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Laser-driven polyplanar optic display

James T. Veligdan[a], Leo Beiser[b], Cyrus Biscardi[a], Calvin Brewster[a] and Leonard DeSanto[a]

[a]Department of Advanced Technology, Brookhaven National Laboratory, Upton, NY 11973
[b]Leo Beiser Inc., Flushing, NY 11354

ABSTRACT

The Polyplanar Optical Display (POD) is a unique display screen which can be used with any projection source. 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 200 milliwatt 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, we discuss the DLP™ chip, the opto-mechanical design and viewing angle characteristics.

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

2. BACKGROUND

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. Due to the inherently poor contrast of a CRT, the pilot's ability to view the information is sometimes compromised when sunlight is shining directly on the display. 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 it has been known that lasers could provide an inherently high brightness and high resolution display, there has never been a method to accomplish this compactly. Conventional laser projection, like the type employed at laser light shows, can provide a bright image on a flat screen in a tightly controlled darkened 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.

3. OPERATION THEORY

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. To eliminate reflection losses, 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 and focusing 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 120 degrees. When the laser is off, the screen appears flat black due to the nature of the interlayer cladding.

4. THE POD SCREEN

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.

Polycarbonate appeared as though it might be a likely candidate since it was available in thin sheets and was very machinable. However, when looking through 15 cm of polycarbonate it was readily apparent that only about 10% of the light was transmitted and the material had a deep blue color. It was learned that a blue tinting agent is added to polycarbonate to make it appear clearer in thin sheets. We then tried the optical grade polycarbonate (without blue tint) and found it unacceptable as it had a yellow color when looking through 15 cm of bulk material.

Materials like styrene and blown films like Korad had poor surface finishes which would create reflection scattering losses as light travels up the sheet by total internal reflection.

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 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 index matched epoxy with a refractive index equal to that of the glass, 1.52.

5. THE LIGHT SOURCE

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 order to keep the entire system as small as possible, a 200 milliwatt laser was chosen having dimensions of 2 in. x 1.25

in. x 6.5 in. This laser is manufactured by CrystaLaser and has an electrical power consumption of 10 watts in order to produce 200 milliwatts of optical power. The specifications of this laser are shown in Table 1.

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

Wavelength	532 nm
CW output power (mW)	> 200 mW
Transversal mode	TEM_{00}
TEM_{00} beam diameter, typical (mm)($1/e^2$)	0.32
TEM_{00} beam divergence (mrad)($1/e^2$)	2
Stability of output power over 8 hours (%)	< 3%
Polarization	Linear 200:1, vertical
Operating voltage	115 V 400 Hz
Power consumption	< 10 watts
Expected operating lifetime	> 10,000 hours

We tested the long term power stability of this laser and found it to be well within ±3%. Although the laser does not get hot, it dissipates approximately 10 watts of heat and the manufacturer states that it must be heat sinked. This laser employs active feedback to ensure power stability and its output power can vary by 10-20% during the first 20 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.

6. OPTICAL MODULATOR

In order to display an image with the laser we examined using both a raster scanning technique and a spatial light modulator. An acousto-optic laser scanning system was employed to raster scan an image into the POD, however, its low efficiency (< 20%) and large size disqualified it as a serious candidate. The spatial light modulators fell into two categories: transmissive and reflective. The most promising transmissive technology was the polysilicon liquid crystal modulators. The polysilicon devices had higher efficiencies than the other liquid crystal devices, however, polysilicon modulators were not yet commercially available in small enough packages for the U.S. Air Force requirements. Two examples of reflective technologies we studied were phase dispersed liquid crystals (PDLC), which were not commercially available and the digital micromirror system from Texas Instruments, Inc. At the time of our down selection, the micromirror technology had the highest figure of merit when comparing efficiency, availability, image quality and size.

The Digital Micromirror Device (DMD™) has been described as a semiconductor light switch comprised of thousands of tiny, 16 x 16 μm, mirrors on hinges.[3] The DMD™ which we used was a 640 x 480 array capable of providing VGA resolution. Each of the 307,000 mirrors is spaced 1 μm from its adjacent mirror and is capable of tilting a total of 20° to either reflect light into the useful optical path or send it to an absorptive beam dump. In order to utilize the advantages of the DMD™, our video signals were first digitized and then converted from RS170 format to a digital RGB format required by the DMD™ since the hardware driving the DMD™ was designed for field sequential color operation.

