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# Polyplanar Optic Display for Cockpit Application

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## ABSTRACT

The Polyplanar Optical Display (POD) is a high contrast display screen being developed for cockpit applications. This display screen is 2 inches thick and has a matte black face which allows for high contrast images. The prototype being developed is a form, fit and functional replacement display for the B-52 aircraft which uses a monochrome ten-inch display.

The new display uses a long lifetime, (10,000 hour), 200 mW green solid-state laser (532 nm) as its optical source. In order to produce real-time video, the laser light is being modulated by a Digital Light Processing (DLP™) chip manufactured by Texas Instruments, Inc. A variable astigmatic focusing system is used to produce a stigmatic image on the viewing face of the POD. In addition to the optical design and speckle reduction, we discuss the electronic interfacing to the DLP™ chip, the opto-mechanical design and viewing angle characteristics.

**Keywords:** DMD, POD, Laser, Display, Optical, Waveguide

## 1. DISPLAY REQUIREMENTS

In cockpit applications, it is vitally important for a pilot to view video information even in the presence of direct sunlight. Current B-52 displays utilize CRTs with a phosphor coating on the screen face, and have inherently poor contrast in high ambient light.

This research program has been designed to meet the needs of the B-52 cockpit displays which are presently using a 10 inch monochrome CRT. Since the POD has a black display screen with inherently high contrast, this technology holds promise for superior displays in high ambient light situations. Because of the high light levels within a military cockpit, a brightness of 1200 footlamberts (fl) is sometimes required.[1] In comparison, a civilian display would be adequate providing only 200 fl. To achieve 1200 fl with a CRT, the phosphor must be driven with an intense electron beam which leads to short CRT lifetime and, therefore, high maintenance costs for the aircraft.

A laser driven display is one method to achieve these high brightness requirements while maintaining a long lifetime for the display.

Although lasers can provide an inherently high brightness and high resolution display, there has never been a method to accomplish this with high contrast. Conventional laser projection, like the type employed at laser light shows, can provide a bright image on a flat screen in a tightly controlled dark environment. In addition, a rear projection laser system could be used, however the physical size of such a device is no less bulky than that of a conventional rear projection display. The Polyplanar Optic Display (POD) being described here uses neither front nor rear projection optics. It is an internal projection system where light is projected into the waveguide structure itself. This system can have high brightness and high contrast while having a compact enclosure.

## 2. THE POLYPLANAR SCREEN

The Polyplanar screen is a unique waveguide which has been designed to be a light trap for ambient light. Since it absorbs ambient light, it appears black when it is off. In addition to this, it transmits all light incident at the input surface which is within the numerical aperture of the waveguide.

Fiber optic wave guides have been well understood and used for decades. An internal fiber known as the core (refractive index n) is surrounded by a cladding (refractive index $<n$) so that light which enters the fiber within a known acceptance angle is confined within the fiber. This confinement occurs due to total internal reflection. The same process occurs if the internal core is a sheet of glass or plastic rather than a fiber of glass. It is understood that each internal core sheet must be adjacent to a sheet of cladding to ensure total internal reflection. Such a device, when constructed with many sheets or planes of glass or plastic is called a polyplanar optic display. See Figure 1. A polyplanar optic device is analogous to a fiber optic device, however, there are a few very important distinctions.

In a fiber optic, the angular information of the incident light beam is lost as the light exits the fiber. In a planar optic sheet, the angle of the incident light (in the plane of the sheet) is preserved at the exit of the sheet. This is a very important characteristic because one now has the capability to direct light into the entrance of a planar optic sheet and have the same light exit the sheet at a predetermined location. This is crucial to the operation of this polyplanar optic display flat panel screen.

Figure 2 shows a detail of a section of the planar optic screen. Each planar sheet corresponds to exactly one vertical line of resolution. However, in a preferred embodiment, several planar sheets may be used for each vertical line of resolution. Therefore, to attain a VGA display with 480 lines of vertical resolution, the screen must contain at least 480 planar sheets. The laser light exits each planar sheet at the front-frosted face which diffuses the beam to provide an extremely wide viewing angle, like conventional CRTs. The diffusive nature of the screen allows for a very wide viewing angle of approximately 160 degrees. When the laser is off, the screen appears flat black due to the nature of the interlayer cladding which absorbs the ambient light.

