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Ten Inch Planar Optic Display*

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ABSTRACT

A Planar Optic Display (POD) is being built and tested for suitability as a high brightness replacement for the cathode ray tube, (CRT). The POD display technology utilizes a laminated optical waveguide structure which allows a projection type of display to be constructed in a thin (1 to 2 inch) housing. Inherent in the optical waveguide is a black cladding matrix which gives the display a black appearance leading to very high contrast. A Digital Micromirror Device, (DMD) from Texas Instruments is used to create video images in conjunction with a 100 milliwatt green solid state laser. An anamorphic optical system is used to inject light into the POD to form a stigmatic image. In addition to the design of the POD screen, we discuss: image formation, image projection, and optical design constraints.

Keywords: POD, optical, waveguide, display, laser

2. BACKGROUND

From data communications in business, to entertainment on the family room TV, the Cathode Ray Tube (CRT) has proven itself to be indispensable as a means of displaying information. It ranks high in brightness, reliability, manufacturability and cost. However, its volume, weight and power consumption have severely limited its portability which is a requirement for the development of many new technologies. In particular, CRT cockpit displays are being replaced by newer flat panel displays which must meet the demanding specifications of brightness, resolution, contrast and cost.[1] For example, a civilian display might require a brightness of only 200 ft. Lamberts (fL) while a military aircraft cockpit requires a brightness of 1200 fL.

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 safely or 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 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 Planar 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. 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 planar optic display. See Figure 1. A planar optic device is analogous to a fiber optic device, however, there are a few very important distinctions.

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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 Planar 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 cladding.

4. EXPERIMENTAL RESULTS

The initial 'proof of principle' screen consisted of a 2.5 cm (1 in.) planar optic display where the individual glass wave guides were 50 microns thick. The glass sheets were bonded together with a low refractive index and low viscosity epoxy. Although the resolution was approximately 35 lines/cm, the contrast was poor because the display was quite opaque. In order to improve contrast, future displays were constructed using a black matrix within the cladding. The first 10 inch display used 145 sheets of Schott D 263 borosilicate glass (200 microns thick) with a refractive index of 1.52. The sheets were bonded together with epoxy (refractive index = 1.50) and the front face was ground flat to act as the display surface. The bottom face of this stack of glass was ground and polished to act as the light input surface. The present VGA resolution screen is made from 480 sheets of 100 micron thick borosilicate glass.

In order to test the POD screens, a vector scanning technique was used in conjunction with a 3mw HeNe laser. This proved to be satisfactory for initial testing, however, the X-Y galvanometers in the scanner were not capable of video rate scanning. It was, therefore, decided to integrate our POD screen with a digital light processing engine which is manufactured by Texas Instruments.

5. OPTICAL DESIGN

5.1. Image formation

Two generic approaches (and their combination) are available for image formation:

a. **Sequential** point-by-point (flying spot) scanning (as by CRT or laser);
b. **Parallel** imaging (as by multi-element array light valve).

Consideration of the state-of-the art of the two options and awareness of the newly-developed digital micromirror device (DMD) by Texas Instruments, Inc.[2] led to significant investigation of methods of adapting this component for effective parallel laser deflection of an image into the Planar Optic Display.

Geometrical characteristics of the TI DMD light valve are approximately as follows:

elemental mirror dimensions:	16μm x 16μm (horizontal and vertical)
elemental pitch:	17μm x 17μm (horizontal and vertical)
640-element array width:	10.9mm
480-element array height:	8.2mm
full array width and height:	13mm x 9.64mm
elemental mirror tilt:	±10° with respect to array plane

5.2. Image Projection Considerations

As applied here, the TI DMD may be described as a 640 x 480-element array of binary light deflectors. Each addressed micromirror is actuated to reflect light *either into* a useful optical path, *or away from* the useful path. In the useful path, the light is collected optically and projected into the POD, forming "bright" elements. When directed away from the useful path, the light by-passes the aperture of the projection optics and fails to propagate into the display, forming "black" elements. This is a form of schlieren or dark field projection. Intensity modulation (to render shades of grey) is provided by controlling the on-time of each element (pulse width

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modulation). The array is refreshed rapidly to form a field rate which exceeds the human persistence of vision at the displayed brightness, thereby avoiding image flicker.

The projection optics is unique to this display because the vertical and horizontal image functions must be handled in differing manners.