7. REVIEW OF IMAGE PROJECTION OPTICS

The Texas Instrument DMD™ is a 640 x 480-element reflective light valve,[4] whose micromirror light deflectors are actuated selectively through a ±10° angle to reflect light into or away from a useful optical path. Intensity variation for "gray scale" rendition is provided by pulse-width modulation of the "on" time of each micromirror.

The optics which direct the modulated light into the POD must handle the vertical and the horizontal image components differently.[5] The vertical image components are focused at the base of the POD, and are confined vertically by its flat laminar "waveguides." They are thus transported focused to the display surface. The horizontal components, not so confined, must converge to focus horizontally within the lamina, such that their focal points join the corresponding vertical image points at the display surface. They must focus over progressively greater distances as they propagate from the "bottom" to the "top" of the display, with correction for the varying focal lengths on a tilted image plane. It is also necessary to constrain the field angle expansion of the horizontal image, to prevent keystoning. This unique control of the vertical and the horizontal image elements is accomplished with combined anamorphic, Scheimpflug and telecentric optics; with due regard to depth of focus and image propagation characteristics within the POD.[1]

Figure 3 illustrates the unfolded optical path (which is subsequently packaged with 3 folding mirrors). The input beam illuminates the DMD™, and the reflected light is directed into one of two selected angles: (1) along the projection axis for display, or (2) into the by-pass "off" position, which diverts the beam from the (horizontal and vertical) cylindrical lenses, C_h and C_v. The focal lengths and positions of these lenses (and keystone-correcting telecentric lens L_t) are designed to form the properly proportioned object/image distances and display format.

8. PROJECTION OPTICS AND SYSTEM PACKAGING

After extensive laboratory testing of these analytic design parameters, with optical bench and full-scale brassboarding using incoherent and coherent illumination on test pattern targets, the task of fitting all the components into the allocated space was initiated. The first requirement was to develop appropriate folding of the optical path within the enclosure, anticipating the need for space for several other basic components. These are: (1) the POD; (2) the laser; (3) the beam-expander/compressor; (4) the laser controller; (5) the DMD™ mount assembly; and (6) the DMD™ electronic drive units. The special electronic adaptation of the last two items has been presented in a previous publication.

Of notable design was the beam-expander/compressor, posing the challenging task of magnifying the tiny (0.32 mm) laser beam diameter by approximately 80x; to a value required for converging properly upon the 13.64 mm diagonal of the DMD from a source located some 90 mm from the DMD. The illumination intensity was to be essentially uniform over its active central portion. The problem was compounded by the need for accomplishing this within a relatively short distance to accommodate the packaging constraints. A classical Keplerian beam expander design was modified by adding a negative expansion lens L_2 following the first positive lens L_1, as represented in Figure 4. By this means, the 11 inch overall length of a 2-element Keplerian telescope was reduced to 3 inches. With the quality of the short focal length lens L_1 an important factor, its careful selection provided good intensity uniformity and freedom from incidental spreading -- as required for this light valve illumination task.

Considering several packaging alternatives, the basic configuration which was adopted and trimmed to match the precise contour of the CRT housing is represented in accompanying Figures 5 and 6. Figure 5 is a side view and Figure 6, a plan view. The major distinction between this layout and that of the final package is that the POD was subsequently mounted in a 2 inch thick frame in front of the main housing, to retain the prescribed focal lengths and design parameters of this initial phase. The next program phase allows for adjustment of the total optical path length (and associated component values), so that the POD may be mounted within the housing.

The 15½ inch overall depth uses the available space within the cockpit recess, unconstrained by a current housing design. It is required that this illumination be incident on the DMD™ at an angle of 20° from the DMD™ surface normal and at 45° with respect to its square micromirror axes. The views of Figures 5 and 6 show, therefore, foreshortened (resolved) angles. Figure 5 also illustrates the 4° Scheimpflug tilt; counterclockwise to account for the number of folding mirrors and the orientation of the POD display surface (with respect to that in Figure 3). The skew angles also accommodate this 4° DMD™ tilt.

