previous figure 1, each diffraction order of the kinoform will produce a ring focus, just like a refractive axicon. Considering all the diffraction orders together, then, the kinoform behaves like many different refractive axicons simultaneously, as shown in figure 2 with the amount of light which "sees" each refractive axicon being determined by the efficiency of the corresponding diffraction order.

Our kinoform is designed to diffract 90% of the light into the ±1 and ±2 orders with the same intensity in each ring. The ±1 orders produce the inner ring shown in figure 1, while the ±2 orders produce the outer ring. The remaining 10% of the light is distributed into higher orders. The intensities in the ±3, ±4 and ±5 orders, which fall on the fiber cladding, is low so very little light is diffracted into the cladding. Furthermore, the design leaves almost no light in the zero order so there will not be a hot spot on-axis if the laser beam has better beam quality than expected.

The kinoform diffracts light into four orders: the +2, +1, -1 and -2 orders. This has a couple of advantages over other possible designs. First, designs which diffract light primarily into only two orders (e.g., a design which utilizes the ±1 orders or one which uses the +1 and +2 orders) have an overall diffraction efficiency which is about 10% lower than our design. On the other hand, designs which utilize more than four orders (e.g., one which uses the ±1, ±2 and ±3 orders) are more sensitive to fabrication errors without a significant increase in diffraction efficiency. Second, the intensity profile on the fiber is quite insensitive to beam centering on the kinoform. To understand this, consider the ray in figure 3 which strikes the top of the kinoform. Ninety percent of the energy in this ray is split into the four rays corresponding to the four diffraction orders of interest and the +1 order ray is diffracted across the center and illuminates the bottom of the inner ring, while the -1 order illuminates the top, with the +2 and -2 orders behaving in a similar manner with respect to the outer ring focus. Now consider what occurs if the whole beam is moved a small amount downward. Due to this splitting between plus and minus orders, half of the displaced light still illuminates the tops of each ring and half the bottoms. So to first order, the system is insensitive to beam decentration.

Figure 3: The splitting of light between plus and minus orders makes the system insensitive to beam decentration.

Figure 4: Profile of one period of the silica kinoform.

The actual design of the kinoform was achieved using the algorithm described in [4]. The resulting silica kinoform is circularly symmetric with a radial period of 288 μm and the surface profile for one period of the kinoform is shown in figure 4. The step-wise nature of the surface profile is a result of the binary optics fabrication process. The kinoform is a 16-level device, of which only 14 levels are required.

5. EXPERIMENTAL RESULTS

The silica kinoform was fabricated by the binary optics program at MIT/Lincoln Laboratory [5]. The surface profile and diffraction efficiency were then measured at MIT/Lincoln Laboratory, using a stylus profilometer and a technique similar to that in [6], respectively. It was then sent to Sandia National Laboratory for testing with the appropriate lens and laser. The ratio between the peak intensity on the fiber face and the average over the fiber face was found to be 3.7 to 1 when a very well aligned laser was used ($\sim$ 2.5 mrad divergence) [7]. Figure 5 shows a typical recorded intensity profile. Next, the lens/kinoform system was used to inject pulses of increasing energy into a fiber until the fiber was damaged. This was repeated for ten fibers and approximately half the fibers were able to deliver pulses of 40 mJ or greater before being damaged.

Figure 5. ***Typical intensity profile on the fiber face, using a well-aligned laser, supplied by SNL.

Regarding damage to the axicon itself, since the device is a surface relief in silica and contains no other materials, we expect it should have damage characteristics similar to that of bulk silica. Our experiments to date confirm this belief.

6. SUMMARY

A system has been designed, built and tested that injects a high power, short pulse, multimode YAG laser beam into an optical fiber without damage. The system can tolerate a significant amount of laser cavity misalignment without damage to the fiber or its cladding.

7. ACKNOWLEDGEMENTS

This work is supported by the United States Department of Energy under contract DE-AC04-~~76DP00789~~ 94AL85000.

This has been a team effort. The authors designed the injector system and the binary optics element, while other people did most of the real work, including the following:

Margaret Stern, Theresa Jay, Joe Theriault and John Glover of MIT/Lincoln Laboratory, who fabricated the binary optics elements.

Steve Kuehn of Sandia National Laboratory and Tom Swann of Optomec, who did the mechanical design.

Bob Setchell, Steve Kuehn, Dante Berry and Mike Hinckley of Sandia National Laboratory and John Greene of MIT/Lincoln Laboratory, who did the testing.

8. REFERENCES

9. *

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[1] J.H. McLeod, "Axicons and their uses," J. Opt. Soc. Am. 50, 166-169 (1960).

[2] I.A. Mikhaltsova, et. al., "Kinoform Axicons," Optik 67, 267-278 (1984).

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[4] M.W. Farn, "New iterative algorithm for the design of phase-only gratings" Proc. Soc. Photo-Opt. Instrum. Eng. 1555, 34-42 (1991).

[5] M.B. Stern, et. al., "Fabricating binary optics: process variables critical to optical efficiency" J Vac Sci and Tech B 9, 3117-3121 (1991)

[6] M. Holz, et. al., "Testing binary optics: accurate high-precision efficiency measurements of microlens arrays in the visible," Proc. Soc. Photo-Opt Instrum. Eng. 1555, ***page numbers. (1991).

[7] Private communication with R.E. Setchell and D.M. Berry of Sandia National Laboratory.

[8] Private communication with S.F. Kuehn and M.K. Hinckley of Sandia National Laboratory.