1. The vertical components of the image *are focused at the base* of the POD. Propagating into the lamina, illustrated in Figure 3, the focused light is confined vertically by the "waveguides." This retains the integrity of the vertical image which expands linearly within the POD while traveling over progressively greater lengths of the lamina, to form the full image height on the display.

2. The horizontal components of the image, however, *converge to focus within the volume* of the display. These image rays, essentially *parallel to the lamina*, are not constrained horizontally by the lamina. They are transported as individual, very thin horizontally converging image elements within each layer. The elements must be brought to focus *over the varying lengths of the lamina*, such that their focal points join with corresponding vertical ones at the display surface, within the tolerable depth of focus.

3. As a consequence of (2), it is necessary to operate on the horizontally projected light such that --

   a. Its image components focus over progressively greater distances, as appearing from "bottom" to "top" of the display. This effective image plane is uniquely not normal to the projector axis. The light must be directed to maintain focus at a tilted image plane.

   b. While propagating into progressively greater distances in the POD, it is necessary to constrain the field angle expansion of the horizontal image -- keystoning. Thus, keystone correction must be instituted.

4. The differing and almost independent handling of the vertical and horizontal components is conducted with the use of anamorphic optics. Where interactions occur, due attention is devoted to their accommodation. Figure 3 shows the use of cylindrical optics for the vertical and horizontal image components, and provides functional accommodation of the diverse image manipulation expressed above.

5.3. Image projection optics

Figure 3 is a functional representations of the projection optics. Light reflected from a TI digital micromirror device (DMD) is directed (unfolded) to the base of the planar optic display. An input laser beam illuminates the DMD at the required input angle. The reflected and scattered beam from the DMD is shown in two allowed (binary) positions: (1) the "useful beam," paraxial with the projection axis, and (2) the "by-pass beam" which is diverted from the axis, avoiding the apertures of (horizontal and vertical) cylindrical lenses C_h and C_v. The useful beam propagates through these lenses and continues to focus on and within the POD. The central ray is derived from a central element of the DMD while marginal rays from the DMD terminate at their conjugate image points on and in the POD to form the complete image at the viewing surface. The focal lengths of the lenses are selected to form reasonable object/image distances for subsequent folding and packaging.

In the vertical projection path, cylindrical lens C_v (having optical power only in the vertical direction) accepts rays from object points on the 8.2mm DMD height and images them to corresponding points on the (50mm thick) base of the POD. Optical magnification is approximately 6.1X. Additional effective vertical magnification occurs as the image propagates through the POD lamina to terminate at greater and greater distances from the "bottom" to the "top" of the display. The resulting total magnification is thus equalized in both vertical and horizontal directions.

The horizontal projection path is affected by the requirement introduced earlier, relating to the effective tilting of the horizontal image plane within the POD. This results from the differing propagation lengths within the POD lamina. The projected image surface (illustrated in Figure 3) is determined by successive calculation of the optical paths within the POD, accounting for an allowed depth of focus of the horizontal component, to be described subsequently. This reveals the effective image tilt for which the propagating light must be rectified to achieve uniform horizontal focus over the entire image surface. Focus in the vertical direction, however, is established simply by focusing on the POD base.

Formation of horizontal focus over the tilted image surface is provided by satisfying the Scheimpflug condition between the object (DMD) plane, the image (POD) plane and the principal plane of the horizontal imaging lens C_h. This is accomplished by orienting these planes such that they intersect at a single line. That is, with C_h plane oriented normal to the projection axis and the effective image plane oriented as determined above, the object (DMD) plane is tipped so that it intersects the intersection of the other two. This relationship is represented by the Scheimpflug rule,[3] expressed by

$$\tan\beta = m \tan\alpha \qquad (1)$$

in which α = image tilt angle with respect to the axis
β = object tilt angle with respect to the axis
m = magnification, image/object

Keystone correction may be accomplished by forming the final image components from telecentric optics, whereby the propagating beam is constrained parallel to the axis, maintaining constant propagating widths. This can be introduced with a lens L_t in front of the POD having a long focal length which is centered near C_h.

5.4. Beam propagation within the POD

Figure 4 provides a section view of the POD, showing its outline (bold lines) and several (horizontal component) image surfaces; actual and effective, derived as described below. The illumination propagating from left to right, traverses the keystone-correcting cylindrical lens C_t and encounters the sloping base of the POD. This tilt (of 20°) is determined by application of Equation (1) for the vertical component α_v, after iterative determination of the tilt of the horizontal image surface α_h and the tilt of the object β. [The tilt of the object must satisfy Equation (1) for both vertical and horizontal components; each having differing magnifications.] The locations and tilts of the effective horizontal image surfaces are established following the sequence of lines numbered (0) to (4), as follows:

Line (0) is the viewing surface of the POD, as illustrated in Figure 3. (In this section view, the horizontal component is in-and-out of the paper.)