Since the illuminating input beam is skewed as represented here, so would be the Aperture By-Pass Beam of Figure 3, if it were illustrated here too. This diverted beam, which represents the "off" components of the image, is absorbed in the blackening of the interior of the housing. The useful Projected Beam is carried forward, perfectly centered in the vertical meridional plane (Figure 6 Plan View). Thus, the POD, the three mirrors and the three lenses in the projection path remain on-axis. In addition to the alternative, described above, of mounting the POD in a separate

2 inch thick frame in front of the housing, another distinction between this optical path and the actual layout is a small reduction in distance between M_2 and M_3 so that these two mirrors may be mounted into an existing rectangular recess at the rear of the housing. Packaging was, therefore, extremely conservant of available space.

9. SUMMARY

The prototype display for Phase 1 was delivered on time, on budget while providing real-time video ahead of schedule. The completion of this display demonstrated the first successful marriage of the DMD™ technology with the POD screen technology. This POD was made using 480 sheets of 100μm glass and was approximately 2 inches thick. However, as thinner materials become available the screen will become thinner with higher resolution. The dual-focus projection system delivered independent image components successfully to the POD. The DMD light engine was modified to operate using a laser as the light source eliminating its lamp and color wheel.

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Further author information -
JTV: Email: jimv@bnl.gov

