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(71) Demandeur/Applicant:
THE ARIZONA BOARD OF REGENTS ON BEHALF OF
THE UNIVERSITY OF ARIZONA, US
(72) Inventeurs/Inventors:
HUA, HONG, US;
ZHANG, RUI, US
(74) Agent: OGILVY RENAULT LLP/S.E.N.C.R.L.,S.R.L.

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(54) Title: HEAD-MOUNTED PROJECTION DISPLAY USING REFLECTIVE MICRODISPLAYS

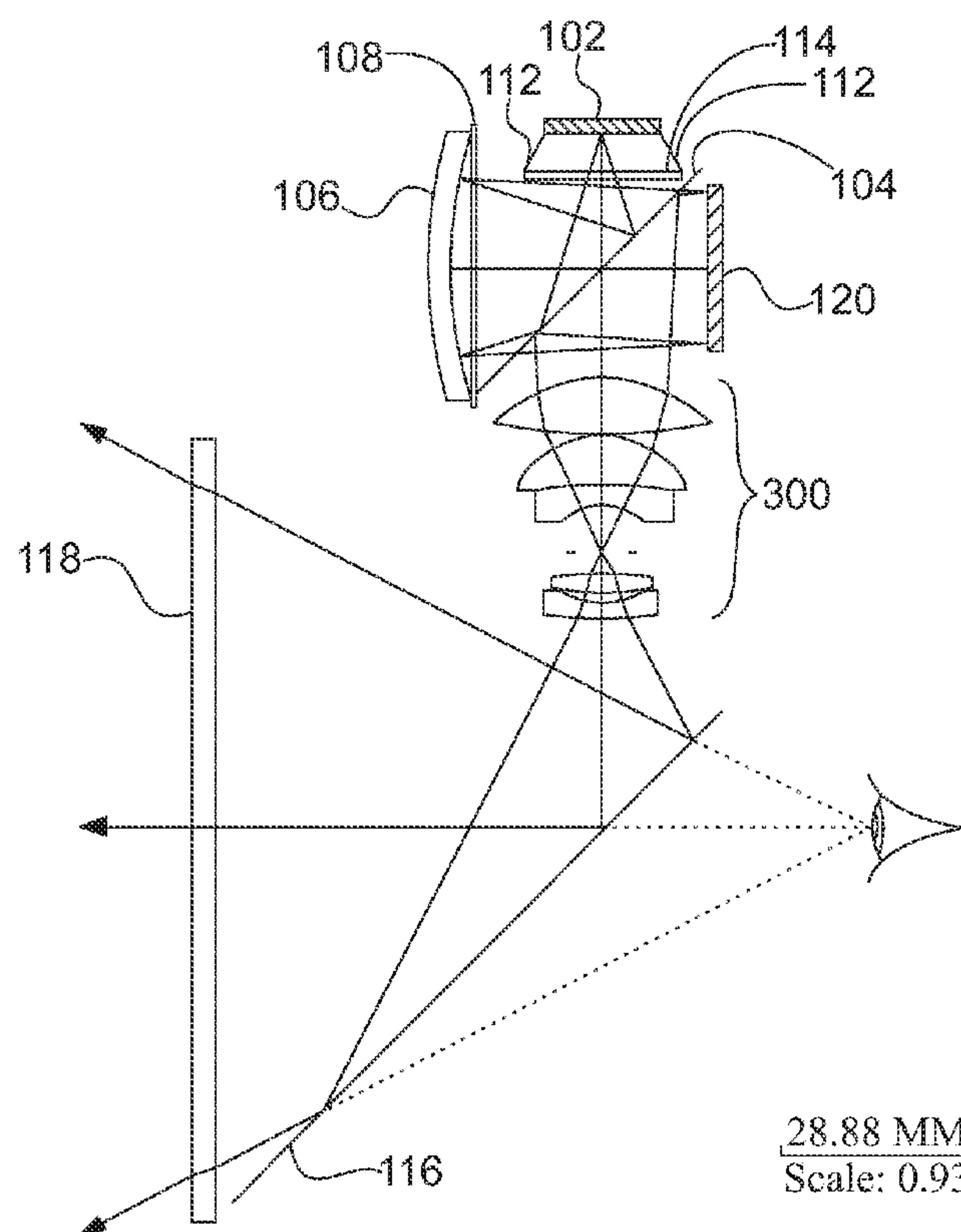


FIG. 14

(57) Abrégé/Abstract:

The present invention relates generally to a head-mounted projection display, and more particularly, but not exclusively to a polarized head-mounted projection display including a light engine and a compact, high-performance projection lens for use with reflective microdisplays.

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(71) Applicant (for all designated States except US): **THE ARIZONA BOARD OF REGENTS ON BEHALF OF THE UNIVERSITY OF ARIZONA** [US/US]; University Services Bldg., Room 204, 888 N. Euclid Avenue, P.O. Box 210158, Tucson, AZ 85721-0158 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **HUA, Hong** [CN/US]; 5956 N. Campo Abierto, Tucson, AZ 85718 (US). **ZHANG, Rui** [CN/US]; 1601 N. Tyndall Avenue, Apt. B5, Tucson, AZ 85719 (US).

(74) Agent: **HAUN, Niels**; Dann, Dorfman, Herrell & Skillman, P.C., 1601 Market Street, Suite 2400, Philadelphia, PA 19103 (US).

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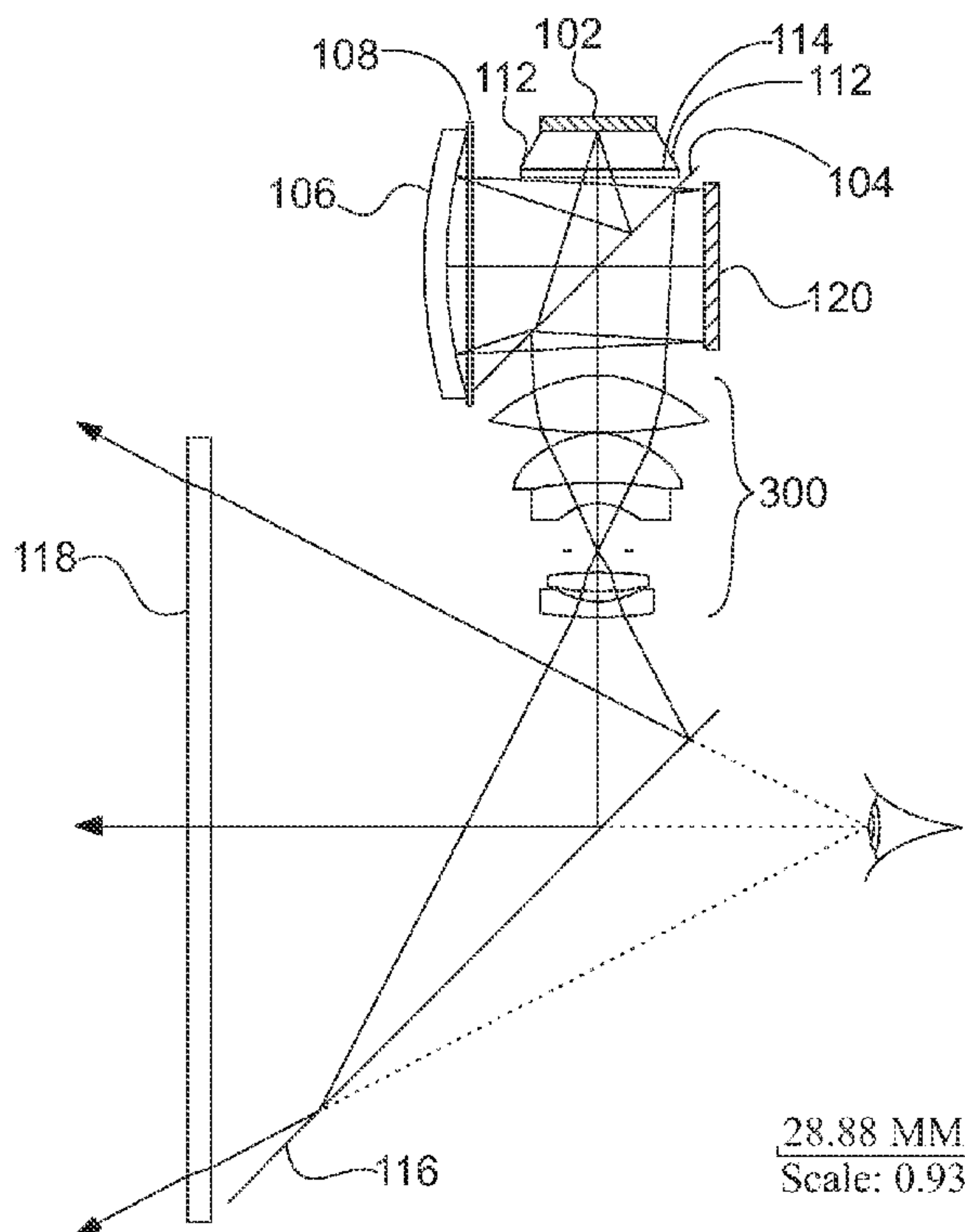


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(57) Abstract: The present invention relates generally to a head-mounted projection display, and more particularly, but not exclusively to a polarized head-mounted projection display including a light engine and a compact, high-performance projection lens for use with reflective microdisplays.