Line (1) is the ideal focal surface in (refractive index) n = 1 material (air). In n = 1.5 material, it is extended optically by 50% to terminate at the viewing surface, line (0). At all points along its length, it is located at 2/3 the propagation (z) distance from the POD base to the viewing surface.

Allowing ± 20mm tolerance for depth of focus, line (2) is the focal surface which will image effectively on the ideal line (1). This reduces significantly the slope of the image plane and the corresponding Schleimpflug tilt of the object plane.

Line (3) is the resulting focal surface inside the n ≈ 1.5 material, accounting for the 50% extension as the beam propagates within the POD.

Finally, line (4) is determined analytically as the surface to which the imaging cylinder C_h must be focused, such that with the additional keystone correcting lens L_t, the image distance is shortened slightly to line (2) in air. It is then extended via the higher index material to line (3) inside the POD.

5.5. Physical optics considerations

Two factors meriting attention as a consequence of using a laser light source for visual display are coherent speckle and coherent imaging. While both result from the substantial coherence of the projected illumination, the detailed causes and effects are different.

When a surface is illuminated with coherent illumination, speckle results from the superposition of adjacent re-radiated coherent wavelets which differ in phase, as imaged by a sensor viewing the radiation. The wavelet amplitudes superpose with reenforcements and cancellations having elemental diffraction-limited size, as determined by the viewing distance and the aperture width of the sensing receiver (e.g., the iris of the eye). When the incident illumination overfills this diffraction-limited spot size, the amplitude additions and subtractions from adjacent nonuniformly phased surface structure registers in intensity as speckle. Speckle size is, therefore, inversely proportional to the linear dimension of the viewing aperture.

Coherent imaging manifests in the formation of intensity ripples at discontinuities of reflectance or transmittance of an image of a coherently illuminated object. These are more evident, therefore, at sharp transitions of spatial information. Whereas, coherent image ripple depends on the information content, speckle depends on the surface texture and the aperture size of the viewing detector.

Control of both of these effects depends on reduction of the coherence of the illuminating radiation. One method of reducing speckle is to randomize the coherence, as that through a diffusor, and to time-integrate that radiation by moving the diffusor. We have conducted lab experiments with several selected diffusors oriented in various positions in the illuminating beam path, and have reduced speckle effectively, while confining the diffuse flux to a sufficiently narrow distribution such that a large fraction of the light is transferred to the display. At the same time, in viewing a binary test pattern (most challenging regarding the ripple effects of coherent imaging), laboratory experiments indicate that the image remains effectively free of these artifacts.

6. SUMMARY

A 10 inch video rate scanner is currently being designed, built and tested at Brookhaven National Laboratory. The current display is being built as a green monochrome device having VGA resolution. In order to produce a video image, a Texas Instrument DMD will be used in conjunction with an anamorphic folded optical system.