One of the first design considerations in the development of the POD was that of the optical core and cladding materials. The core material must have high optical transmittance, be available in the proper thicknesses and be robust enough to be machined into a display. Although many plastics appear to have good optical properties in thin cross sections, their bulk transmission is usually poor. Acrylic, or polymethyl methacrylate (PMMA) is the exception having a high transmittance with a loss factor of as low as 50 db/km.[2] Although the optical and mechanical properties of PMMA are attractive, it is not presently available in sheets thinner than 0.010 inch, since there has been no need for optical quality PMMA films.

We examined an alternate method of using acrylic films in the waveguide lamina. Master Bond Corp. manufacturers a line of ultraviolet curing acrylic liquids which have a viscosity low enough to be sprayed onto a substrate. We chose two materials to use in a spray deposition process. Masterbond UV-15 was chosen as the core material while UV-15-LR1 was used as the cladding. The refractive indices of the core and cladding were $n = 1.52$ and $n = 1.49$, respectively. The cladding had a black dye added to the solution in order to give the POD its black appearance. A robotically controlled spraying machine ensured a uniform thickness for each layer, however, the exact amounts of core solvent were not standardized from layer-to-layer. The feed supply for the core material had to be replenished often and the viscosity was not monitored closely enough which produced variations in thickness from 20 $\mu$m to 100 $\mu$m. See Figure 3. The cladding layers were a consistent 2 $\mu$m thickness, since the cladding feed supply only had to be filled once and the viscosity remained constant for the entire spraying operation. The sprayed screen, when completed, measured 12 in. x 18 in. x 1¼ in. Although occasional sheets within the waveguide exhibited good transmission, the majority of the screen had high attenuation to the incident light. This loss was due to an inadequate surface finish of each layer, which is a requirement for total internal reflection. For this process to work, either the feed material must be sprayed at a lower viscosity or the material must be allowed to flow out more than 30 seconds before UV curing takes place.

After a comparison of all available optical materials, glass was chosen as the material to be used for the display screens. A borosilicate glass from Schott Corp., D-263, was used since it was available in sheet thicknesses

## DISCLAIMER

from 0.001 inch to 0.010 inch Although this low alkali glass is primarily manufactured for the LCD display industry, its optical properties and refractive index (1.52) make it quite suitable for our applications.

In order to fabricate a 10 inch diagonal display, 480 sheets of glass (.004 inch thick) were each cut to a size of 6 in. x 8 in. These sheets were then assembled such that there was a 0.0002 inch layer of adhesive between the sheets which served as the low index cladding. In addition to acting as a cladding, this optically black layer provides the display with its black face which gives it its high contrast. This laminated assembly of glass and cladding is then diagonally cut on a diamond band saw into two POD screens. In order to easily obtain an optically polished input face, a piece of .008 inch glass is bonded to the input face using an epoxy with a refractive index equal to that of the glass, 1.52.

## 3. THE LASER

One of the design criteria of this program was to have a long lifetime light source, 10,000 hours, to reduce maintenance costs as well as down time. We, therefore, chose to use a solid-state green laser operating at 532 nm.

In Phase 1 we used a small, frequency doubled Nd:YAG laser operating at 1064 doubled to 532 nm wavelength, built by Coherent (Model DPY315m). The Nd:YAG is pumped by a diode laser which is temperature tuned to optimize the performance of the Nd:YAG crystal. This laser produced 100 mW, cw, at a wavelength of 532 nm in the green portion of the spectrum. It measures only 1 in. x 1.5 in x 3.5 in. and has an output beam diameter of 0.012 in. In addition, it has a small controller that measures 1 in. x 2.5 in. x 3 in. and a 28 Vdc power supply that is 1 in. x 3 in. x 11 in. The laser controller is capable of varying the laser output power from 35 mW to 100 mW. For our application we hard wired the laser to continually output maximum power.