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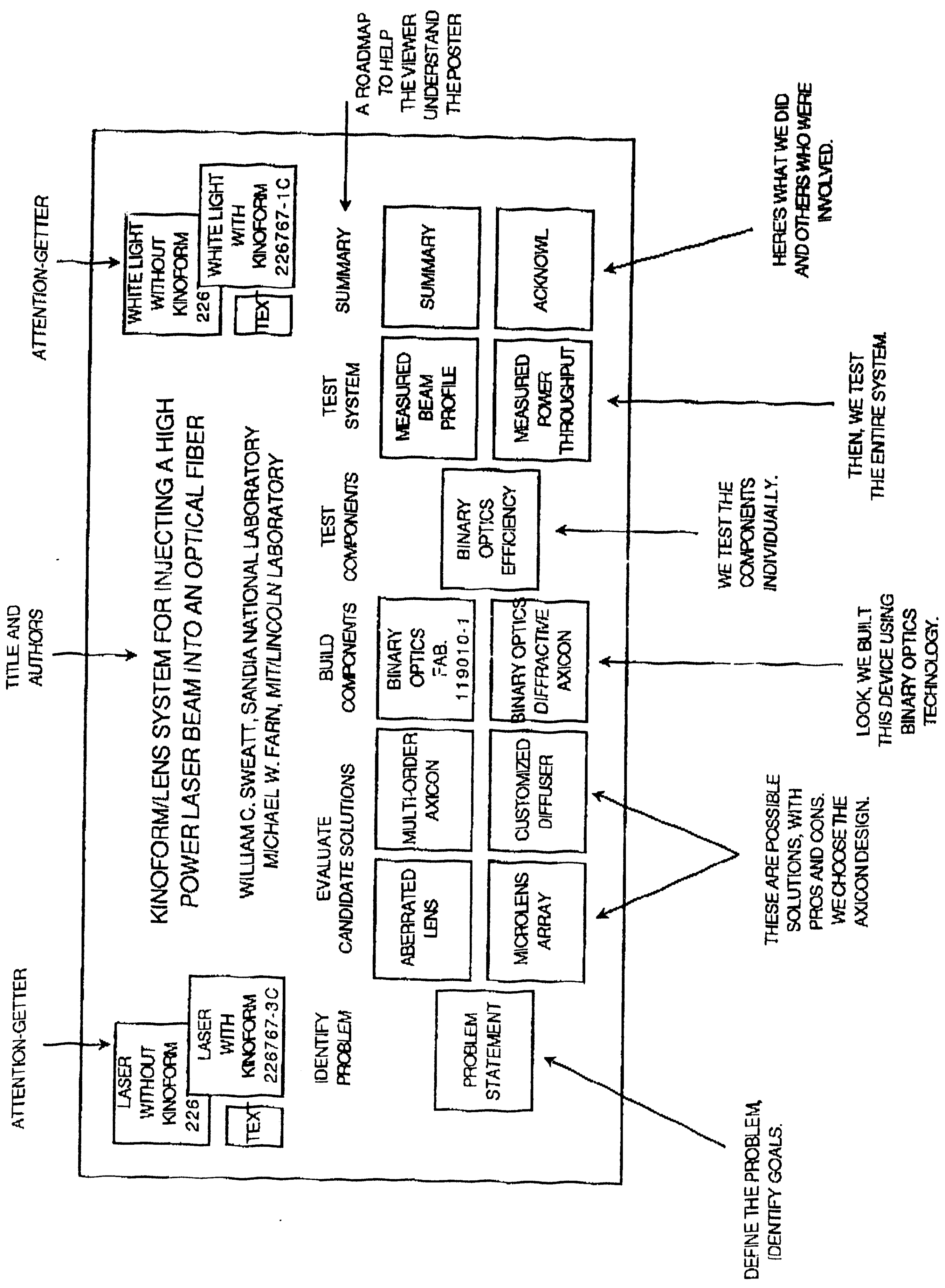
List of Figures


ATTENTION-GETTER
LASER WITHOUT KINOFORM 226
LASER WITH KINOFORM 226767-3C
TEXT
TITLE AND AUTHORS
KINOFORM/LENS SYSTEM FOR INJECTING A HIGH POWER LASER BEAM INTO AN OPTICAL FIBER
WILLIAM C. SWEATT, SANDIA NATIONAL LABORATORY
MICHAEL W. FARN, MIT/LINCOLN LABORATORY
ATTENTION-GETTER
WHITE LIGHT WITHOUT KINOFORM 226
WHITE LIGHT WITH KINOFORM 226767-1C
TEXT
IDENTIFY PROBLEM
PROBLEM STATEMENT
EVALUATE CANDIDATE SOLUTIONS
ABERRATED LENS
MULTI-ORDER AXICON
MICROLENS ARRAY
CUSTOMIZED DIFFUSER
BUILD COMPONENTS
BINARY OPTICS FAB. 119010-1
BINARY OPTICS DIFFRACTIVE AXICON
TEST COMPONENTS
BINARY OPTICS EFFICIENCY
TEST SYSTEM
MEASURED BEAM PROFILE
MEASURED POWER THROUGHPUT
SUMMARY
SUMMARY
ACKNOWL
A ROADMAP TO HELP THE VIEWER UNDERSTAND THE POSTER
DEFINE THE PROBLEM, IDENTIFY GOALS.
THESE ARE POSSIBLE SOLUTIONS, WITH PROS AND CONS. WE CHOOSE THE AXICON DESIGN.
LOOK, WE BUILT THIS DEVICE USING BINARY OPTICS TECHNOLOGY.
WE TEST THE COMPONENTS INDIVIDUALLY.
THEN, WE TEST THE ENTIRE SYSTEM.
HERE'S WHAT WE DID AND OTHERS WHO WERE INVOLVED.