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HEAD-MOUNTED PROJECTION DISPLAY USING REFLECTIVE MICRODISPLAYS

Hong Hua

Rui Zhang

Related Applications

[0001] This application claims the benefit of priority of U.S. Provisional Application No. 61/011,789, filed on January 22, 2008, the entire contents of which application are incorporated herein by reference.

Government Rights

[0002] This invention was made with government support under government contract IIS0534777 awarded by the National Science Foundation. The government has certain rights in the invention.

Field of the Invention

[0003] The present invention relates generally to a head-mounted projection display, and more particularly, but not exclusively to a polarized head-mounted projection display including a light engine and a compact, high-performance projection lens for use with reflective microdisplays.

Background of the Invention

[0004] The head mounted projection display (HMPD), as an alternative to the conventional eyepiece-based head mounted display (HMD), has attracted much interest in recent years, because it offers the ability to design a wide field of view (FOV), low distortion and ergonomically compact optical see-through head mounted display (OST-HMD). Like most OST-HMDs, however, one of the limiting factors for the HMPD technology is its low image brightness and contrast, which limits the feasibility to apply such information to outdoor or well-lit indoor environments such as operating rooms. Due to the multiple beamsplitting through a beamsplitter and low retroreflectivity of typical retroreflective materials, the overall efficiency of a HMPD is around 4%. For instance, with a miniature backlit active matrix liquid crystal display (AMLCD) as the image source, the luminance of the observed image is estimated to be 4cd/m^2 , while the average luminance of a well-lit indoor environment is over 100cd/m^2 . As a result, the

low-brightness image of HMPDs will appear washed out in such well-lit environments. In fact, most optical see-through HMDs, including HMPD, are typically operated under a dimmed lighting condition.

[0005] To address this problem, a polarized head-mounted projection display (p-HMPD) was proposed (H. Hua and C. Gao, "A polarized head-mounted projective displays," *Proceedings of 2005 IEEE and ACM International Symposium on Mixed and Augmented Reality*, pp. 32-35, October 2005) and a prototype based on a pair of transmissive AMLCDs was designed recently (H. Hua, C. Gao "Design of a bright polarized head-mounted projection display" *Applied Optics*, Vol. 46, Issue 14, pp. 2600-2610, May 2007). A pair of 1.3" color AMLCDs was used as the image sources which have a resolution of $(640 \times 3) \times 480$ pixels. 1.4" AlphalightTM RGB LED panels (Teledyne Inc., Los Angeles, CA) were used as the backlighting sources. By carefully manipulating the polarization states of the light propagating through the system, a p-HMPD can potentially be three times brighter than a traditional non-polarized HMPD design using the same microdisplay technologies. A schematic design of a monocular p-HMPD configuration is illustrated in Fig.1.

[0006] The image on the LCD display is projected through the projection lens, forming a real intermediate image. The light from the LCD is manipulated to be S-polarized so that its polarization direction is matched with the high-reflection axis of the polarized beamsplitter (PBS). After the projected light is reflected by the PBS, it is retroreflected back to the same PBS by a retroreflective screen. The depolarization effect by the retroreflective screen is less than 10% within ± 20 degrees and is less than 20% up to ± 30 degrees. As a result, the retroreflected light remains dominantly the same polarization as its incidence light. In order to achieve high transmission through the PBS after the light is retroreflected back, a quarter-wave retarder is placed between the PBS and the retroreflective screen. By passing through the quarter wave retarder twice, the incident S-polarized light is converted to P-polarization and transmits through the PBS with high efficiency. Thus the projected image from the microdisplay can be then observed at the exit pupil of the system where the eye is placed.

[0007] However, since a transmissive LCD microdisplay has a low transmission efficiency of around 5%, the overall performance of the first p-HMPD prototype is still unsatisfactory in a well-lit environment. Furthermore, owing to its inherent low pixel fill

factor, a transmissive AMLCD microdisplay typically has a relatively low resolution. Accordingly, it would be an advance in the field of head-mounted projection displays to provide a head-mounted projection display which has higher luminance while maintaining high contrast.

Summary of the Invention

[0008] In one of its aspects, the present invention provides a compact, telecentric projection lens for use in a head-mounted projection display system. The projection lens may include a plurality of lens elements configured to have an overall length that is no more than about two times the effective focal length of the projection lens. In addition, the plurality of lens elements may be configured so that the projection lens is telecentric in image space. As one measure of the compactness the projection lens may have an overall length that is no more than about 85% larger than the effective focal length of the projection lens. Further, the projection lens may have a back focal length that is about 40% larger than the effective focal length. To further facilitate the use of the projection lens in a head-mounted display, the projection lens may also be lightweight and have a ratio of the weight of the projection lens to the square of the F-number of the projection lens of less than about 2 to 1. For example, in one configuration the present invention provides a projection lens with a F-number of 2.1 and a weight of only 8.2 g.

[0009] In another of its aspects the present invention provides a telecentric optical illumination system for use with a reflective microdisplay. The illumination system may include a source of optical radiation having a first polarization state and a polarized beamsplitter disposed at a location to receive optical radiation from the optical radiation source. The beamsplitter may further be oriented relative to the source of optical radiation to reflect the received optical radiation. In addition, the illumination system may include an optical retarder disposed at a location relative to the beamsplitter to receive optical radiation reflected by the beamsplitter and oriented to convert the polarization state of the received optical radiation to be circularly polarized. A reflector having optical power may also be disposed at a location to receive the circularly polarized optical radiation from the optical retarder and to reflect the received optical radiation back through the retarder and beamsplitter. The reflector may be a concave spherical reflector. Still further, in order to provide an optical illumination system that is

telecentric in image space, the illumination system may include a pupil disposed at the source of optical radiation.

[0010] In yet another of its aspects, the present invention provides a head-mounted projection display system which may include the aforementioned illumination system, a microdisplay disposed one reflector focal length away from the reflector for receiving optical radiation from the reflector, and a telecentric projection lens. The projection lens may assume the configuration of the aforementioned projection lens.

Brief Description of the Drawings

[0011] The foregoing summary and the following detailed description of the preferred embodiments of the present invention will be best understood when read in conjunction with the appended drawings, in which:

[0012] Figure 1 schematically illustrates a polarized HMPD system comprising a transmissive AMLCD and retroreflection screen;

[0013] Figure 2 illustrates the luminance distribution of an exemplary LED illuminator used in a light engine of the present invention;

[0014] Figure 3 schematically illustrates an exemplary design of a light engine in accordance with the present invention;

[0015] Figure 4 illustrates a prototype of a mirror based light pipe of the light engine of the present invention;

[0016] Figure 5 schematically illustrates an exemplary design of the tapered light pipe of Fig. 4;

[0017] Figures 6A, 6B illustrate the illuminance distribution on the microdisplay provided by the light engine of Fig. 3, without and with light pipe, respectively;

[0018] Figure 7 illustrates the layout of an initial lens used as a starting point in the design of a projection lens of the present invention;

[0019] Figures 8A, 8B illustrate a lens layout and MTF performance, respectively, for an optimized version of the lens of Fig. 7;

[0020] Figures 9A, 9B illustrate a lens layout and MTF performance, respectively, for further optimized version of a projection lens of the present invention which is more compact than the lens of Fig. 8;

[0021] Figure 10 illustrates the layout of the final design of an exemplary projection lens of the present invention;

[0022] Figures 11A, 11B illustrate the diffraction efficiency versus radius and diffraction efficiency versus wavelength, respectively, for the projection lens of Fig. 10;

[0023] Figures 12A, 12B illustrate a spot diagram and ray fan plot, respectively, for the projection lens of Fig. 10;

[0024] Figures 12C-12E illustrate the longitudinal spherical aberration, astigmatism, and distortion at 450 nm, 550 nm, 650 nm, respectively, for the projection lens of Fig. 10;

[0025] Figure 12F illustrates the MTF performance for the projection lens of Fig. 10;

[0026] Figures 13A, 13B illustrate a front view and a side perspective view, respectively, of a prototype of a polarized head-mounted projection display of the present invention; and

[0027] Figure 14 schematically illustrates polarized head-mounted display in accordance with the present invention which includes the light engine of Fig. 3 and projection lens of Fig. 10.