In Phase 2 we wanted to use the most powerful laser available that would be able to fit into the confines of the display chassis. After an exhaustive search we narrowed the selection down to two lasers.

The first laser that we tried to work into our design was manufactured by Laser Power Corporation. This laser first caught our attention because of its high power and small size. It is a frequency doubled Nd:YAG laser operating in the green portion of the spectrum with an output power of 2½ W. The laser head with its heat sink was approximately 10 in. x 6 in. x 4 in. which was within our design dimensions. The heat sinking requirements of the laser head, while demanding, were still within the realm of our design.

The biggest obstacle for us was the size and power consumption of the power supply and control unit, which measured 14 in. x 10 in. x 6 in., and required 115 Vac. We immediately discussed the possibility of doing away with the ac portion of the power supply and using the 28 Vdc bus from the aircraft. The dc requirement for the laser power supply and controller is 18 Vdc but at a current of almost 20 A. Even though this laser was high power and relatively small in size, its power supply was just not small enough for our application at this time.

The second laser that we looked at was manufactured by a small company called CrystaLaser. This laser is also a frequency doubled Nd:YAG laser operating in the green portion of the spectrum with an output power of 200 mW. The laser head measures 1.25 in. x 2 in. x 6.5 in. which fit into out design even better than the Laser Power laser head because of the relaxed heat sinking requirements.

The most appealing factor in this laser was the size and power consumption of the power supply and controller. The power supply and controller measures only 2 in. x 4 in. x 6 in. and draws only 9 W of electrical energy. Originally the laser came with the choice of a 115 Vac/60 cycle or a 220 Vac/50 cycle power supply. Given the choice of 28 Vdc or 155 Vac/400 cycle, the two power sources available in the B-52, the manufacturer was willing to design and fabricate the laser with a supply that ran off the 115 Vac/400 cycle bus. The laser specifications are listed below in Table 1.

Table 1 532 nm, Single Frequency Diode Pumped, Nd: YAG Laser

| | |
|---|---|
| Wavelength | 532 nm |
| CW output power (mW) | >200 |
| Transversal mode | $TEM_{00}$ |
| $TEM_{00}$ beam diameter, typical (mm)(1/$e^2$) | 0.4 mm |
| $TEM_{00}$ beam divergence (mrad)(1/$e^2$) | <2.2 |
| Stability of output power over 8 hours (%) | 3% |
| Noise(<10 Hz to > 1 GHz)(% rms) | 0.5% |
| Polarization | Linear 200:1, vertical |
| Inherent line width | 0.1 nm |
| Operating voltage | 115 V @ 400 Hz |
| Power consumption | Typical 10 W |
| Expected operating lifetime | >10,000 hours |

We tested the long term power stability of this laser and found it to be well within ±2%. This laser employs active feedback to ensure power stability and its output power can vary by 10-20% during the first 30 seconds of operation. Although the output power is controllable, we adjusted the laser to always produce maximum output power and the optical modulator was used to control brightness. Figures 4 and 5 show a side and top view which details how the laser is integrated with the projection optics within the B-52 chassis.

## 4. SPECKLE ELIMINATION

Although the solid-state laser has many desirable traits such as long lifetime and low power consumption, it has speckle which is characteristic of all lasers. Speckle is a manifestation of the spatial coherence of laser light which makes laser-illuminated objects appear granulated in nature. Furthermore, an observer always sees the speckle in perfect focus whether or not the eye is focused on the object. Another annoying characteristic of speckle is that the speckle pattern moves with the observer's head movement even though the object being viewed does not move. We, therefore, had a goal to eliminate speckle from the display.

A common technique for reducing speckle is with the use of a moving diffuser in the laser beam path. Such a device was built and demonstrated to Brookhaven National Laboratory by Leo Beiser, Inc. The diffuser was found to have approximately 60% efficiency but it only reduced, not eliminated the speckle. We then tried injecting the laser into a glass optical fiber and physically moving the fiber to randomize the phase of the laser. Although the fiber can have an efficiency of over 90%, approximately 1 inch of fiber movement was necessary to remove most of the speckle. We then experimented with a liquid filled light guide. It was determined that a 3 mm diameter light guide with the optimum fluid was able to completely eliminate visible speckle with only .001 inch of movement. This liquid light guide was routed along the periphery of the enclosure as shown in Figure 4 and was only fastened to the chassis in three places which allowed it slight freedom to vibrate. Even aircraft vibrations as small as those from the ventilation system were sufficient to eliminate speckle. This liquid light guide had an efficiency of 60% and we are currently searching for more efficient liquid light guide materials.