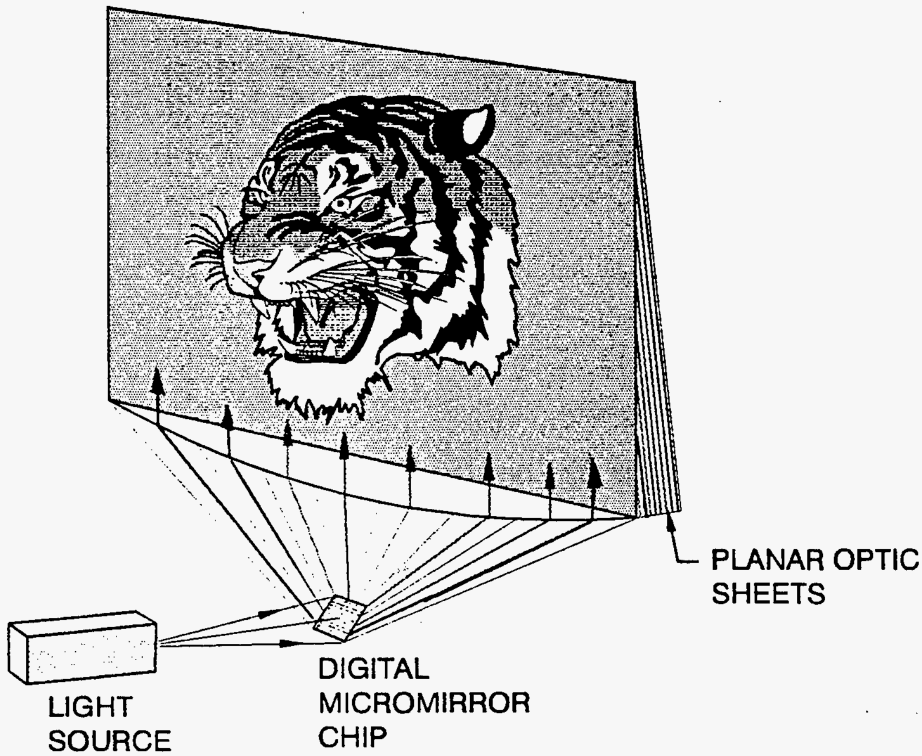

Figure 1 Functional Illustration of a Polyplanar Optic Display

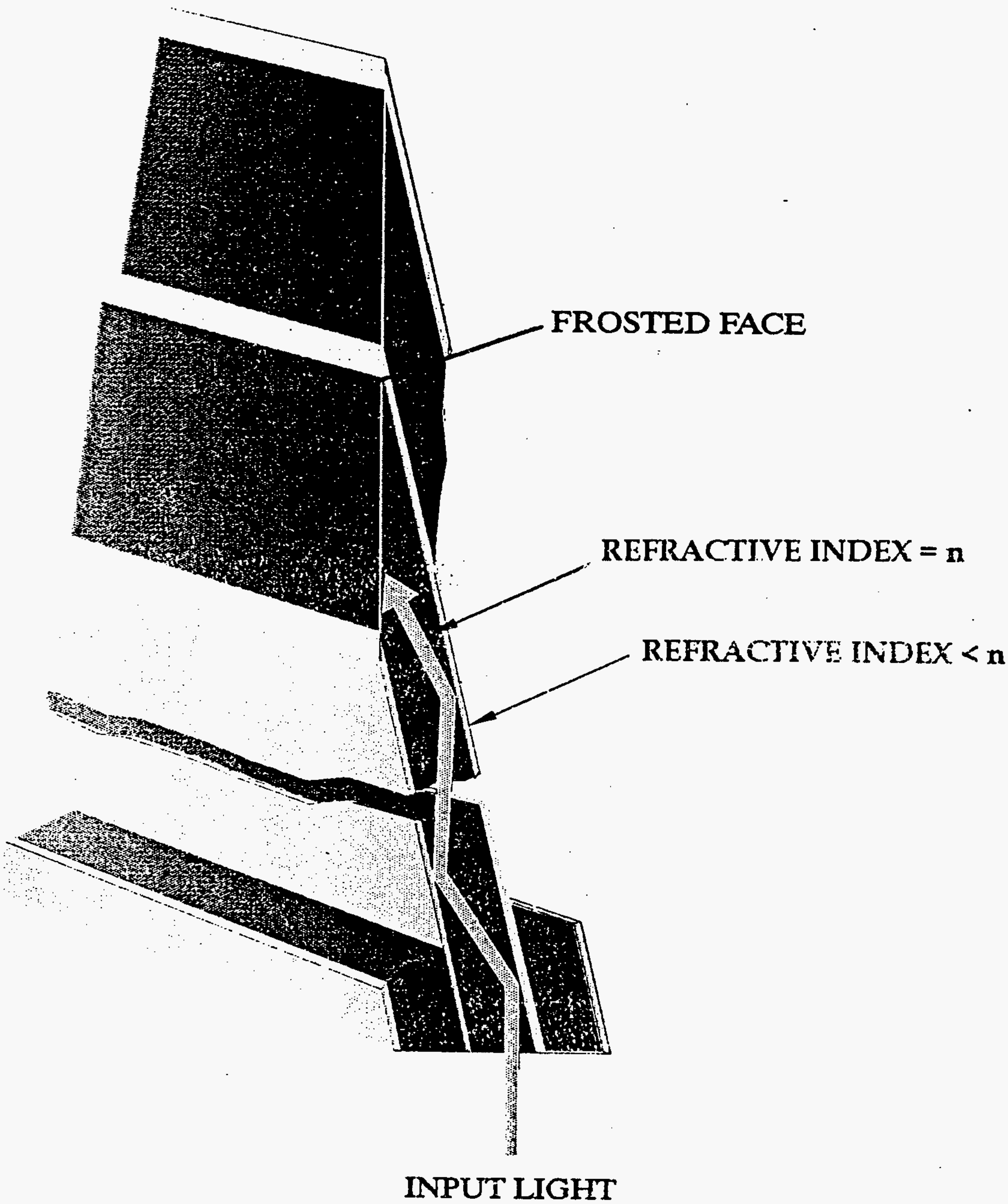