Detailed Description

[0028] In order to realize the above-mentioned benefits afforded by a reflective microdisplay 120 in the context of a head-mounted projection display, suitable optical designs are required for both a light engine 100, to deliver uniform, telecentric illumination to the microdisplay 120, and for a telecentric projection lens 300 to collect the light reflected by the microdisplay 120 for delivery to the user, Fig. 3. In addition to the requirements of telecentricity and uniformity, the light engine 100 and projection lens 300 must be sufficiently compact and lightweight to permit their use as part of the head-mounted system. In this regard, in one of its aspects, the present invention provides a compact, telecentric light engine 100 that includes a light pipe 110 and polarization manipulating components 104, 108 to increase the overall uniformity and brightness, respectively, of the light delivered to a reflective microdisplay 120, Fig. 3. In another of its aspects, the present invention provides a telecentric projection lens 300 comprising all plastic components having aspheric surfaces and a diffractive optical element to yield a lens 300 that is simultaneously compact, telecentric, and lightweight,

Fig. 10. Together, the light engine 100, reflective microdisplay 120, and projection lens 300 provide a polarized HMPD in accordance with the present invention, Fig. 14.

[0029] Turning now to the overall system, design began by selection of an exemplary microdisplay 120 from which the performance requirements of both the light engine 100 and projection lens 300 may be derived. Major properties of several candidate microdisplay technologies were evaluated, including AMLCD, organic light emitting displays (OLEDs), liquid crystal on silicon (LCOS), and ferroelectric Liquid-crystal-on-Silicon (FLCOS) were considered. For use in the examples provided below, the SXGA-R2D FLCOS microdisplay kit (Forth Dimensional Displays Limited, Birmingham, UK) was selected as an exemplary microdisplay for use in the present invention due to its high resolution, optical efficiency, and compactness. However, though a FLCOS microdisplay is used for illustrative purposes in the designs presented below, it is understood that the present invention is not limited to such a microdisplay, but may be used in conjunction with suitable other displays, such as, reflective microdisplay types like LCOS, MEMS, Texas Instruments DLP, and so forth, for example.

[0030] The usage of a FLCOS microdisplay 120 makes the prototype design of a HMPD quite different from previous designs of HMPD optics. One of the key differences is the requirement for the custom-designed light engine 100 to illuminate the microdisplay 120. The FLCOS microdisplay 120 is considered as the combination of a mirror and an electrically switchable quarter-wave retarder formed by the liquid crystal layers. The FLCOS microdisplay 120 works most efficiently when the illumination rays are normally incident upon the display surface. To ensure the high contrast of the output image, it is recommended to limit the incident angle to the range of ± 16 degrees, which imposes a critical requirement on the design of both the light engine 100 and projection lens 300. The key requirements for the light engine 100 include: (1) that the illumination system be image-space telecentric to ensure that for every pixel on the display surface the incident chief ray is normal to the display surface; and (2) that the cone angle of the ray bundle is smaller than 16 degrees.

[0031] Likewise, owing to the reflective nature of the microdisplay 120, the output ray bundles from every pixel of the microdisplay 120 are telecentric with a cone angle smaller than 16 degrees. To efficiently collect rays from the microdisplay 120 and form a projected image with uniform illumination, the projection lens 300 must be image-

space telecentric. To the contrary, a projection system using backlit AMLCDs, which have a relatively large viewing angle, and thus relaxed requirement for the angle of incidence ray bundles, can relax the telecentric constraint to gain compactness.

Parameters	Specifications
FLCOS microdisplay	
Diagonal Size	22.3mm
Active area	17.43 x 13.95 mm
Resolution	1280x 1024 pixels
Pixel size	13.6 μm
Color technique	Field sequential color
LED panel	
Body Dimensions	18.4 x 14.1mm
Active area	8.4 x 6.5mm
Weight	4 \pm .5 grams
Luminance	34800 (cd/m^2)
Color Coordinates	Red: x = .67-.43, y = .27-.33 Green: x=.14-.28, y = .64-.73 Blue: x = .11-.15, y = .04-.10
Power	340mW

Table 1. Specification of microdisplay and LED panel

Design of a compact light engine

[0032] Light source selection is the first step in the light engine design. Based on the design requirement of a HMPD, there are several constraints on the source selection and the light engine design. First, safety is a primary concern in any head-mounted device. Therefore sources with low power consumption and low heat dissipation are highly desired. Secondly, compactness and low weight are always critical for HMD systems. Finally, in order to generate an image with high brightness and uniformity across the whole FOV, the illumination on the microdisplay 120 should be uniform and bright. A 0.5" AlphalightTM color LED panel 102 (Teledyne Inc., Los Angeles, CA) is selected for the p-HMPD prototype design. The LED panel 102 is compatibly driven by the color sequential technique of the FLCOS displays. Table 1 summarizes the major specifications of the microdisplay 120 and LED panel 102. The luminance distribution of the LED panel 102, Fig. 2, is relatively uniform within 18 degrees of the emitting angle. With the requirement of image-space telecentricity on the light engine 100, a compact light engine design in accordance with the present invention is shown in Fig. 3.

[0033] The basic idea of the design of the light engine 100 is to place the LED panel 102 at the front focal point of a positive lens (or reflector) and the microdisplay 120 at the back focal point. In order to make a compact system, a concave spherical reflector 106, a PBS 104 and a quarter wave retarder 108 are used to fold the length of the system in half. The microdisplay 120 is disposed at the conjugate position of the LED panel 102, and both the microdisplay 120 and LED panel 102 are at the focal point of the reflector 106. With a polarizer 114 in front of the LED panel 102, S-polarized light from the LED panel 102 is transmitted through the polarizer 114 and is reflected by the PBS 104. A quarter-wave retarder 108 is placed between the reflector 106 and PBS 104 and its fast axis is at 45 degrees with the polarization direction of S-polarized light. By passing through the retarder 108 twice, the reflected light by the reflector 106 becomes P-polarized light and will transmit the PBS 104 to illuminate the microdisplay 120 with high efficiency.

[0034] In this design, the LED panel 102 itself can be taken as the pupil of the system to form an image-space telecentric system, where the ray bundle received by the microdisplay 120 is symmetric with the display normal. With both LED panel 102 and microdisplay 120 at the focal point of the reflector 106, the light distribution on the microdisplay 120 is the Fourier transform of that of the LED panel 102. Thus the spatial distribution on the microdisplay 120 can be derived as

$$E_{display}(x, y) = L * \Omega = L_{LED}(\arctan(\frac{\sqrt{x^2 + y^2}}{f})) * \frac{S_{LED}}{f^2}, \quad (1)$$

where $E_{display}(x, y)$ is the illuminance at (x, y) on the display assuming the center of the display is at the origin, $L_{LED}(\theta)$ is the luminance of LED panel 102 as a function of angle, S_{LED} is the area of the LED panel 102 and f is the focal length of the reflector 106. Across the microdisplay 120, the ratio of the luminance at the center of the microdisplay 120 to that at the edge is $L_{LED}(0^\circ) / L_{LED}(\arctan(\frac{D}{2f}))$ while D is the diagonal size of the microdisplay 120. To get better uniformity on the microdisplay 120, a reflector 106 with larger focal length is preferred. But meanwhile, larger focal length will result in a less compact structure and a smaller solid angle with lower luminance efficiency.

Considering all these factors, a reflector 106 with 35mm focal length and 35mm diameter was selected. As a result, the ratio of the maximum luminance to the minimum

luminance on the microdisplay 120 is 1: 0.82, and the cone angle of the ray bundle on the microdisplay 120 is within 8.6 degrees. The light within the cone angle of 18 degrees emitted by the LED panel 102 can be collected by the reflector 106 to illuminate the microdisplay 120 while the light emitted at a larger angle is wasted.

[0035] In order to further improve the light efficiency and uniformity of the light engine 100, a mirror-based tapered light pipe 110 was designed to recycle the light with emission angles larger than 18 degrees. Figure 4 shows a prototype design of the light pipe 110. It is composed of four mirrors 112, each of which is tilted by an angle with respect to the LED surface, forming a truncated pyramid shape. The light emitted from the LED panel 102 with large angles will be reflected by the enclosing mirrors 112. After reflection, more rays from LED panel 102 can be collected by the reflector 106 to illuminate the microdisplay 120. To get the best performance of the light engine 100, both tilt angle, α , and length, t , of the light pipe mirror 112, as shown in Fig. 5, should be optimized.