## 5. SYSTEM LAYOUT

This current form-fit-function display differs from previous prototypes in several respects. This unit occupies 160 cubic inches less volume than the Phase 1 display such that it conforms to the B-52 size specification.

This display also has had the laser speckle removed via a liquid light guide. Earlier displays were operationally designed to accept a VCR input and use wall plug power. The current display accepts the B-52 data bus and operated on 400 Hz aircraft power.

The laser in this unit produces 200 mW which is twice the power of the previous version and this display screen has better contrast and surface finish. An improved method of screen construction has resulted in the glass layers being much more uniform. The entire lay up thickness of 480 sheets has a thickness uniformity better than .001 inch where previous versions had variations in thickness of .020 to .030 inches over the width of the 480 layers.

## 6. SUMMARY

The Phase 2 B-52 display was delivered on time and on budget to Wright-Patterson (U.S.) Air Force Base. We were able to successfully eliminate all visible speckle from the display through the use of a liquid light guide. Although our goal was to double the brightness of previous displays, this prototype resulted in a 15% increase due to the inefficiency of the speckle eliminator. The electronic interface was designed and built to accept the B-52 data bus and 400 Hz aircraft power.

We successfully demonstrated the capability to operate a DMD™ without its color wheel, using custom sync circuits, while illuminating it with a 200 mW solid-state laser to produce real-time video images.

## 7. ACKNOWLEDGMENTS

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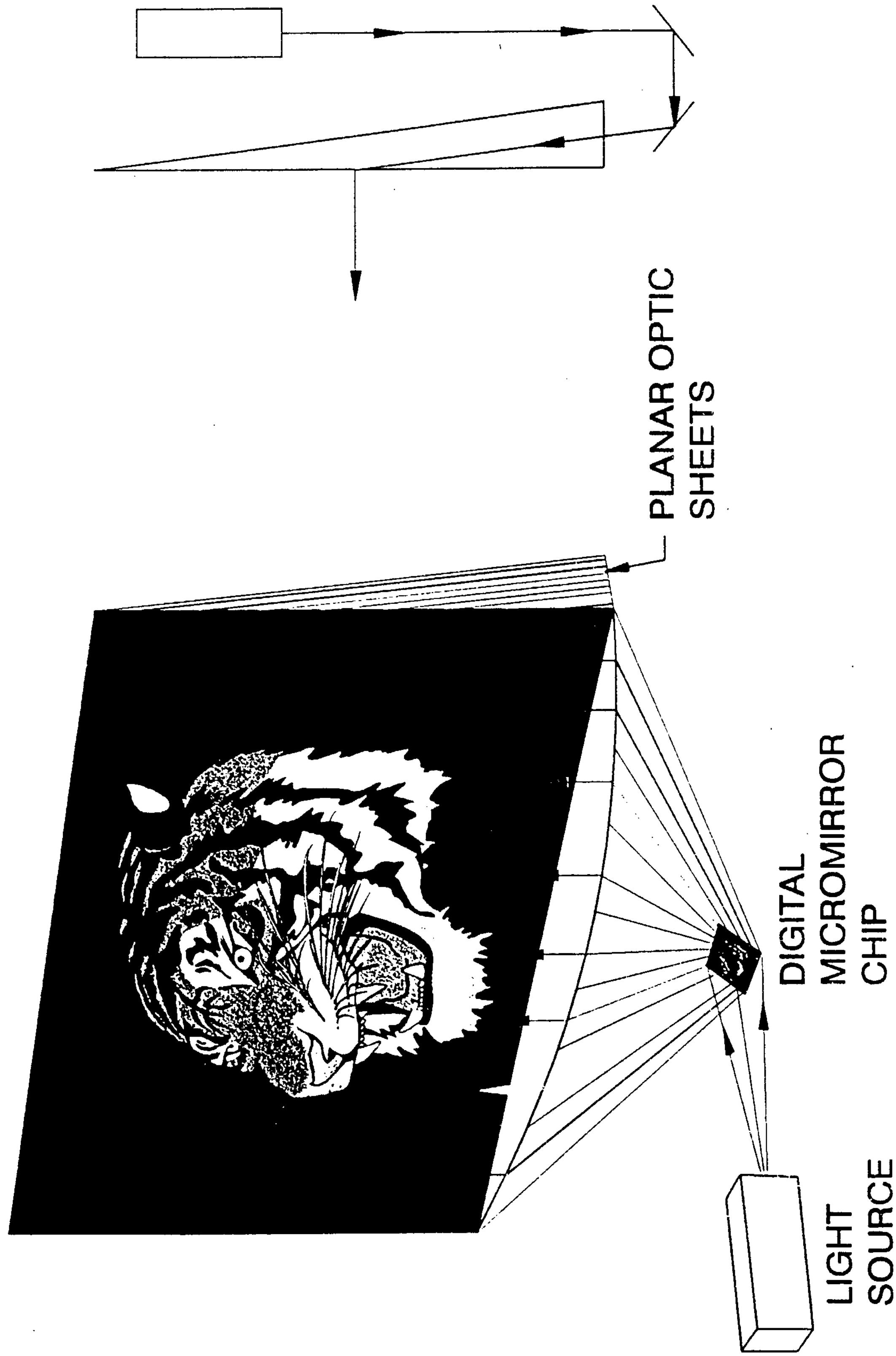