7. ACKNOWLEDGMENTS

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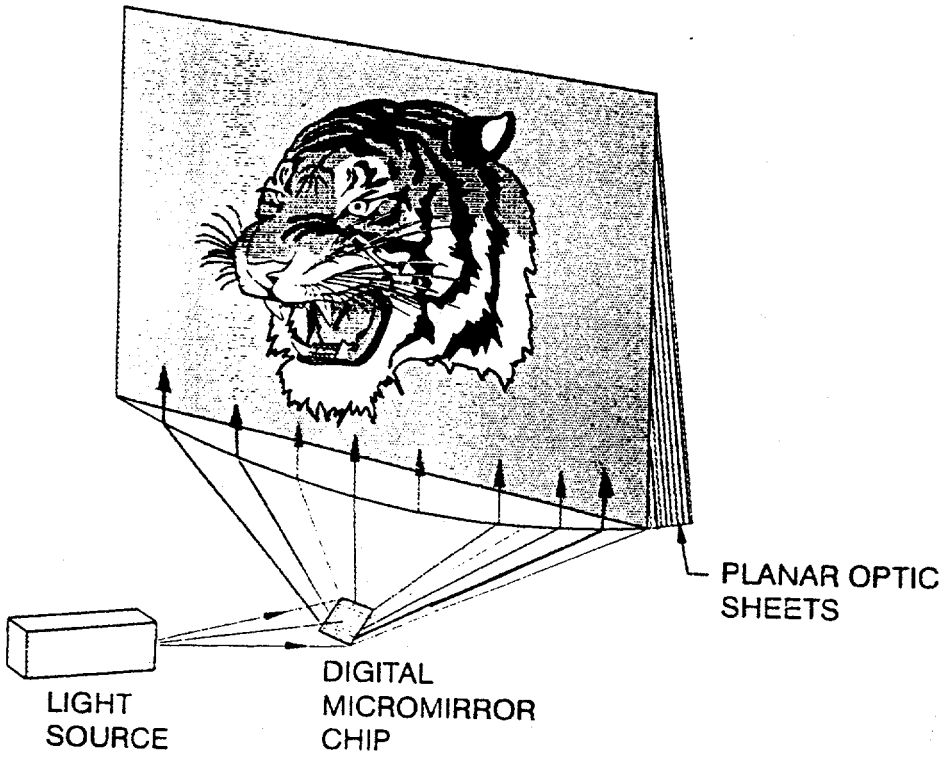