Figure 2 Polyplanar Optic Display Detail

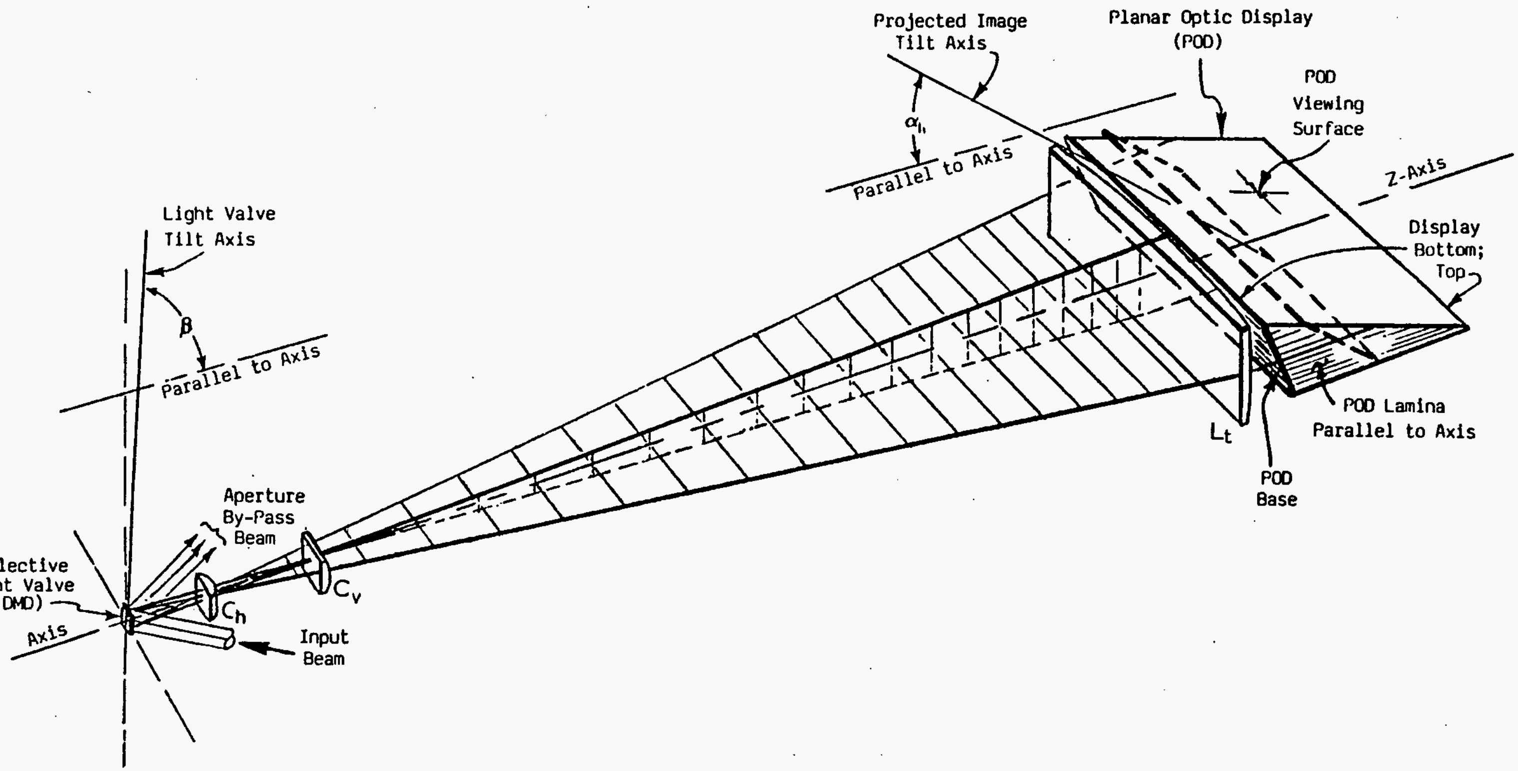

Figure 3   Projection Optics for Polyplanar Optic Display (POD)