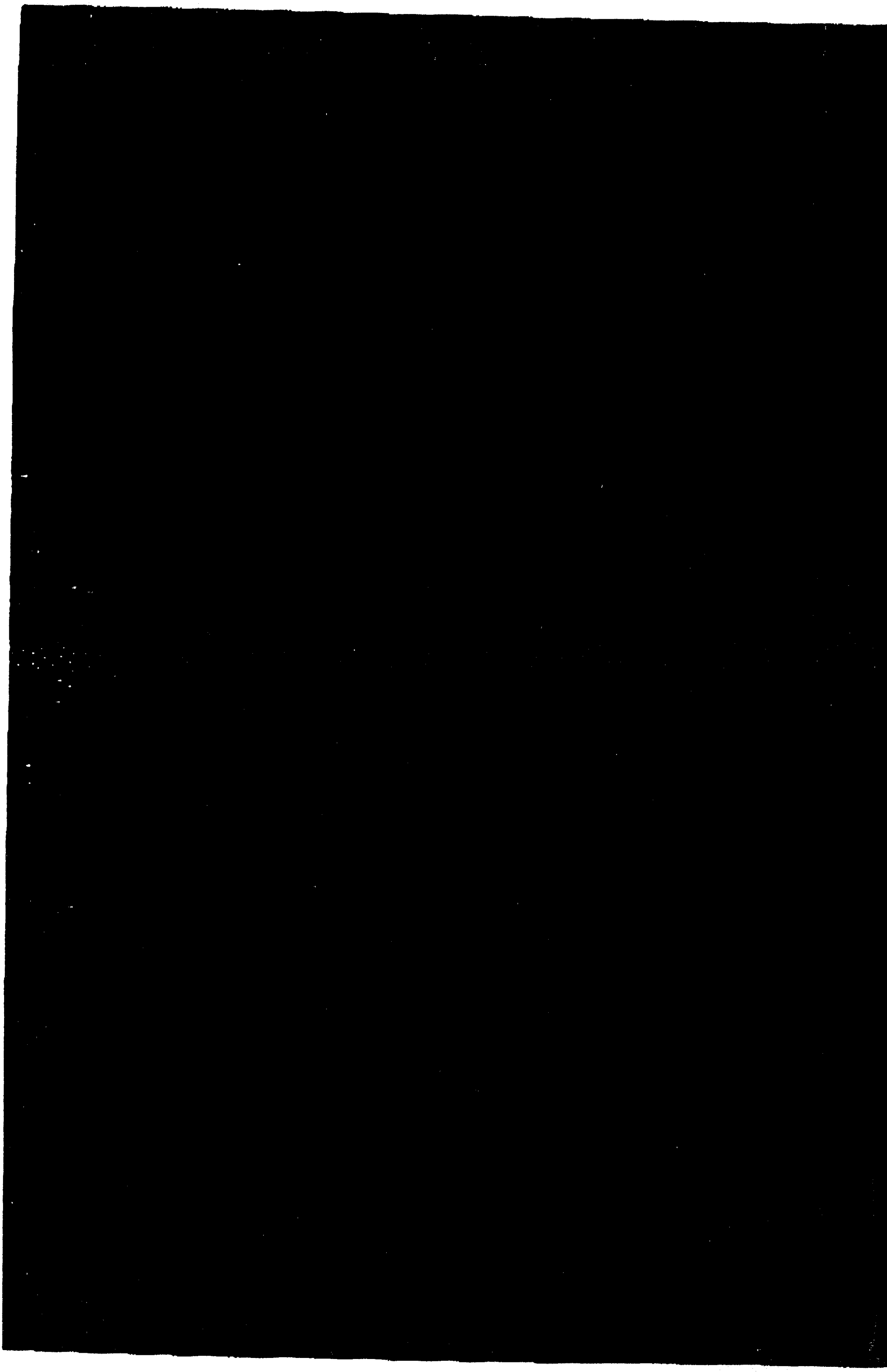
TEXT FOR FOLLOWING PHOTOS

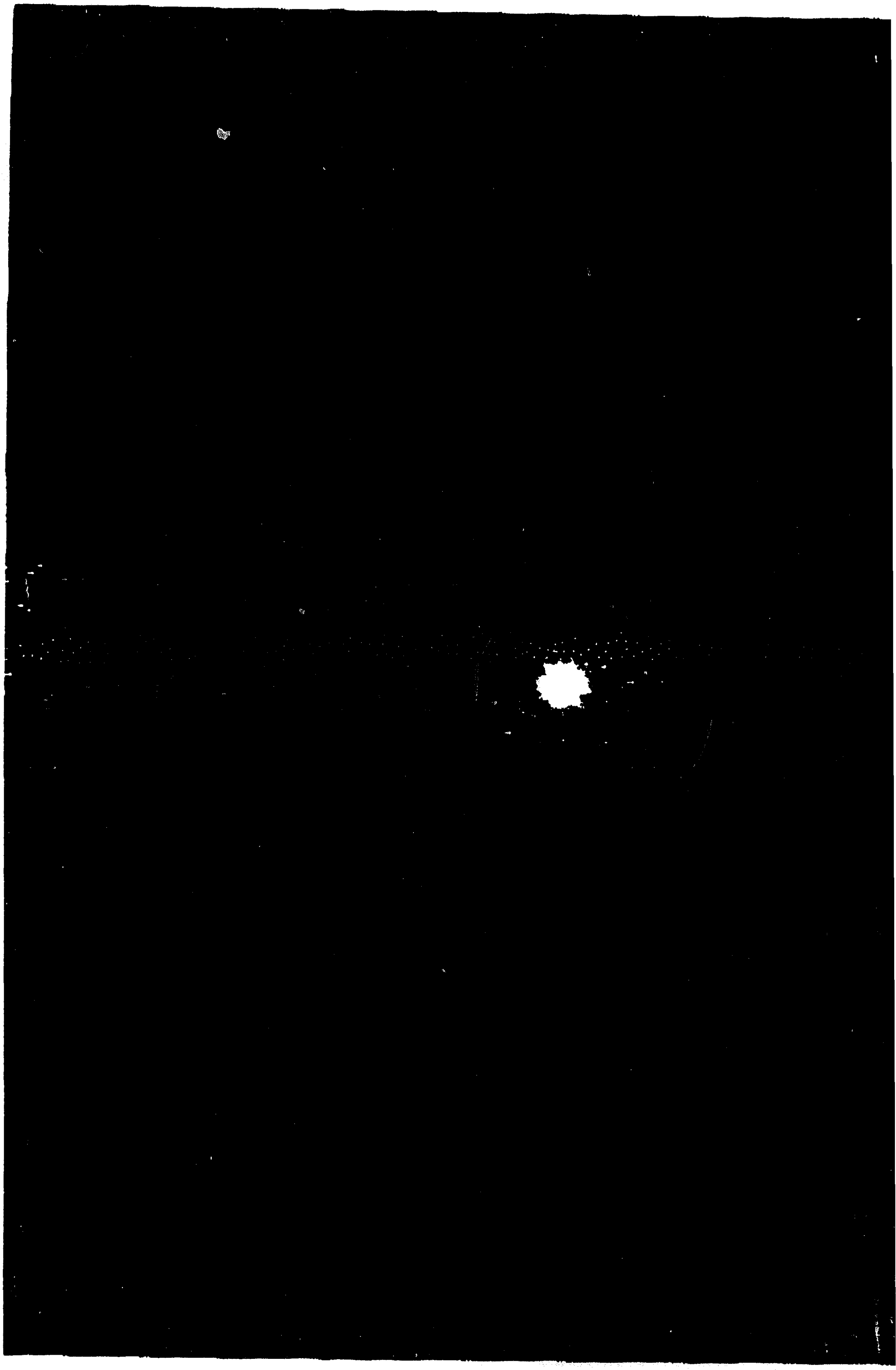
(ABOVE)
A LASER IS IMAGED BY A LENS INTO A SINGLE FOCAL SPOT. THE RADIAL SPOKES IN THE PHOTOGRAPH ARE A RESULT OF DIFFRACTION FROM THE APERTURE AND OVEREXPOSURE OF THE FILM.