Figure 1 Polyplanar Optic Display (POD)

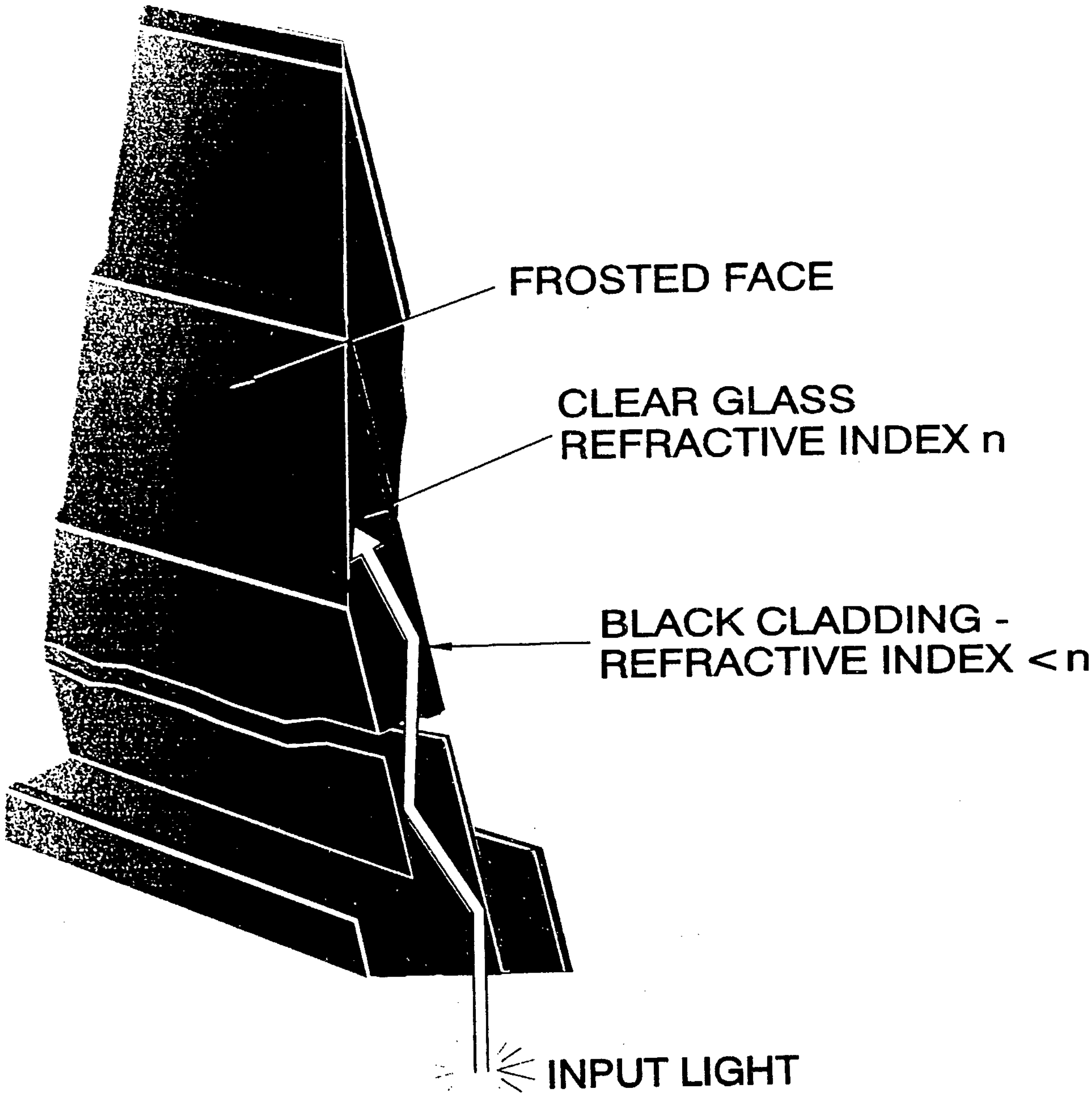


Figure 2 Principle of