Numerical Simulation

[0036] To determine the parameters of the tapered light pipe 110 and to examine the light efficiency and uniformity of the light engine 100, the light engine 100 was modeled using LightTools[®] (Optical Research Associates, Pasadena, CA). In the simulation, the total power of the source was set to be 1 lumen. A light receiver was placed on the microdisplay 120 to estimate the efficiency of the light engine 100 and to evaluate the light distribution on the microdisplay 120. Through the simulation, it is shown that the light engine 100 has higher uniformity and light efficiency when the tilt angle, α , of the mirror is 18 degrees. By balancing the performance and space constraint of the light engine 100, the mirror length, t , is selected to be 8mm. Figure 6B shows the output illuminance distribution on the microdisplay 120 for a system with the mirror based light pipe 110, and Figure 6A shows the output illuminance distribution on the microdisplay 120 for the same system as Fig. 6B but without the light pipe mirrors 112 in place. Hence, comparison between Figs. 6A, 6B illustrates the improvement in performance of the light engine 100 due to the presence of the light pipe mirrors 112.

[0037] As indicated by the simulation results, with a mirror based light pipe 110, the light efficiency has increased from 8.93% to 12.3%, and the non-uniformity, quantified

by the average standard deviation of the illuminance distribution across the display area, has reduced from 5.61% to 2.15%. Thus, the system with the light pipe 110 has higher efficiency and better uniformity than without.

Design of a compact, high-performance projection lens

[0038] Based on the design of the light engine 100, a lightweight and compact image-telecentric projection lens 300 is designed. In this section, the design process of the projection lens 300 is described and the performance of the projection lens 300 is analyzed.

Parameter	Specification
Effective focal length	21.6 mm
Entrance pupil	10 mm
Image mode	Image space telecentric
OAL	< 40 mm
OAL/BFL	<1.85
BFL	30.5 mm
FOV	55°
Wavelength range	486—656 nm
Distortion	<4% over FOV
Weight	< 15-20 grams

Table 2 Design targets for the projection lens

Projection lens specification

[0039] Although projection optics do not scale as much with the increase of FOV as eyepiece-type optics, which makes designing wide FOV, optical see-through HMPD systems relatively easier than conventional HMDs, there are a few factors in HMPD systems that impose limits on the FOV. First of all, the use of a planar PBS 116 or a regular beamsplitter in front of the eye, which is oriented at 45 degrees with the optical axis, sets up the FOV upper limit of 90 degrees. Furthermore, a wide FOV requires a large size of PBS 116 and retarder 118 and consequently challenges the compactness and lightweight of the display system. The limit of allowable PBS and retarder dimensions is set by the interpupillary distance (IPD), which is in the range of 55 to 75mm for over 95% of the population. Thirdly, previous investigation on retroreflective materials shows that the retroreflectance of currently available materials drops off significantly for light incident at angles beyond $\pm 35^\circ$. A FOV beyond 70 degrees will inevitably cause vignetting-like effect and compromise image uniformity. Finally, the angular resolution of the microdisplay 120 degrades with the increase of the FOV.

Taking into account these factors, a target was set to design the projection system with a FOV of 55 degrees, which corresponds to an effective focal length (EFL) of 21.6mm for the selected FLCOS microdisplay 120.

[0040] In addition to being image-space telecentric, the projection lens 300 must have a large back focal length (BFL) to ensure enough space for the PBS 104 which is placed between the microdisplay 120 and projection lens 300. Based on the light engine design, the BFL is chosen to be at least 30.5mm. Thus this projection lens 300 is also a reverse telephoto lens. (It is understood that, in the designs below, the microdisplay 120 is located at the image plane, hence the reason that the BFL represents the space allotted for the PBS 104 placed therebetween.)

[0041] Since a user's eye is positioned at the conjugate position to the entrance pupil of the projection lens 300, the entrance pupil diameter is very critical for comfortable observation. Typically it is suggested the pupil diameter of the projection system for HMPDs should be around 10-12mm. This range of pupil size allows an eye swivel of about $\pm 21^\circ$ up to 26.5° within the eye sockets without causing vignetting or loss of image with a typical 3-mm eye pupil in the lighting conditions provided by HMPDs. Furthermore, it allows a ± 5 mm to 6mm IPD tolerance for different users without the need to mechanically adjust the IPD of the binocular optics. Considering the short focal length of the optics, a target entrance pupil with a diameter of at least 10mm was selected, which leads to a projection system with an F/# of 2.16.

[0042] A lens 10 from Nanba US 6,236,521 was used as the starting point of the design, with Fig. 7 showing the layout. The starting lens 10 was designed for a digital projector, and is reverse-telephoto and telecentric. Unlike a double Gauss lens, the starting lens 10 has an asymmetric structure relative to the stop because of the telecentric requirement in image space. This five-element starting lens 10 offers a full FOV of 65 degrees with an F/# of 2.5. Among the five glass elements, a doublet 12 is used, and the front surface 14 of the last element 16 is aspheric to help correct spherical aberration. The ratio of the BFL to the EFL of the lens 10 is 1.13 and the ratio of the overall length (OAL. As used herein, OAL refers to the distance from the first surface of the first optical element to the last surface of the last optical element) of the optics to the EFL is 3.15. The ratio of the exit pupil distance to the EFL is 13.6, which makes the lens 10 telecentric in image space. By scaling and several cycles of optimization with CODE V[®] (Optical Research

Associates, Pasadena, CA), a new starting lens 210 was obtained to meet the first-order design targets of 21.1mm EFL, 30mm BFL and 68 mm OAL, as shown in Fig. 8A and Table 3. The full FOV is set to be 55 degrees. As shown in Fig. 8B, the MTF of the lens 210 is around 30% at the spatial frequency of 37-lp/mm, which shows acceptable performance as a first-order starting point for the design.

Surface No.	Surface type	Radius	Thickness	Lens material
1	Sphere	151.9831514	7.199	772499.496
2	Sphere	18.31108732	18.74851	
3	Sphere	37.26417226	4.646097	772499.496
4	Sphere	51.05918244	9.065786	
stop	Sphere	1.00E+18	11.41511	
6	Sphere	14.31228599	4.642326	846660.238
7	Sphere	121.7152043	6.393417	677900.553
8	Sphere	20.60785676	0.1	
9	Asphere	60.8179454	5.789755	772499.496
10	Sphere	38.94828517	29.99994	
Asphere parameters for surface 9				
4th Order Coefficient (A)			-8.95E-06	
6th Order Coefficient (B)			6.83E-09	
8th Order Coefficient (C)			-1.56E-11	
10th Order Coefficient (D)			2.28E-14	

Table 3. Numerical values for lens of Fig. 8.

[0043] The projection lens 210 is rotationally symmetric, and thus the optimization is only necessary over half of the full FOV for the radial direction. Three representative wavelengths (i.e., 486nm, 589nm and 656nm) were set with the weights of 1, 2 and 1, respectively. Five fields, corresponding to 0°, 7°, 14°, 21° and 27.5°, respectively, were used in the optimization process to represent the half FOV. The weights of the five fields were adjusted in the optimization process to balance the MTF performances across the entire FOV. During the optimization, all surface curvatures, surface thicknesses, and coefficients of aspheric surfaces were set to be variables. Several constraints were set to satisfy the specifications of the overall system and each individual lens element, including the EFL, BFL, OAL, distortion requirements, and the center thickness of individual elements, for example. The telecentric requirement was satisfied by setting the exit pupil distance to be at least 210mm from the image plane. This distance corresponds to a deviation of the chief ray by 3° from a perfectly telecentric system, which yields a good balance between the overall optical performance and the system

compactness considering the difficulty in designing a perfectly telecentric lens with a short OAL.

[0044] One of the major problems of the lens 210 in Fig. 8A is its compactness: the OAL is too large for a head-mounted system and a more compact solution is needed. This initial lens 210 was gradually optimized by adjusting the parameter constraints and field weights through a local optimization approach. While the OAL was reduced down to about 40mm in the process of optimization, the overall performance was degraded as well. In order to further improve its performance, the back surface 211 of the first lens element 212 was set to be aspheric, which helped to correct most of the spherical aberration. After gradual optimization, a system was obtained with satisfactory performance. The resulting lens layout and MTF are shown in Figs. 9A, 9B.

[0045] This lens 220 is composed of five glass elements 221-225 (with aspheres on two surfaces 227, 229) and weighs about 38.7 grams, which needs to be significantly reduced to obtain a lightweight p-HMPD system. Plastic materials were selected to replace the glass elements 221-225. Considering that the density of glass is about three times of most plastics, it is expected that the weight of the lens 220 would drop to around 10 grams. The drawback of using the plastic materials is also obvious. While there are many choices of optical glass, from low to high refractive index and low to high Abbe number, for plastics only very limited number of materials are available for diamond turning fabrication.