(RIGHT)
WHEN THE DIFFRACTIVE AXICON IS INSERTED, THE SINGLE FOCAL SPOT IS TRANSFORMED INTO A SERIES OF CONCENTRIC FOCAL RINGS, WITH EACH RING CORRESPONDING TO A DIFFRACTION ORDER.

(ABOVE)
THE SAME CASE AS IN THE PHOTOGRAPHS TO THE LEFT, EXCEPT THAT THE LASER IS REPLACED BY A WHITE LIGHT SOURCE.

(RIGHT)
EACH WAVELENGTH PRODUCES A SERIES OF CONCENTRIC RINGS, WITH THE SPACING OF THE RINGS BEING PROPORTIONAL TO THE WAVELENGTH. WHERE THE RINGS OVERLAP, SECONDARY COLORS ARE PRODUCED.



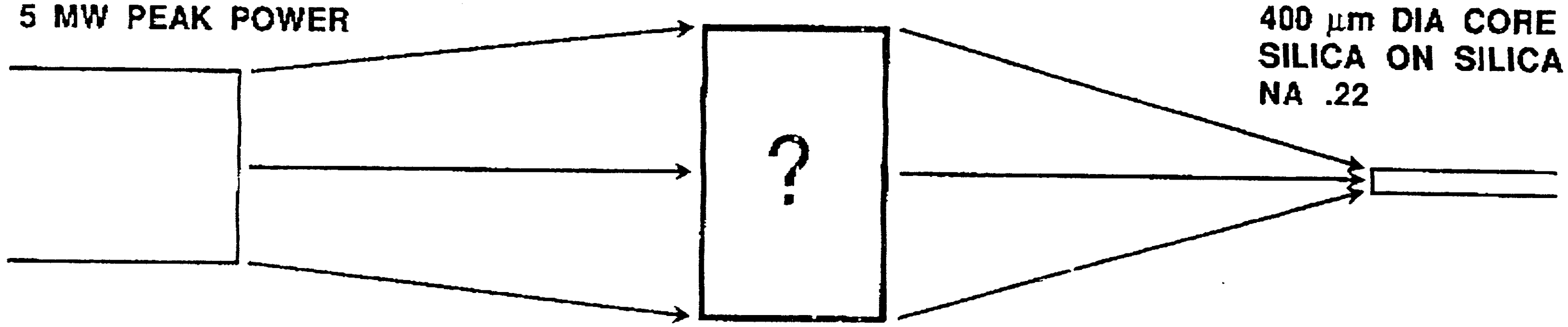


PROBLEM STATEMENT

LASER
MULTI-MODE LASER
λ = 1.06 µm
15 ns PULSE
5 MW PEAK POWER

BEAM
5 mm DIA BEAM
+/-0.5 mm DECENTRATION
2-5 mrad DIVERGENCE
+/-2 mrad TILT ERRORS
NON-UNIFORM INTENSITY

FIBER
400 µm DIA CORE
SILICA ON SILICA
NA .22

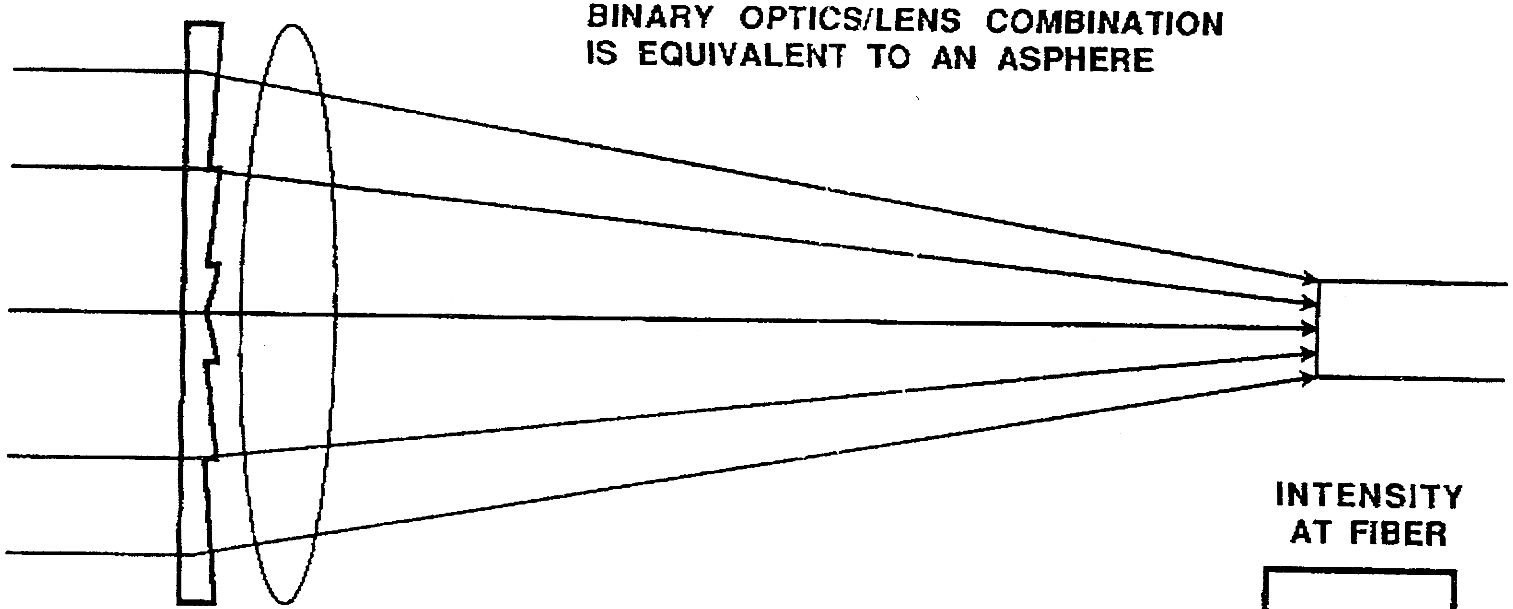


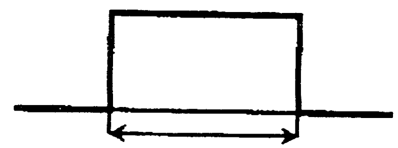
DESIGN GOALS:
- GOOD BEAM HOMOGENIZATION
- EFFICIENT COUPLING
- INSENSITIVE TO INTENSITY FLUCTUATIONS
- INSENSITIVE TO CHANGES IN DIVERGENCE
- SIMPLE FABRICATION, SIMPLE DESIGN
- RELIABILITY, LOW RISK