Polyplanar Optics

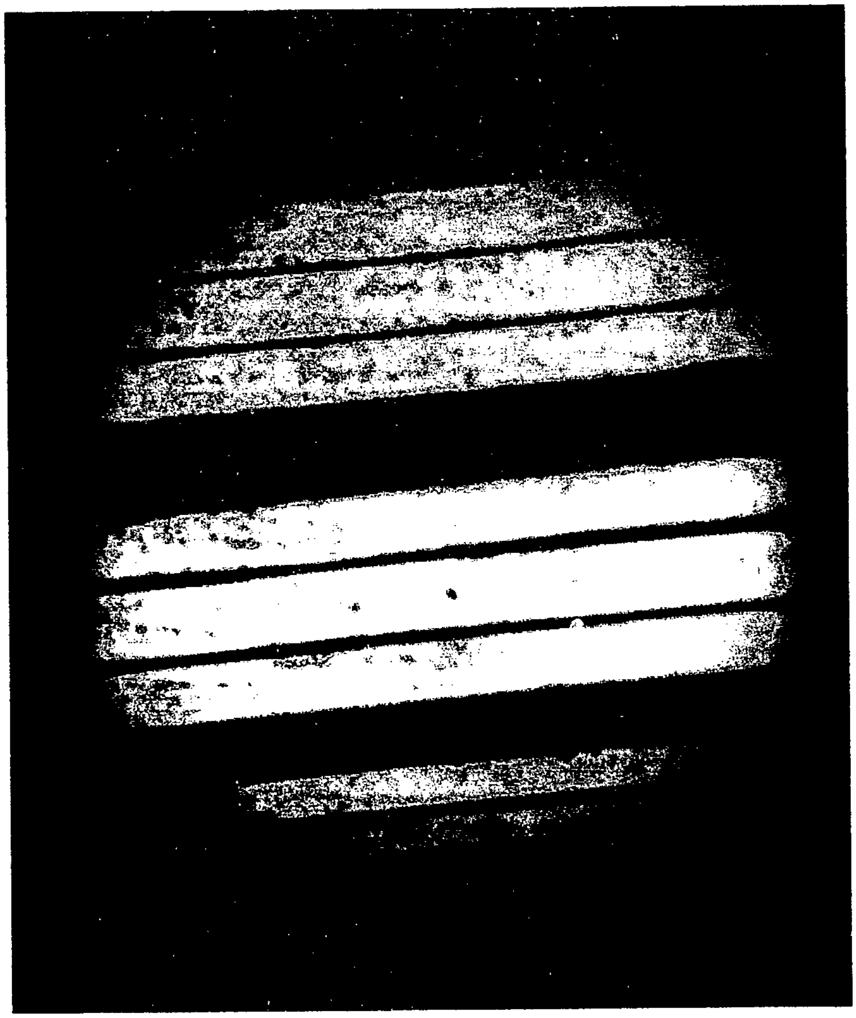

Figure 3 Section of Polyplanar Optic Display