[0046] The initial target was to replace the glass elements 223-225 on the right side of the stop with the plastics, since they contributed most of the weight due to their large aperture. Polystyrene with low Abbe number and Cyclic Olefin Polymer (COC) with relatively high Abbe number were selected to replace the glass materials of the doublet 223, 224. After this replacement, the optimization was rerun to achieve the desired specifications of the lens 220. Since the last element 225 has the highest optical power among all the elements in the lens 220 and high Abbe number, COC was selected for the last element 225. Unfortunately, after the plastic replacement the system had much worse performance compared with the system before replacing the last glass element 225. Chromatic aberration dominates the resulting system. To effectively correct the residual chromatic aberration, a diffractive optical element (DOE) was added to the system.

[0047] A DOE can be viewed as a material with large dispersion but opposite in sign to conventional materials, i.e., the Abbe number of a DOE is approximately -3.5 for the visible spectrum. This DOE with negative Abbe number would help to correct the chromatic aberration. The substrate shape of a diffractive surface DOE can be spherical, planar being a special case, or aspheric. The commonly used orders of diffraction are 0, -1, or 1. The +1 order of diffraction was adopted. The diffractive surface can be used on any of the lens surfaces as long as it can help to correct the chromatic aberration. However, after a few trials, it was found to be most effective to place the diffractive surface on the left surface 227 of the last element 225. The DOE quadratic coefficient was set to be a variable up to 12 orders in the optimization process. Finally, to further reduce the lens weight, the first two glass elements 221, 222 on the left of the stop were replaced with Acrylic and Polystyrene, respectively.

[0048] Considering the fact that a doublet requires higher cost in the fabrication process, the doublet 223, 224 was split into two single elements. The split of the doublet 223, 224 also offered extra freedom in the optimization, and helped improve the overall performance. Finally, through several rounds of optimization, a telecentric lens 300 with an OAL of 34mm and a total weight of 8.2 grams was obtained. The ratio of the weight of the lens to the square of the F-number was 1.86 to 1. Figure 10 shows the layout of the final design of the projection lens 300, and Tables 4-9 shows the design parameters and first order properties of the lens 300.

Surface No.	Surface type	Radius	Thickness	Material
1	Sphere	54.31648697	2	Acrylic
2	Asphere	11.67695001	1.31979	
3	Sphere	29.18891338	2.71793	
4	Sphere	-53.75253258	3.106908	
5(stop)	Sphere	Infinity	6.769705	Polystyrene
6	Asphere	-9.34878697	2.5	
7	Sphere	-109.22569406	0.2	
8	Sphere	-93.99209709	7.088732	Cyclic Olefin Polymer
9	Sphere	-14.34048220	0.1	
10	Asphere	36.51968881	8.196935	Cyclic Olefin Polymer
11	Sphere	-22.22836849	30.5	
image	Sphere	Infinity	0	

Table 4. Numerical values for the lens of Fig. 10.

Element	Focal length (mm)
1 st element	-30.7666976612
2 nd element	32.4497012224
First two elements	-7837.900440744
3 rd element	-17.48717528244
4 th element	30.96961073305
5 th element	25.97749355667

Table 5. Numerical values for aspheric surfaces of the lens of Fig. 10.

Surface	Surface 2	Surface 6	Surface 10
Conic Constant (K)	1.19517273E+00	2.87739760E-01	-1.73713081E+01
4th Order Coefficient (A)	-9.17398530E-05	1.55078027E-04	1.87808847E-07
6th Order Coefficient (B)	-6.00685014E-06	1.60075455E-06	-1.36998214E-07
8th Order Coefficient (C)	2.67960130E-07	-1.10443177E-07	7.55859302E-10
10th Order Coefficient (D)	-9.29841239E-09	4.67064799E-09	-2.04509691E-12
12th Order Coefficient (E)	1.54727549E-10	-8.56490951E-11	2.26702680E-15
14th Order Coefficient (F)	-1.16675172E-12	6.81530567E-13	-1.54585020E-19

Table 6. Numerical values for aspheric surfaces of the lens of Fig. 10.

Diffraction Order = 2	
Construction Wavelength = 550	
R**2 (C1)	-1.06653506E-03
R**4 (C2)	4.09441040E-06
R**6 (C3)	-4.17021652E-08
R**8 (C4)	2.36559269E-10
R**10 (C5)	-6.59579639E-13
R**12 (C6)	7.29317846E-16

Table 7. Numerical values for the DOE of the lens of Fig. 10.

	Acrylic	Polystyrene	Cyclic Olefin Polymer
Trade Name	Plexiglas	Styron	Zeonex
nf (486.1 nm)	1.497	1.604	1.537
nd (589 nm)	1.491	1.590	1.530
nc (656.3 nm)	1.489	1.585	1.527

Table 8. Numerical values for optical materials of the lens of Fig. 10.

EFL	21.6000
BFL	30.5000
FFL	4.5965
F No	2.1600
Image distance	30.5000
OAL	34.0000
Paraxial image height	11.2442
Paraxial image Ang	27.5000
Ent pupil diameter	10.0000
Ent pupil thickness	7.0384
Exit pupil diameter	88.4570
Exit pupil thickness	-160.5672

Table 9. First order properties of the lens of Fig. 10 at infinite conjugates.

[0049] The lens 300 includes five lens elements 310, 320, 330, 340, 350 ordered left-to-right from object space to image space. The first two lens elements 310, 320 form a first lens group 315 having very little optical power (e.g., the focal length of the lens group 315 is two orders of magnitude larger than that of the lens 300, see Tables 5, 9) disposed to the left of the stop. The first lens element 310 is a negative meniscus lens having two surfaces that are concave towards image space, with the surface 311 closest to image space being aspheric. The second lens element 320 is a positive lens disposed adjacent the first lens element 310. The third through fifth lens elements 330, 340, 350 are disposed on the right side of the stop, with the third element 330 closest to the stop being a negative lens and the fourth and fifth elements 340, 350 closest to the image plane being positive lenses. The first surface 331 of the third lens element 330 closest to the stop is aspheric as is the first surface 351 of the fifth lens element 350. In addition, the first surface 351 of the fifth lens element 350 includes the aforementioned DOE.

Performance analysis of the projection lens

[0050] The diffraction efficiency of a DOE drops as its physical features become finer near the edge. Figure 11A shows the diffraction efficiency as a function of the radius of diffractive surface at the designed wavelength 550nm. The overall efficiency varies from 98.7% at the center to 98.5% at the edge. The diffraction efficiency is also wavelength dependent. Figure 11B plots the diffraction efficiency as a function of wavelengths as well as the levels of the binary masks (i.e., 2, 4, 8, 16). Level 16 could be an accurate prediction for the Kinoform DOE using diamond turning method for fabrication. It shows that the diffraction efficiency varies from 80% to 100% across the visible spectrum.

[0051] The optical performance of the optimized lens 300 is assessed on the image plane at the five representative field angles for three different wavelengths. The spot diagrams are shown in Fig. 12A. The average RMS spot diameter across the FOV is around $16\mu\text{m}$, which is slightly larger than the $13.6\mu\text{m}$ pixel size to avoid pixellated artifacts. Figures 12C-E shows longitudinal spherical aberration, astigmatism, and the distortion curves. The longitudinal spherical aberration and astigmatism are well balanced, and the distortion of the system is limited within 4% across the FOV. The MTF of the lens 300 is presented in Fig. 12F. The FLCOS microdisplay 120 has a threshold spatial frequency of 36.8-lp/mm given a $13.6\mu\text{m}$ pixel size (i.e. threshold spatial frequency = $1/(2 * \text{pixel size})$). The modulation is about 40% at 36.8-lp/mm across the whole FOV, which means the performance of the system is currently limited by the display resolution.

p-HMPD prototype

[0052] With the design of the light engine 100 and projection lens 300 complete, a prototype of the new p-HMPD was built, Figs. 13-14. The p-HMPD included the light engine 100, microdisplay 120, and projection lens 300, as well as an additional PBS 116, quarter-wave retarder 118, and retro-reflective screen, which are disposed in the same relative positions to provide the same function as the PBS, quarter-wave retarder, and retro-reflective screen of Fig. 1. Compared with the p-HMPD prototype using transmissive LCD microdisplays of Fig. 1, the mounting of the optics in the new p-HMPD of Fig. 3 is more challenging for the following reasons. First, the use of the light engine 100 requires some extra space and weight. Second, the projection lens 300 designed for the FLCOS microdisplay 120 is longer due to the image-space telecentric requirement and higher image quality requirement.