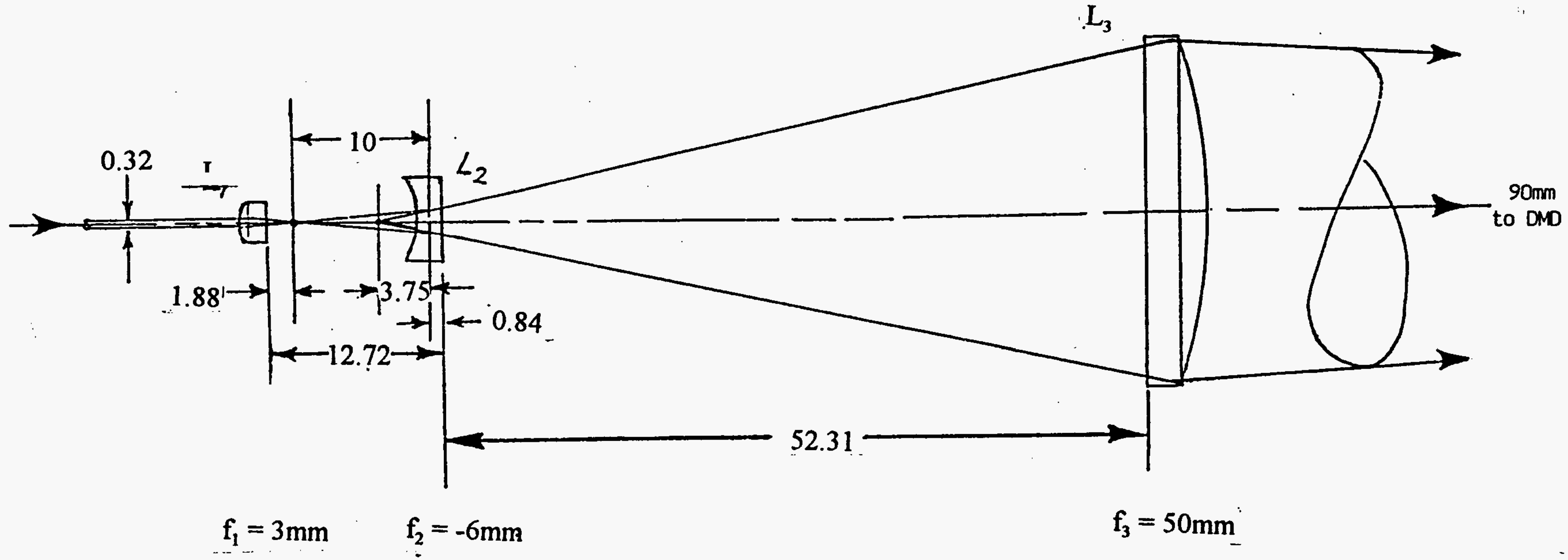

Figure 4 Beam-Expander/Compressor
Magnification = 80x Overall length = .75mm

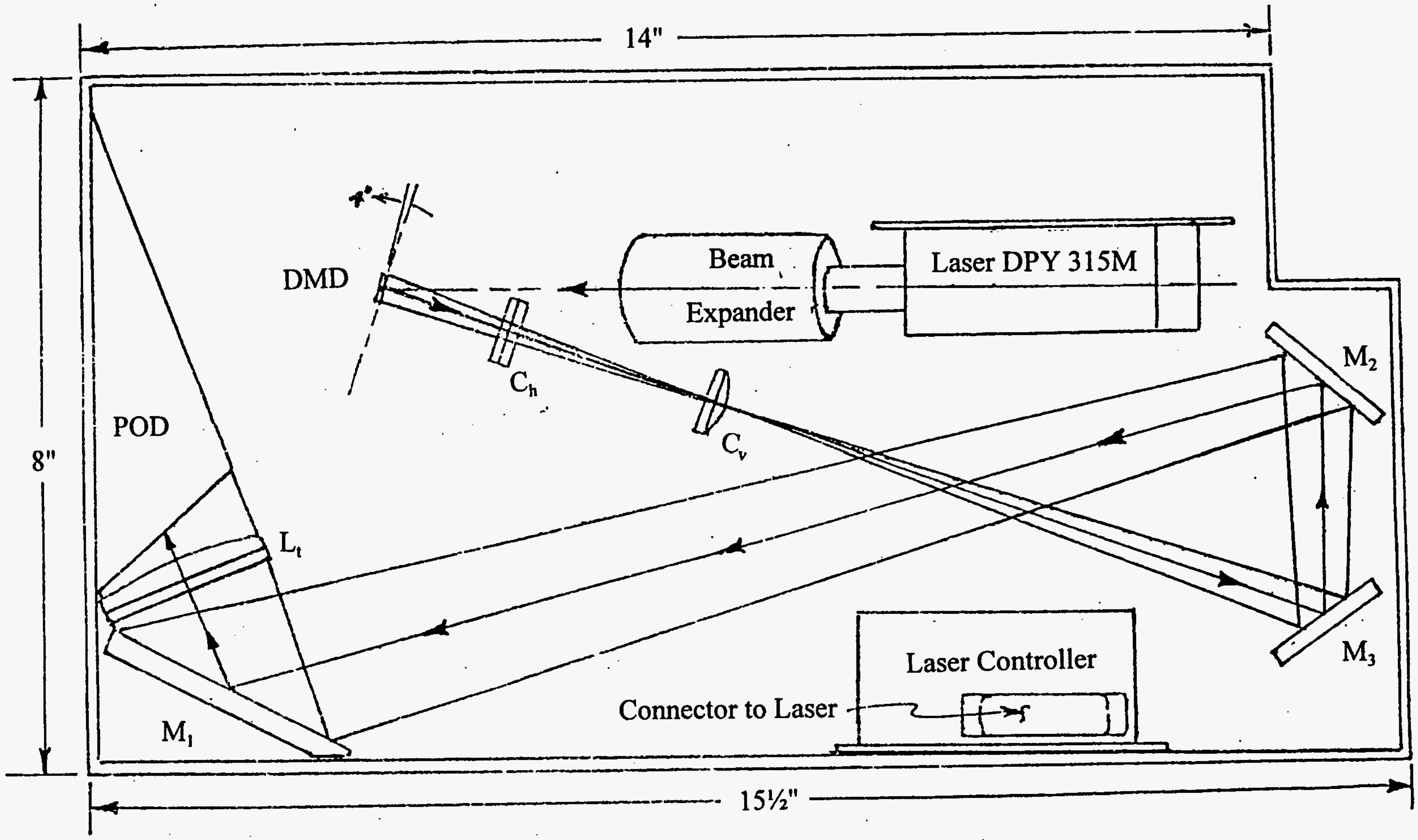

Figure 5 Packaging Design Layout -- Side View