Lamina Using Spray Deposition

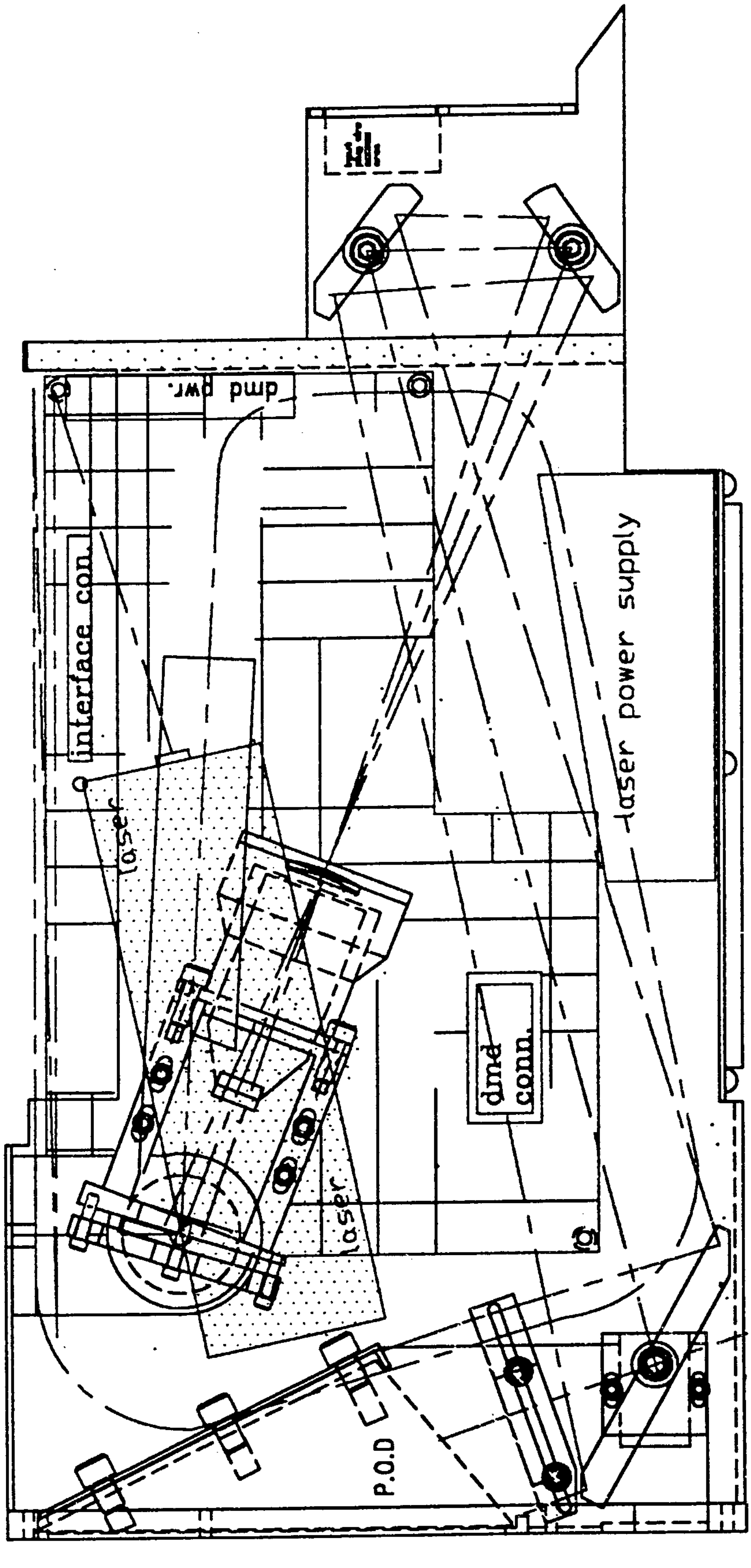


Figure 4 Right Side View