[0053] Considering both the ergonomic and aesthetic factors, the optics 100, 120, 300, were mounted vertically so that the width of the helmet was around the average width of the adult head. In the vertical direction, the optics were mounted according to the shape of the head, and the associated electronics were mounted on the top of the helmet. A main drawback of the vertical mount is that a ghost image of the ground formed by the PBS 104 is overlaid with the projected image, which leads to reduced image contrast. This problem, however, can be solved by blocking the optical path from the ground.

[0054] To make the system more compact and lighter, the mount of the light engine 100 with the microdisplays 120 was fabricated separately and then integrated with the shell as a whole. The lens 300 position relative to the microdisplay 120 is adjustable to provide a projected image with adjustable magnification.

[0055] The helmet shells were fabricated using rapid prototyping techniques, in which physical models are fabricated layer by layer directly from a 3D CAD model. The helmet shells were assembled and attached to an off-the-shelf headband that offers head-size adjustment. The front and side views of the prototype are shown in Figs. 13A, 13B, respectively.

[0056] These and other advantages of the present invention will be apparent to those skilled in the art from the foregoing specification. Accordingly, it will be recognized by those skilled in the art that changes or modifications may be made to the above-described embodiments without departing from the broad inventive concepts of the invention. It should therefore be understood that this invention is not limited to the particular embodiments described herein, but is intended to include all changes and modifications that are within the scope and spirit of the invention as set forth in the claims.

Claims

What is claimed is:

1. A compact, telecentric projection lens for use in a head-mounted projection display system, comprising a plurality of lens elements configured to have an overall length that is no more than about two times the effective focal length of the projection lens and configured so that the projection lens is telecentric in image space.
2. The compact, telecentric projection lens according to claim 1, wherein the overall length is no more than about 85% larger than the effective focal length of the projection lens.
3. The compact, telecentric projection lens according to any one of the preceding claims, wherein the back focal length is about 40% larger than the effective focal length of the projection lens.
4. The compact, telecentric projection lens according to any one of the preceding claims, wherein the projection lens comprises a diffractive optical element.
5. The compact, telecentric projection lens according to any one of the preceding claims, wherein the plurality of lens elements includes a final lens element closest to the image plane, the final lens element including a diffractive optical element disposed thereon.
6. The compact, telecentric projection lens according to claim 5, wherein the final lens element includes an aspheric surface.
7. The compact, telecentric projection lens according to claim 6, wherein the diffractive optical element is disposed on the aspheric surface.
8. The compact, telecentric projection lens according to any one of the preceding claims, wherein at least two-thirds of the optical elements comprise plastic.

9. The compact, telecentric projection lens according to any one of the preceding claims, wherein the ratio of the weight of the projection lens to the square of the F-number of the projection lens is less than about 2 to 1.
10. The compact, telecentric projection lens according to any one of the preceding claims, wherein the projection lens comprises a lens group disposed on the object side of the stop of the projection lens, the lens group having an effective focal length of at least two orders of magnitude larger than the effective focal length of the projection lens.
11. A compact, telecentric projection lens, wherein the ratio of the weight of the projection lens to the square of the F-number of the projection lens is less than about 2 to 1.
12. A telecentric optical illumination system for use with a reflective microdisplay, comprising:
- a source of optical radiation having a first polarization state;
 - a polarized beamsplitter disposed at a location to receive optical radiation from the optical radiation source and oriented relative to the source of optical radiation to reflect the received optical radiation;
 - an optical retarder disposed at a location relative to the beamsplitter to receive optical radiation reflected by the beamsplitter and oriented to convert the polarization state of the received optical radiation to be circularly polarized;
 - and
 - a reflector having optical power disposed at a location to receive the circularly polarized optical radiation from the optical retarder and to reflect the received optical radiation back through the retarder and beamsplitter,
- wherein the pupil of the illumination system is disposed at the source of optical radiation to provide an optical illumination system that is telecentric in image space.
13. The optical illumination system according to claim 12, wherein the reflector is disposed one reflector focal length away from the source of optical radiation.

14. The optical illumination system according to any one of claims 12-13, wherein the reflector comprises a concave spherical surface.
15. The optical illumination system according to any one of claims 12-14, wherein the retarder comprises a quarter-wave retarder placed between the reflector and beamsplitter with the fast axis of the retarder oriented at about 45 degrees to the polarization direction of the first polarization state.
16. The optical illumination system according to any one of claims 12-15, wherein source of optical radiation comprises a LED.
17. The optical illumination system according to any one of claims 12-16, comprising a tapered light pipe disposed proximate the source of optical radiation.
18. The optical illumination system according to any one of claims 17, wherein the light pipe comprises a plurality of mirrors oriented in the shape of a truncated pyramid.
19. A head-mounted projection display system, comprising:
 - the optical illumination system according to any one of claims 12-18;
 - a microdisplay disposed one reflector focal length away from the reflector for receiving optical radiation from the reflector; and
 - a projection lens, telecentric in image space, located so that the image plane is disposed proximate the microdisplay.
20. The head-mounted projection display system according to claim 19, comprising:
 - a polarized projection beamsplitter disposed at about a 45 degree angle relative to the optical axis and disposed at a location to receive optical radiation transmitted by the projection lens;
 - a projection system quarter-wave retarder disposed at a location to receive optical radiation reflected by the projection beamsplitter; and
 - a projection screen disposed at a location to receive optical radiation from the projection system quarter-wave retarder.

21. The head-mounted projection display system according to any one of claims 19-20, wherein the overall length of the projection lens is no more than about 85% larger than the effective focal length of the projection lens.
22. The head-mounted projection display system according to any one of claims 19-21, wherein the back focal length of the projection lens is about 40% larger than the effective focal length of the projection lens.
23. The head-mounted projection display system according to any one of claims 19-22, wherein the projection lens comprises a diffractive optical element.
24. The head-mounted projection display system according to any one of claims 19-23, wherein the projection lens comprises a final lens element disposed closest to the image plane, the final lens element comprising a diffractive optical element disposed thereon.
25. The head-mounted projection display system according to claim 24, wherein the final lens element includes an aspheric surface.
26. The head-mounted projection display system according to claim 25, wherein the diffractive optical element is disposed on the aspheric surface.
27. The head-mounted projection display system according to any one of claims 19-26, wherein the projection lens comprises a plurality of optical elements, and at least two-thirds of the optical elements comprise plastic.
28. The head-mounted projection display system according to any one of the claims 19-27, wherein the ratio of the weight of the projection lens to the square of the F-number of the projection lens is less than about 2 to 1.
29. The head-mounted projection display system according to any one of claims 19-28, wherein the projection lens comprises a lens group disposed on the object side of the stop of the projection lens, the lens group having an effective focal length two orders of magnitude larger than the effective focal length of the projection lens.

30. The head-mounted projection display system according to any one of claims 19-29, wherein the projection lens comprises a plurality of lens elements configured to have an overall length that is no more than about two times the effective focal length of the projection lens and configured so that the projection lens is telecentric in image space.