ABERRATED LENS

INTENTIONAL ABERRATIONS OPTIMALLY MISFOCUS LENS

BINARY OPTICS/LENS COMBINATION
IS EQUIVALENT TO AN ASPHERE

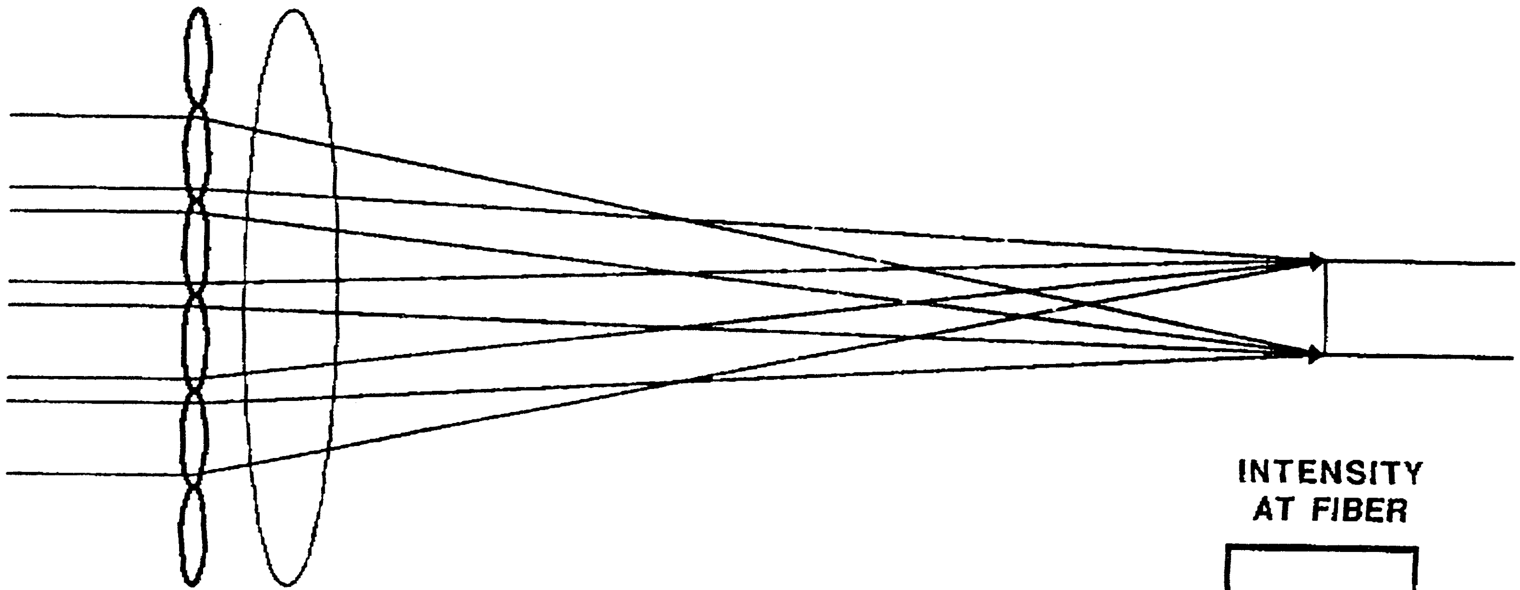


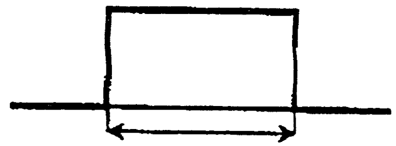


CHARACTERISTICS:
+ GOOD HOMOGENIZATION FOR IDEAL BEAM
+ LOW FAB LOSSES (<5%)
- INTENSITY VARIATIONS ARE IMAGED ONTO FIBER
- DIVERGENCE AFFECTS SPOT SIZE
o MULTI-LEVEL FABRICATION
+ THE "DEFAULT" APPROACH

MICROLENS ARRAY

EACH LENS FORMS AN IMAGE ON THE FIBER, IMAGES COMBINE INCOHERENTLY





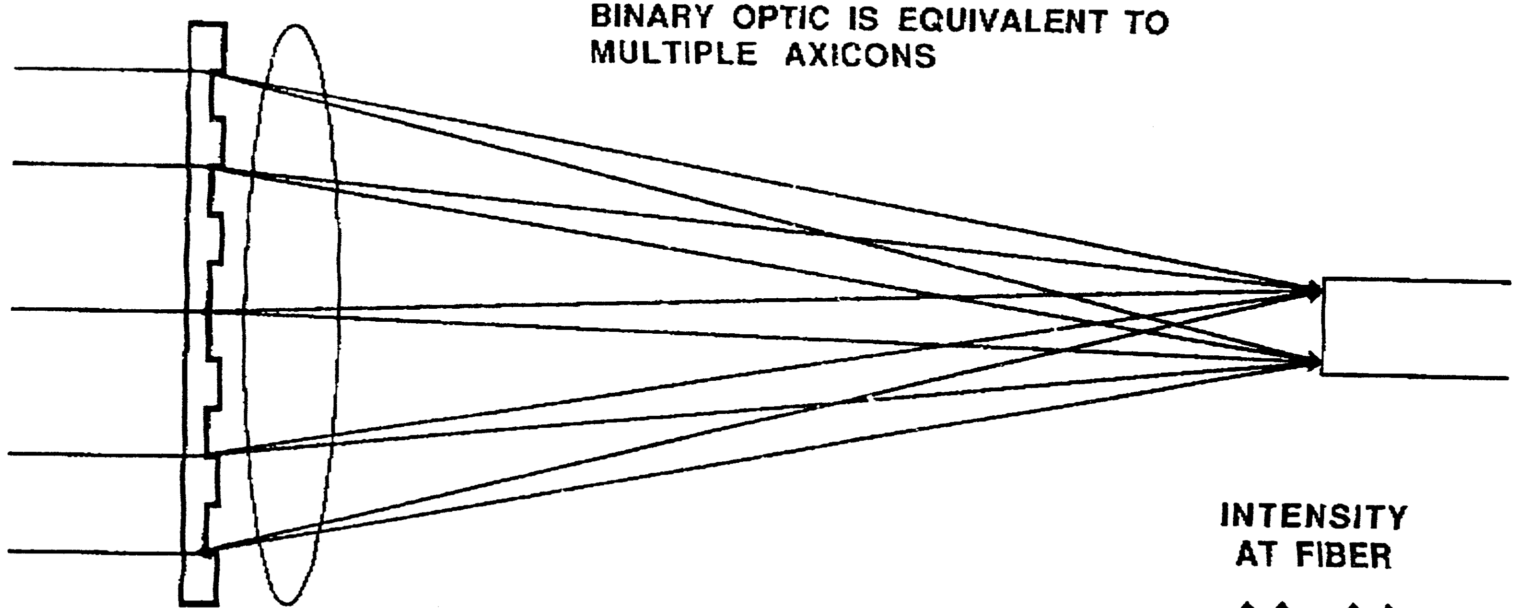
CHARACTERISTICS:

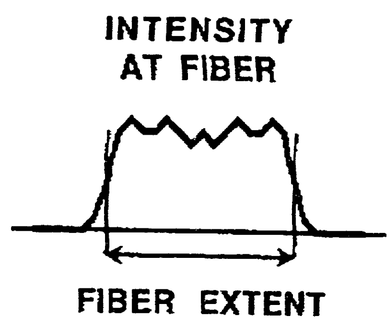
+ GOOD HOMOGENIZATION FOR KNOWN BEAM
  - REQUIRES SPATIALLY INCOHERENT BEAM
o SCATTER AND FAB LOSSES (10%)
+ INTENSITY VARIATIONS ARE SMOOTHED
- DIVERGENCE AFFECTS IMAGE SIZE
o MULTI-LAYER FABRICATION
o USED IN COMMERCIAL APPLICATIONS

MULTI-ORDER AXICON

MULTIPLE ORDERS RESULT IN MULTIPLE RING FOCI

BINARY OPTIC IS EQUIVALENT TO MULTIPLE AXICONS

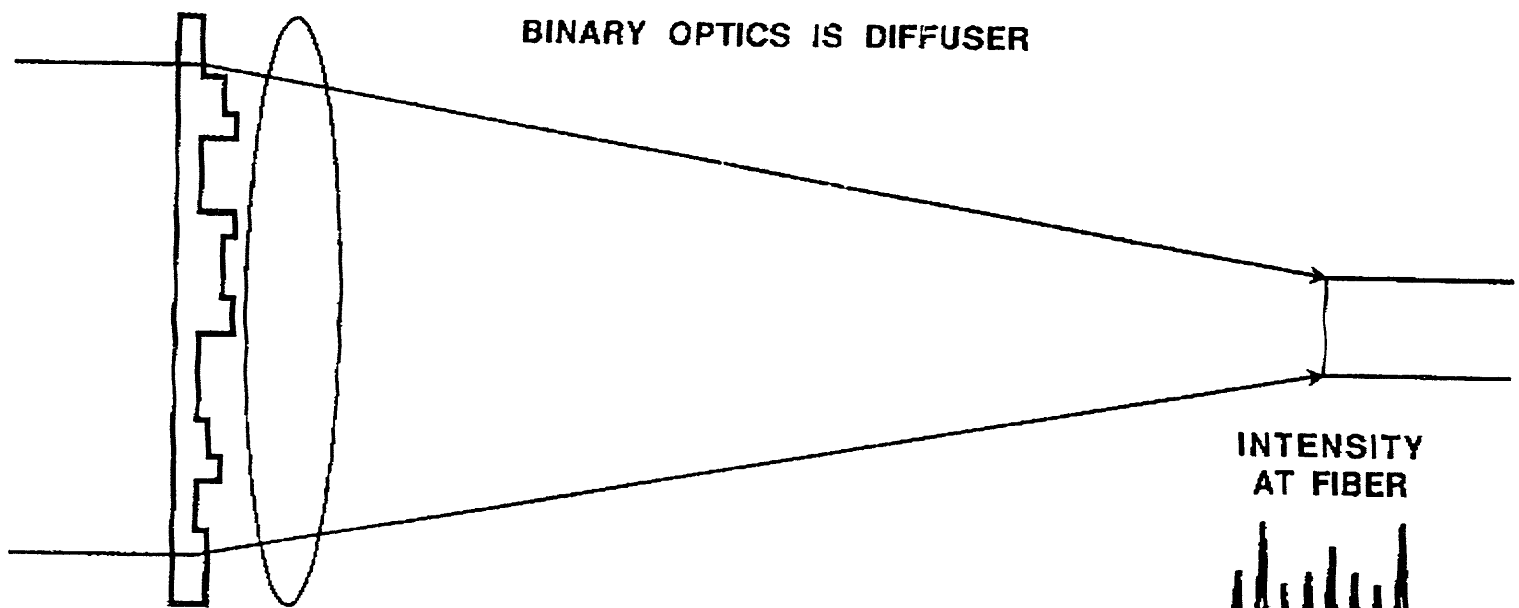




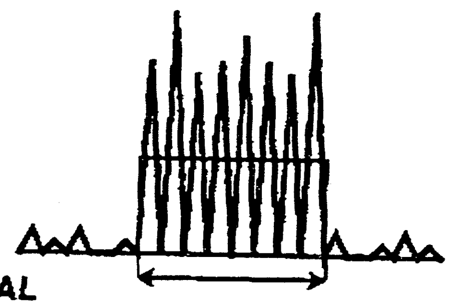
CHARACTERISTICS:
- o SOME RESIDUAL INTENSITY FLUCTUATIONS
- o DIFFRACTION AND FAB LOSSES (10%)
- o EFFECTS OF INTENSITY VARIATIONS ARE REDUCED
- o DIVERGENCE EFFECTS ARE REDUCED
- o MULTI-LAYER FABRICATION
- + WELL-KNOWN PHENOMENON