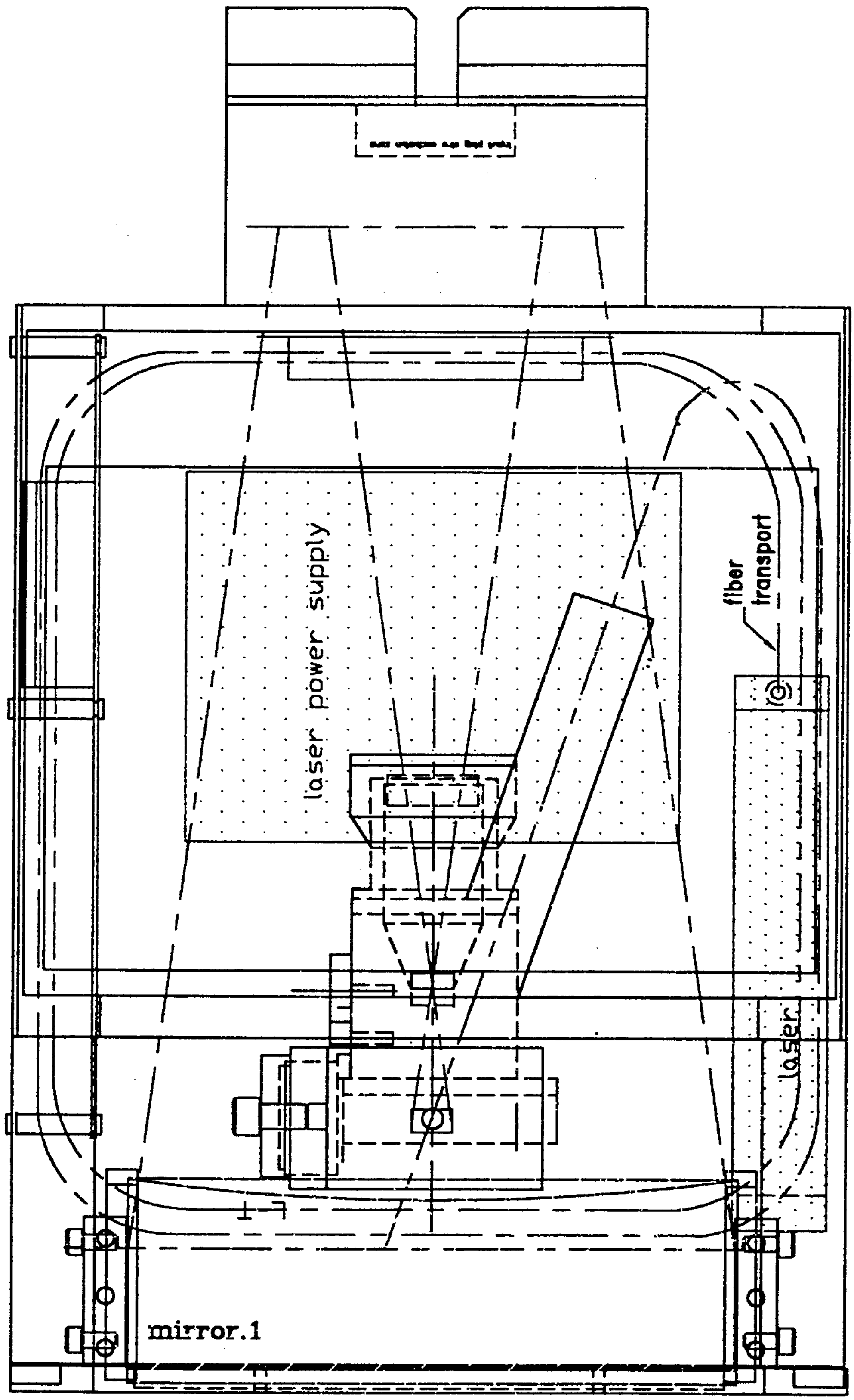


Figure 5 Top View

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