Figure 1 Functional Illustration of a Planar Optic Display

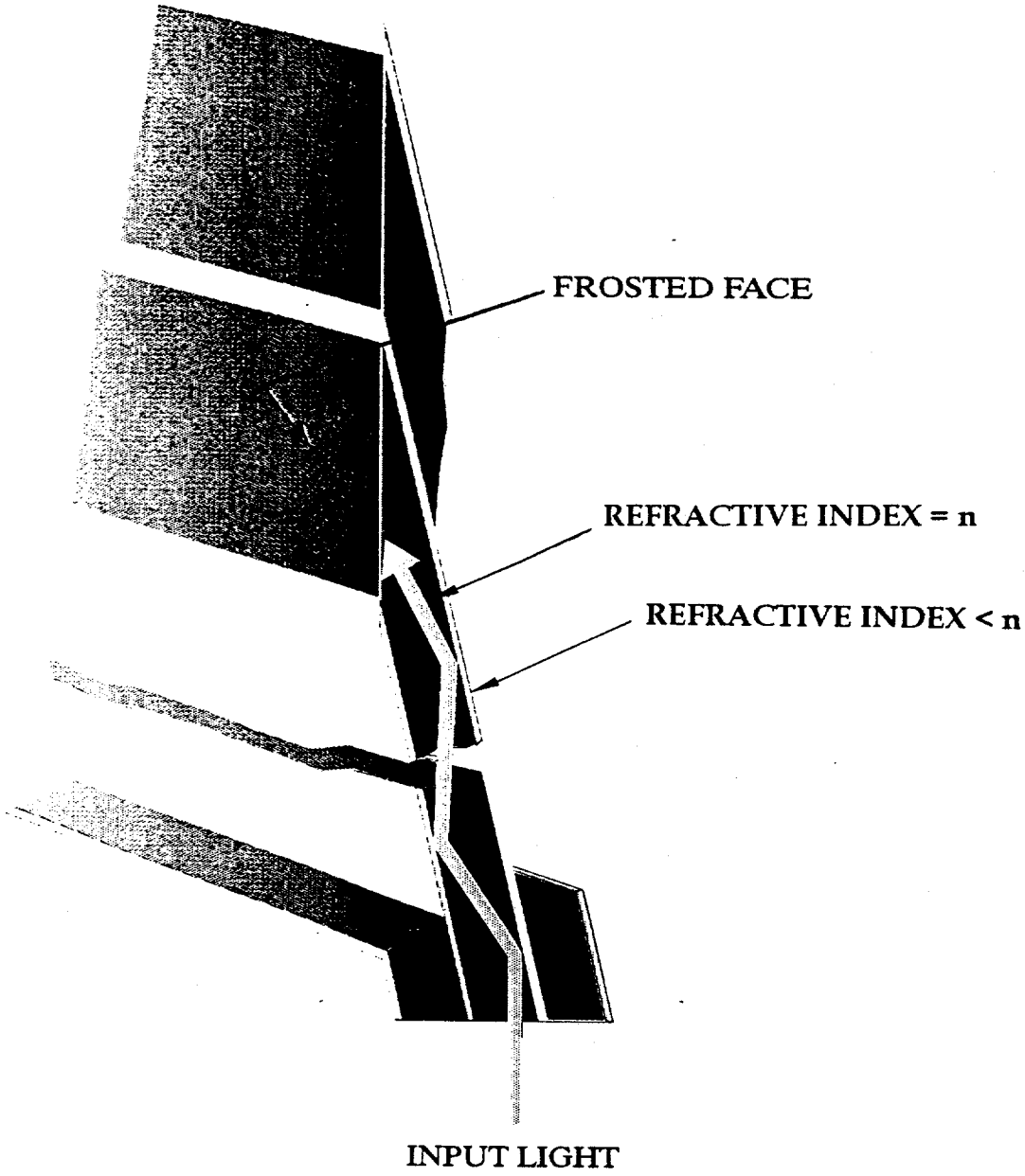

Figure 2 Planar Optic Display Detail

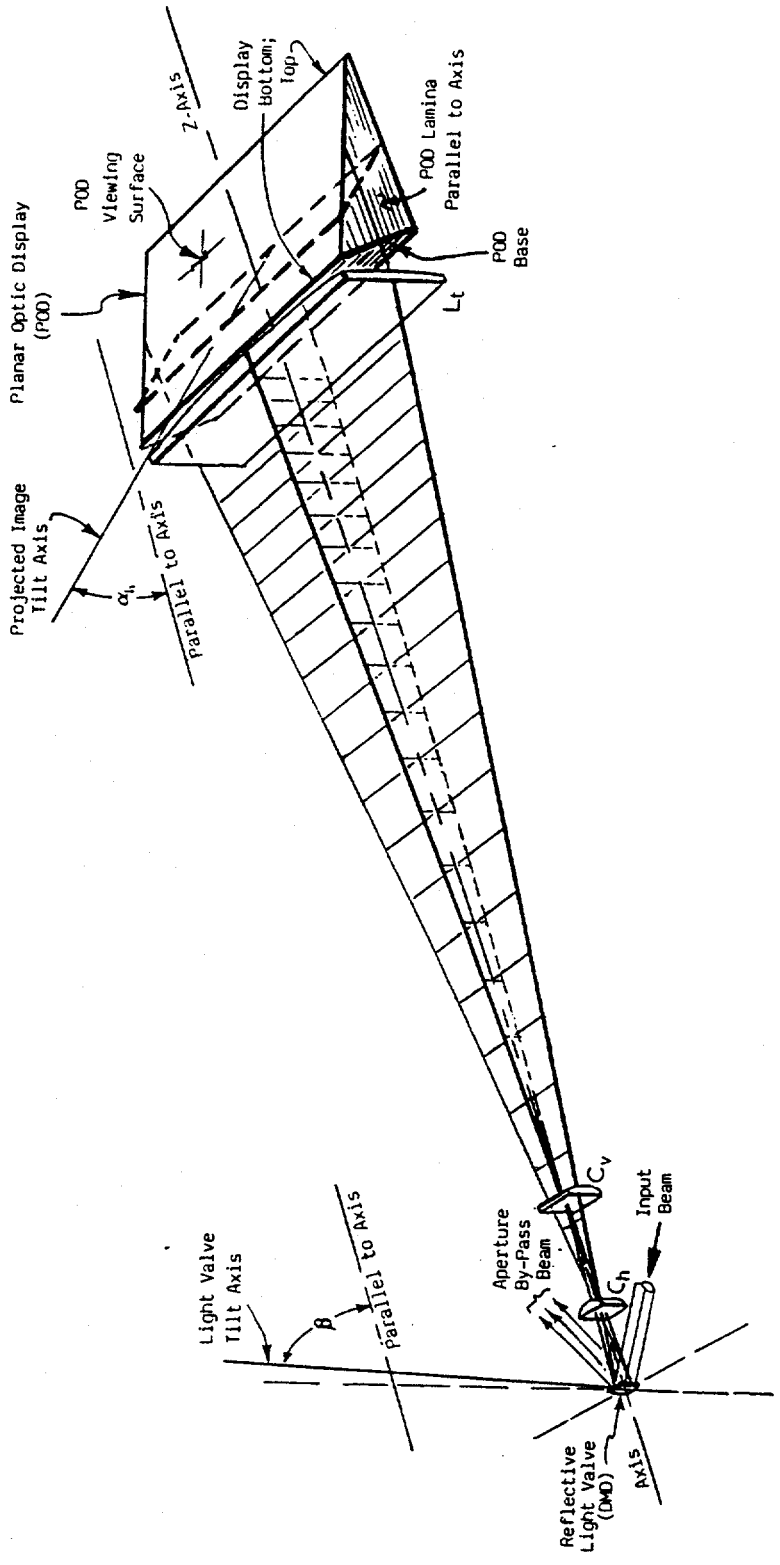

Figure 3 Illustration of Projection Optics for Planar Optic Display (POD)