Scale = ½

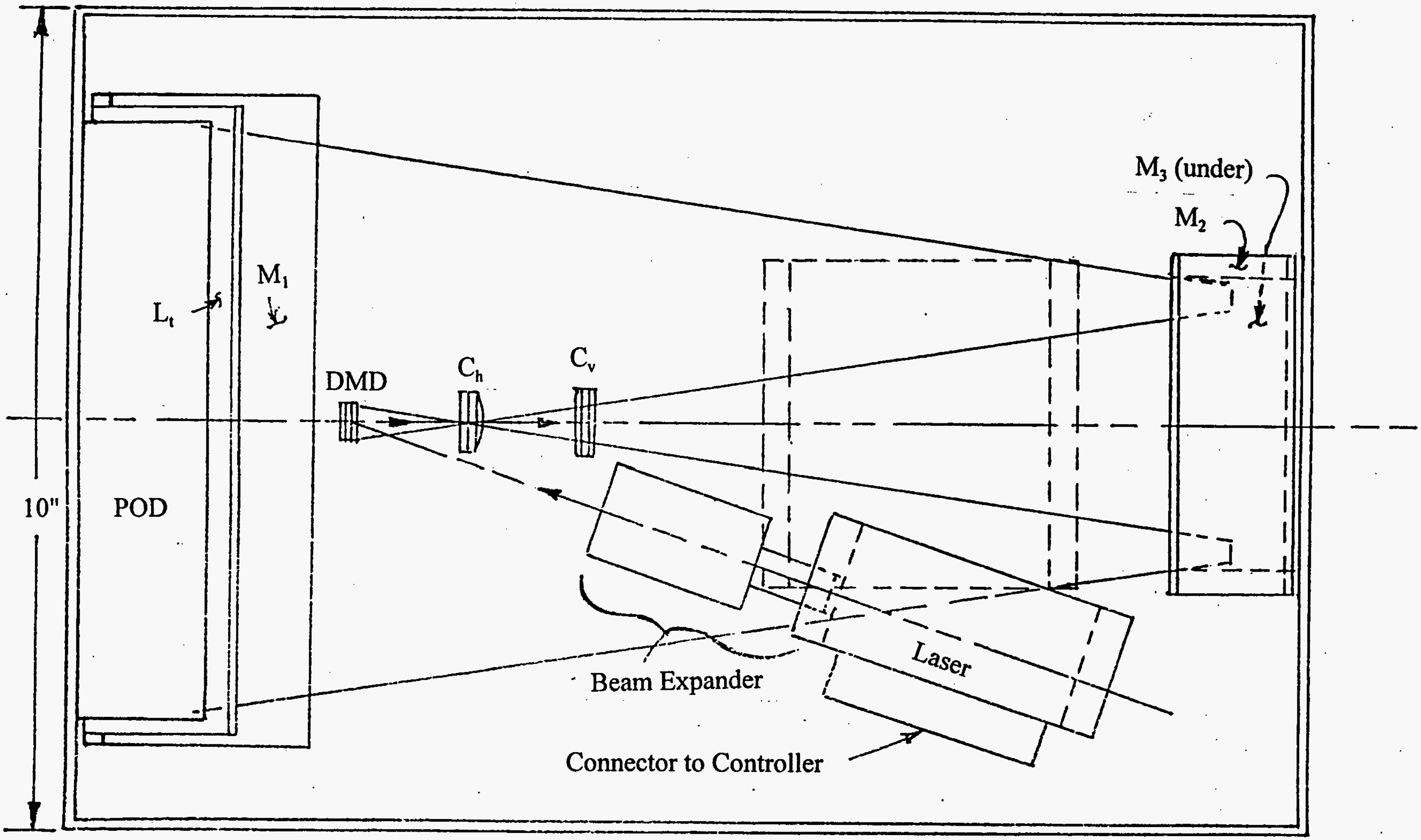

Figure 6 Packaging Design Layout -- Plan View
Scale = ½

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