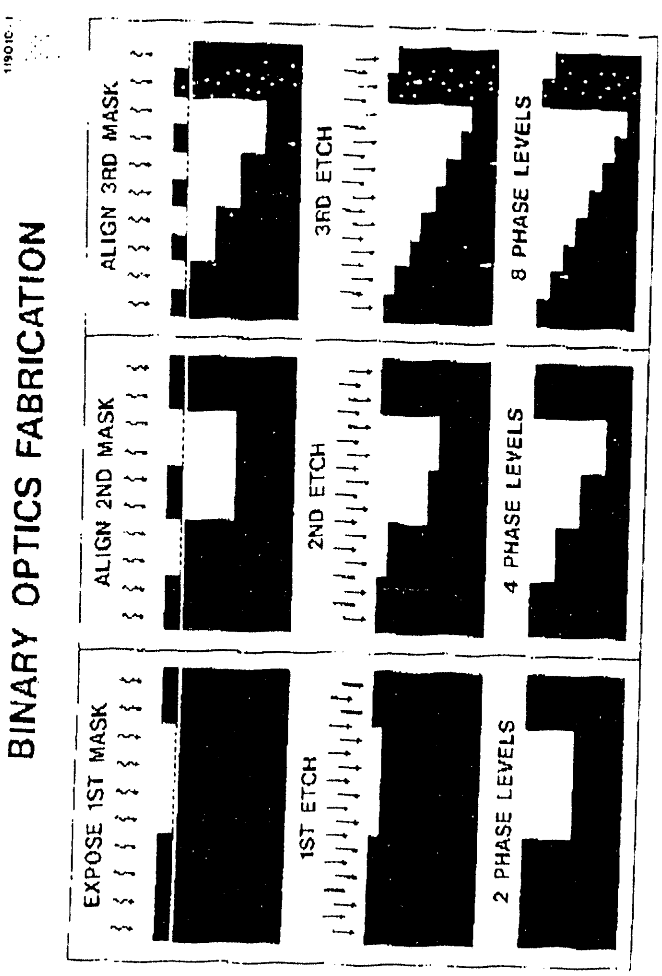
CUSTOMIZED DIFFUSER

DIFFUSER IS DESIGNED TO BE BAND-LIMITED



CHARACTERISTICS:
- o SPECKLE CAUSES HIGH INTENSITY PEAKS
- o SCATTER AND FAB LOSSES (10%)
- + EFFECTS OF INTENSITY VARIATIONS ARE MINIMAL
- + DIVERGENCE EFFECTS ARE MINIMAL
- o BINARY FABRICATION, DIFFICULT DESIGN
- o STATISTICAL APPROACH




BINARY OPTICS FABRICATION
EXPOSE 1ST MASK
ALIGN 2ND MASK
ALIGN 3RD MASK
1ST ETCH
2ND ETCH
3RD ETCH
2 PHASE LEVELS
4 PHASE LEVELS
8 PHASE LEVELS

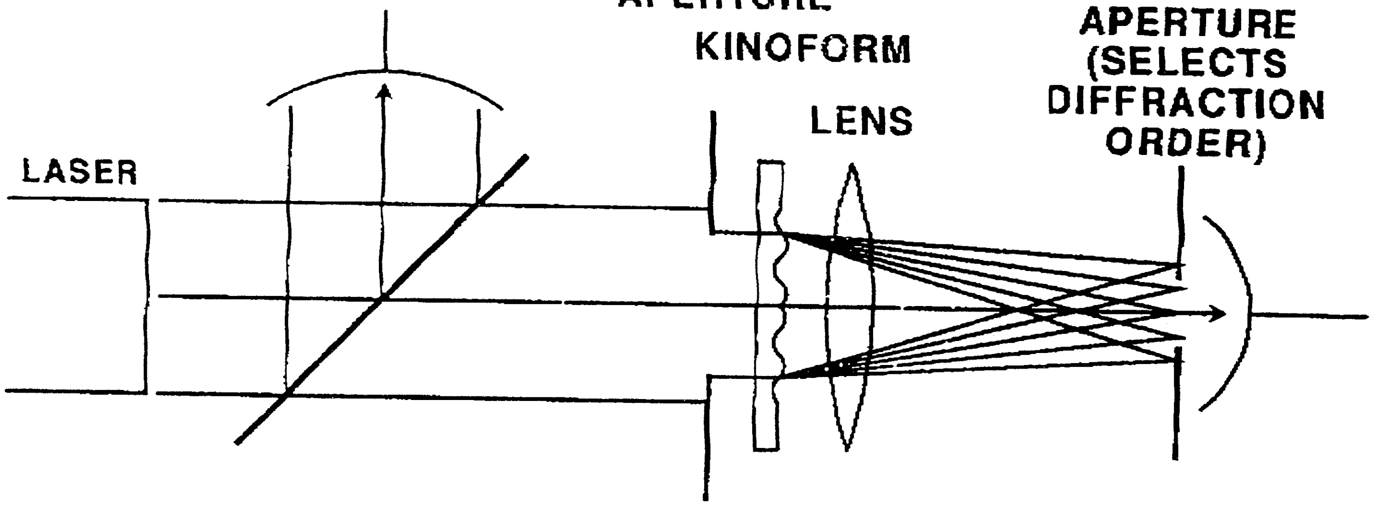
BINARY OPTICS DIFFRACTIVE AXICON

PROFILE OF ELEMENT,
EITHER TENCOR TRACE
OR IDEAL PROFILE.
BY M. STERN?.

PHOTO OF ELEMENT
UNDER MICROSCOPE
OR SEM.
BY M. STERN.

- 14 PHASE LEVELS
- 288 μm PERIOD
- 10 mm DIAMETER
- SURFACE RELIEF IN SILICA
- $\lambda = 1.06\ \mu$m

BINARY OPTICS EFFICIENCY



	DOE 1	DOE 2	DOE 3	THEORY
0 ORDER	4%	2%	1%	0%
+/-1 ORDER	24%	29%	33%	30%
+/-2 ORDER	66%	56%	61%	61%
HIGHER ORDERS	6%	12%	5%	9%