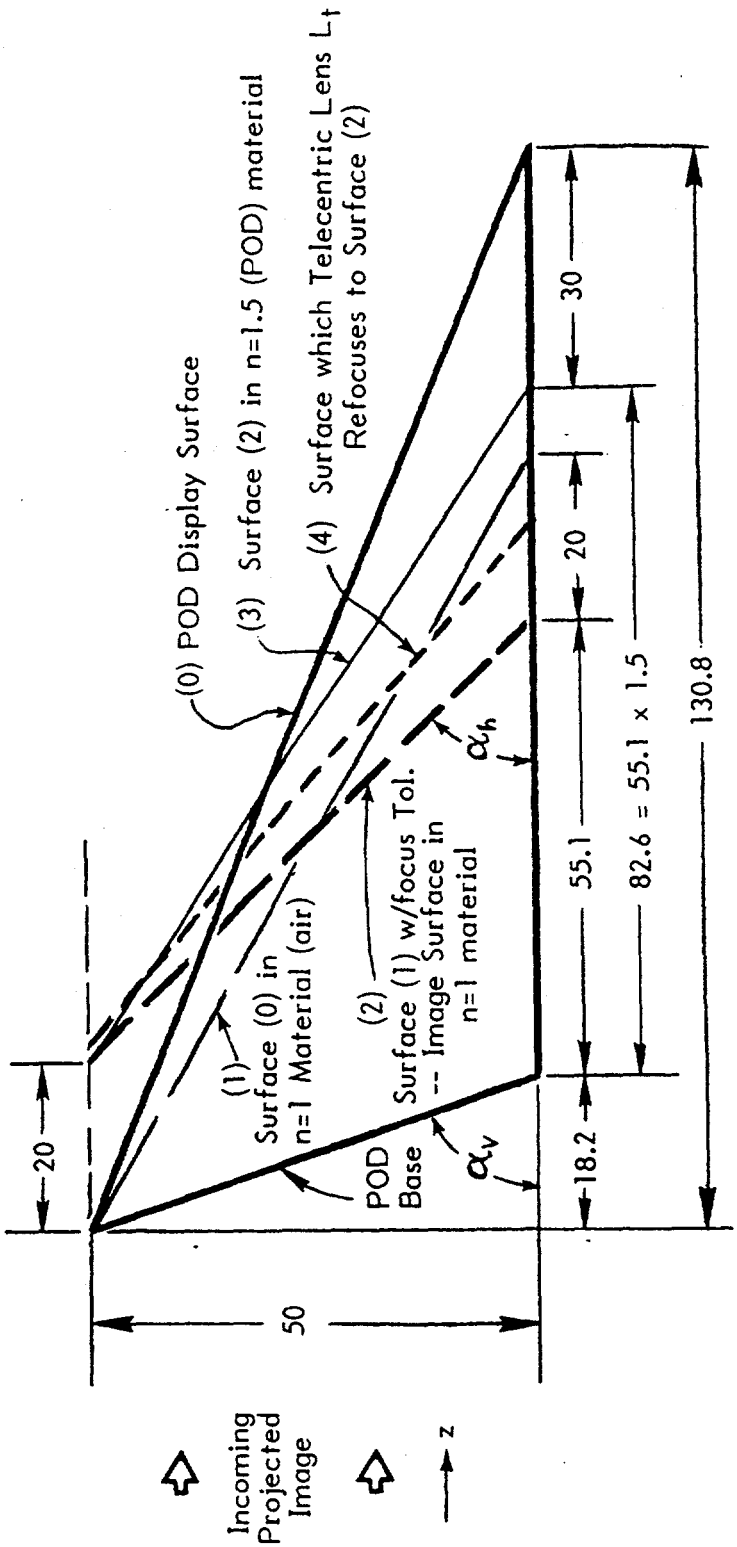

Figure 4 Section View of POD (bold solid lines) showing the Display Surface (0) and several analytic image surfaces (1) to (4). POD lamina (not shown) are parallel to the z-axis, is illustrated in Figure 3.