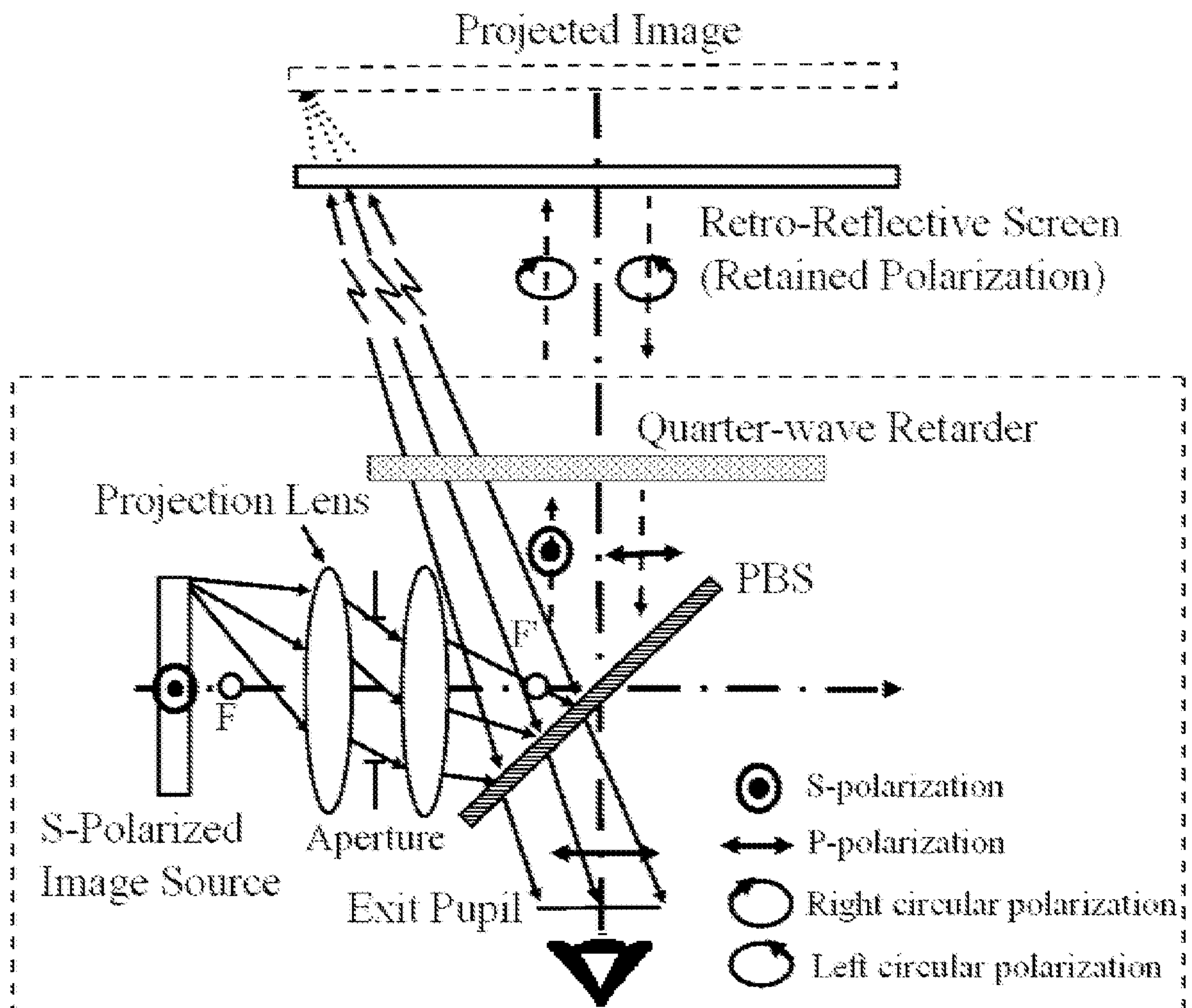


FIG. 1

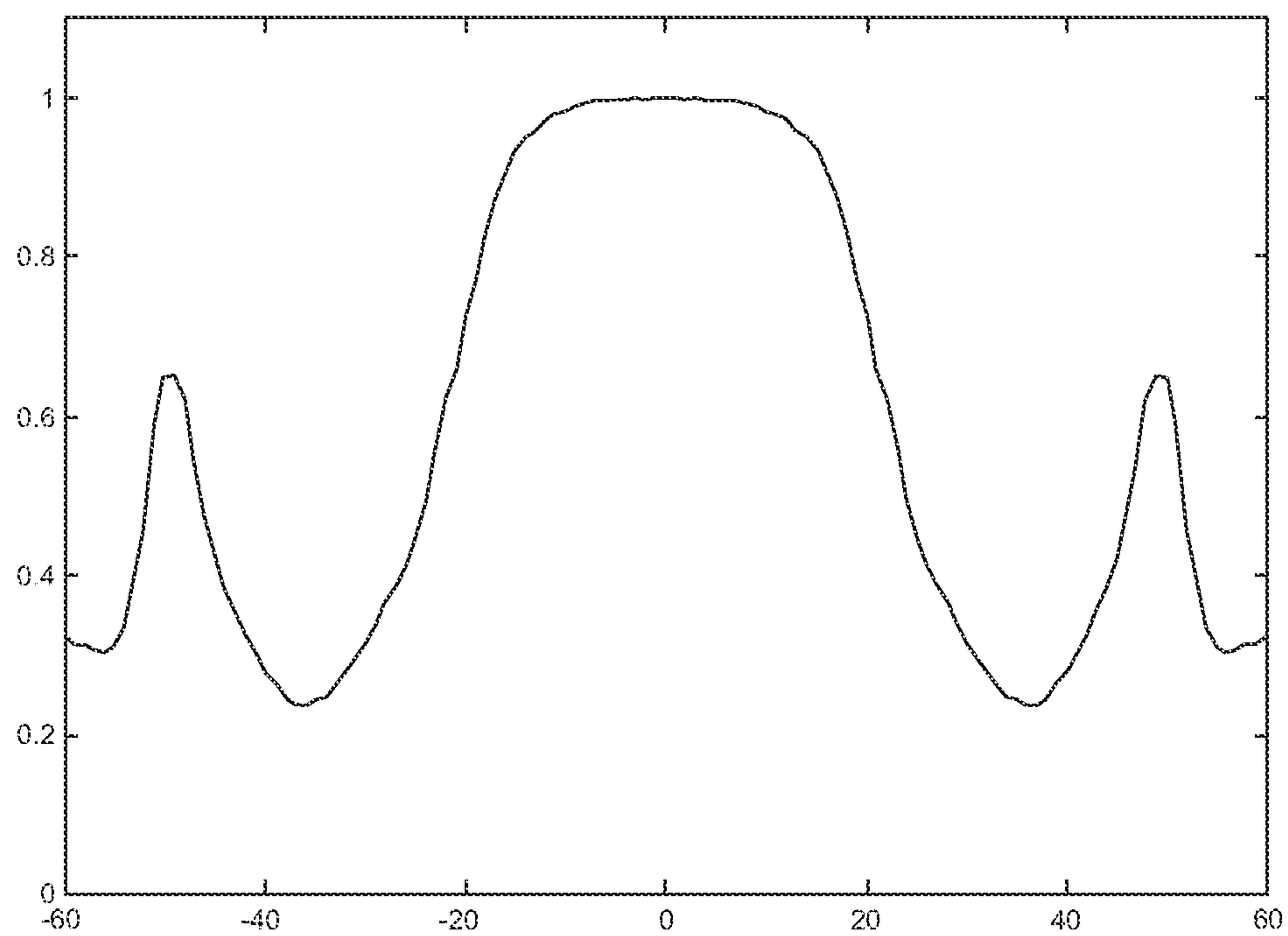


FIG. 2