MEASURED BEAM PROFILE

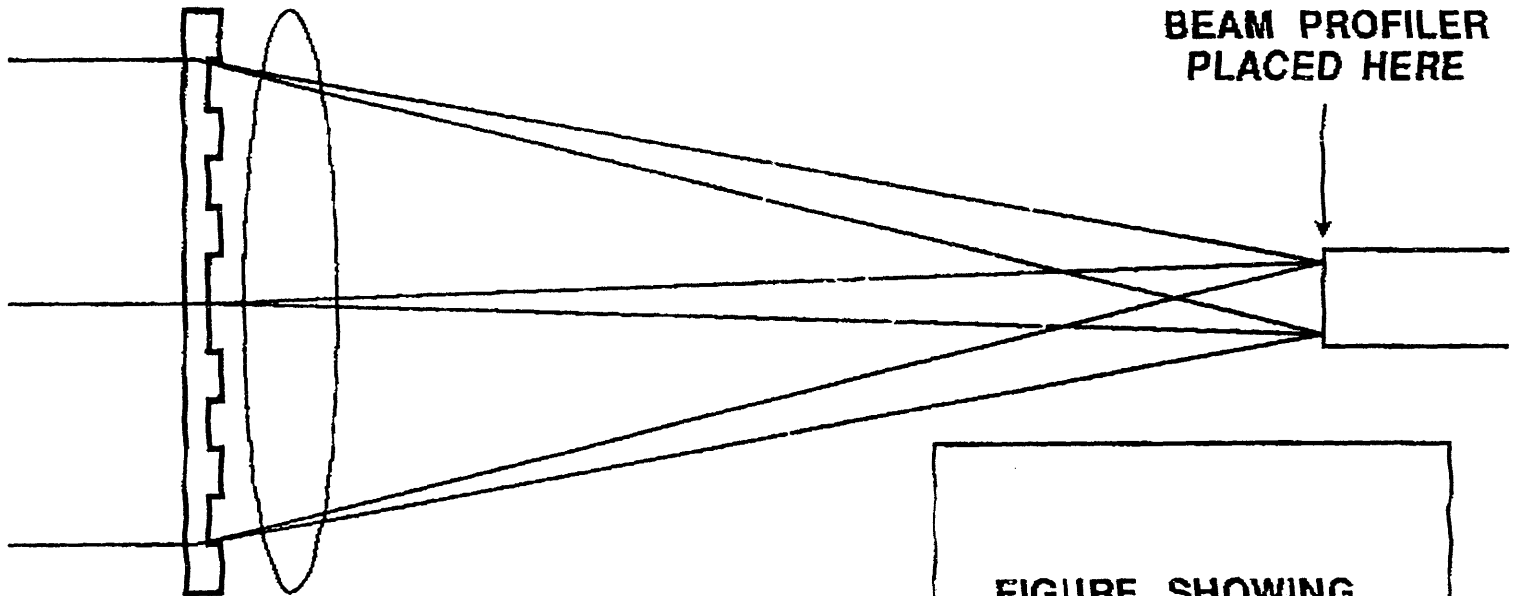


FIGURE SHOWING
TYPICAL
BEAM PROFILE,
SEE ALSO FIG 5
IN PROCEEDINGS.
BY SNL.

MEASURED POWER THROUGHPUT

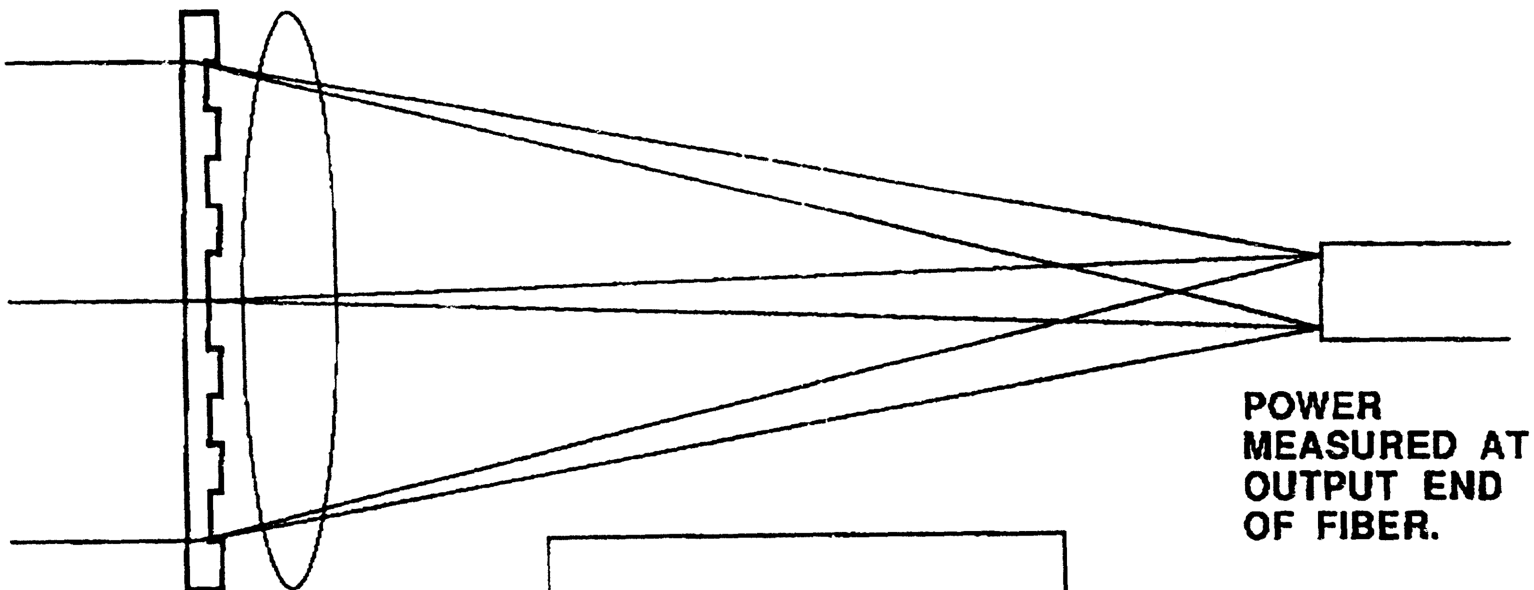


FIGURE SHOWING
TYPICAL
POWER THROUGHPUT,
45 mJ DEMONSTRATED.
BY SNL.

SUMMARY

- WE DEVELOPED A LENS/KINOFORM SYSTEM TO INJECT A HIGH POWER, SHORT PULSE, MULTIMODE LASER BEAM INTO A MULTIMODE FIBER.
- THE SYSTEM IS ROBUST TO VARIATIONS IN THE LASER BEAM AND TO MECHANICAL MISALIGNMENTS.
- FIFTY PERCENT OF THE TESTED FIBERS TRANSMITTED PULSES OF 40 mJ OR GREATER.

ACKNOWLEDGEMENTS

THIS WORK IS SUPPORTED BY THE UNITED STATES DEPARTMENT OF ENERGY UNDER CONTRACT DE-AC04-76DP00789.

WE GRATEFULLY ACKNOWLEDGE THE FOLLOWING:

- M. STERN, T. JAY, J. THERIAULT AND J. GLOVER, FOR FABRICATION OF THE BINARY OPTICS.
- S. KUEHN AND T. SWANN, FOR MECHANICAL DESIGN.
- R. SETCHELL, S. KUEHN, D. BERRY, M. HINCKLEY AND J. GREENE, FOR TESTING.

END

DATE
FILMED
2/23/94