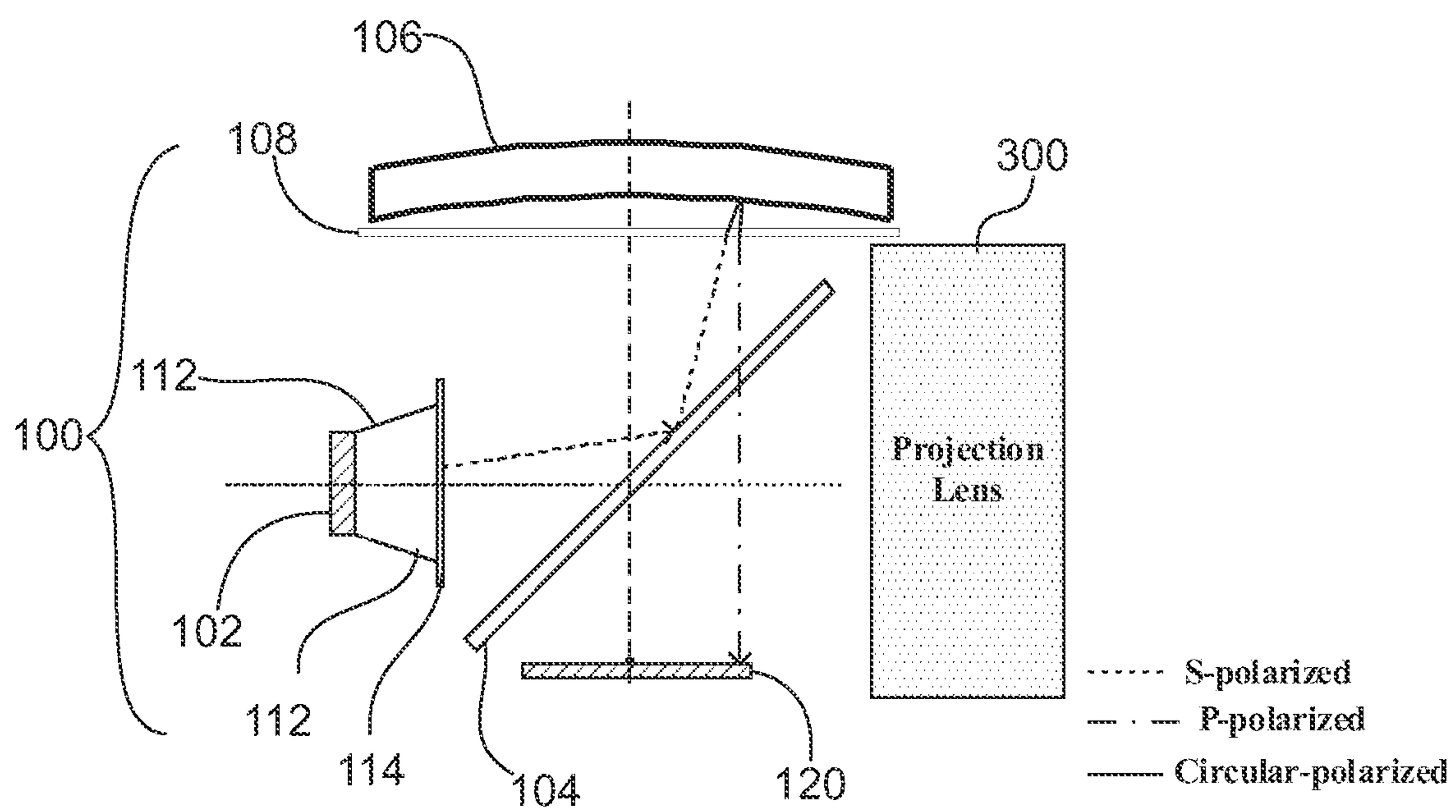


FIG. 3

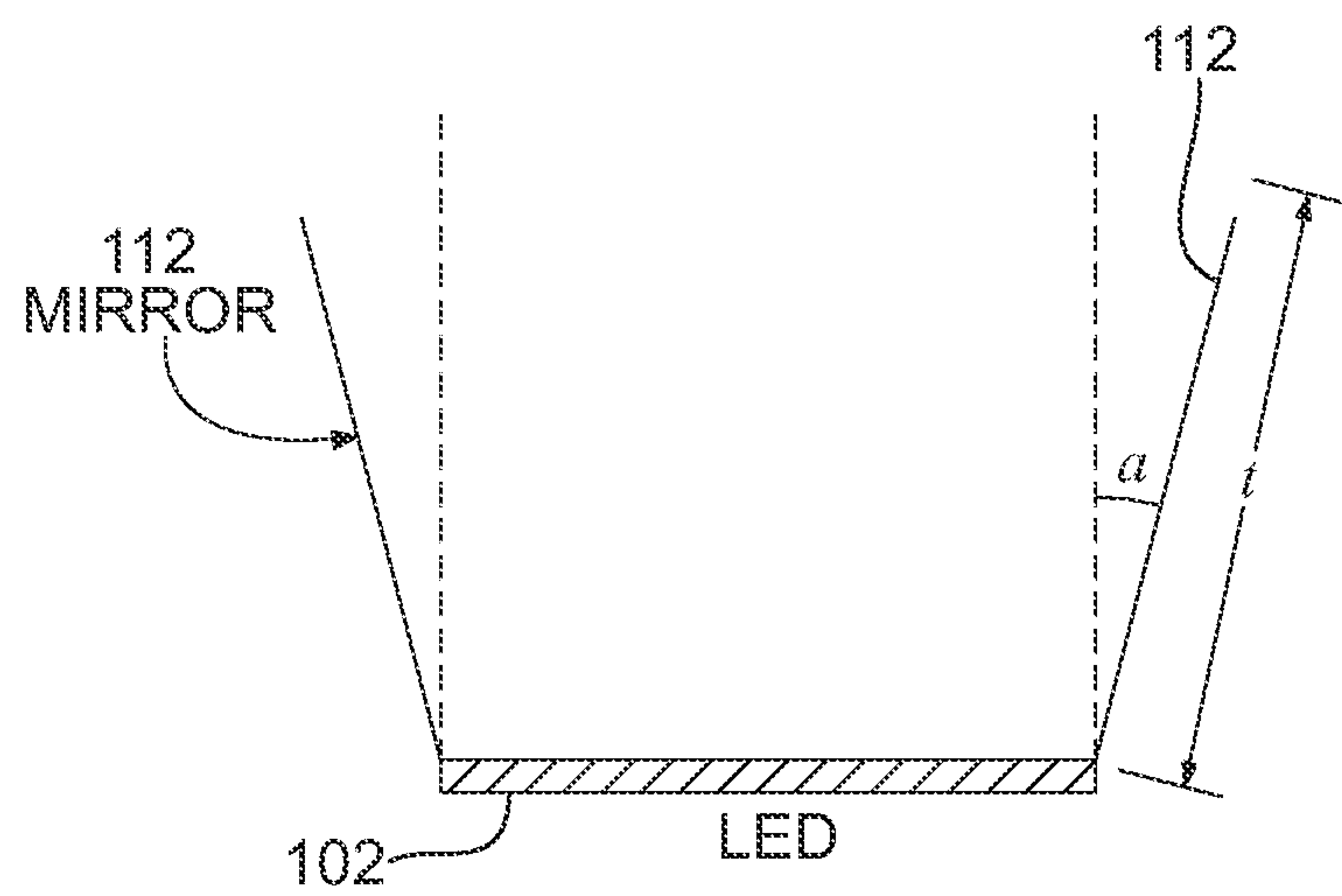
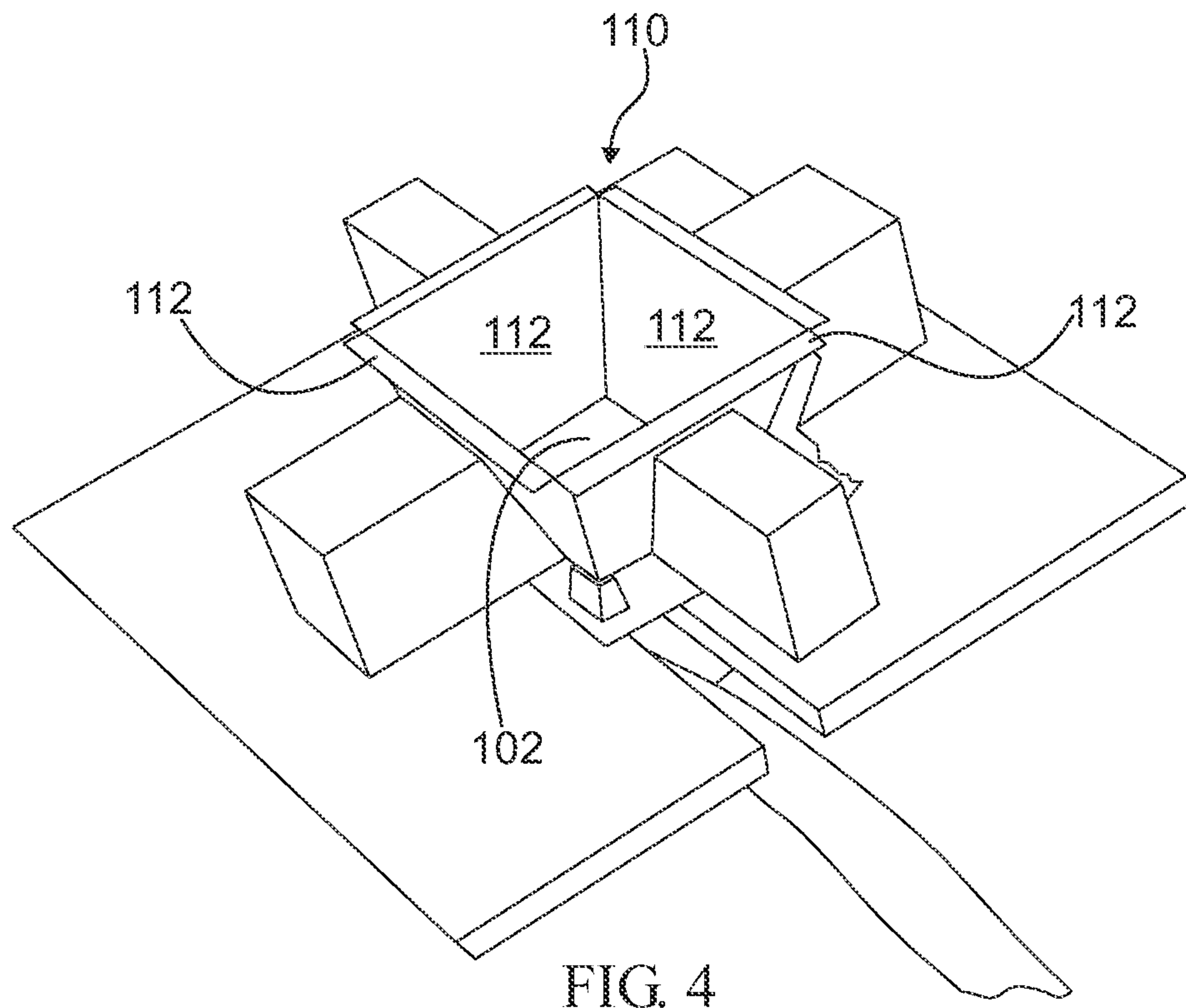


FIG. 5

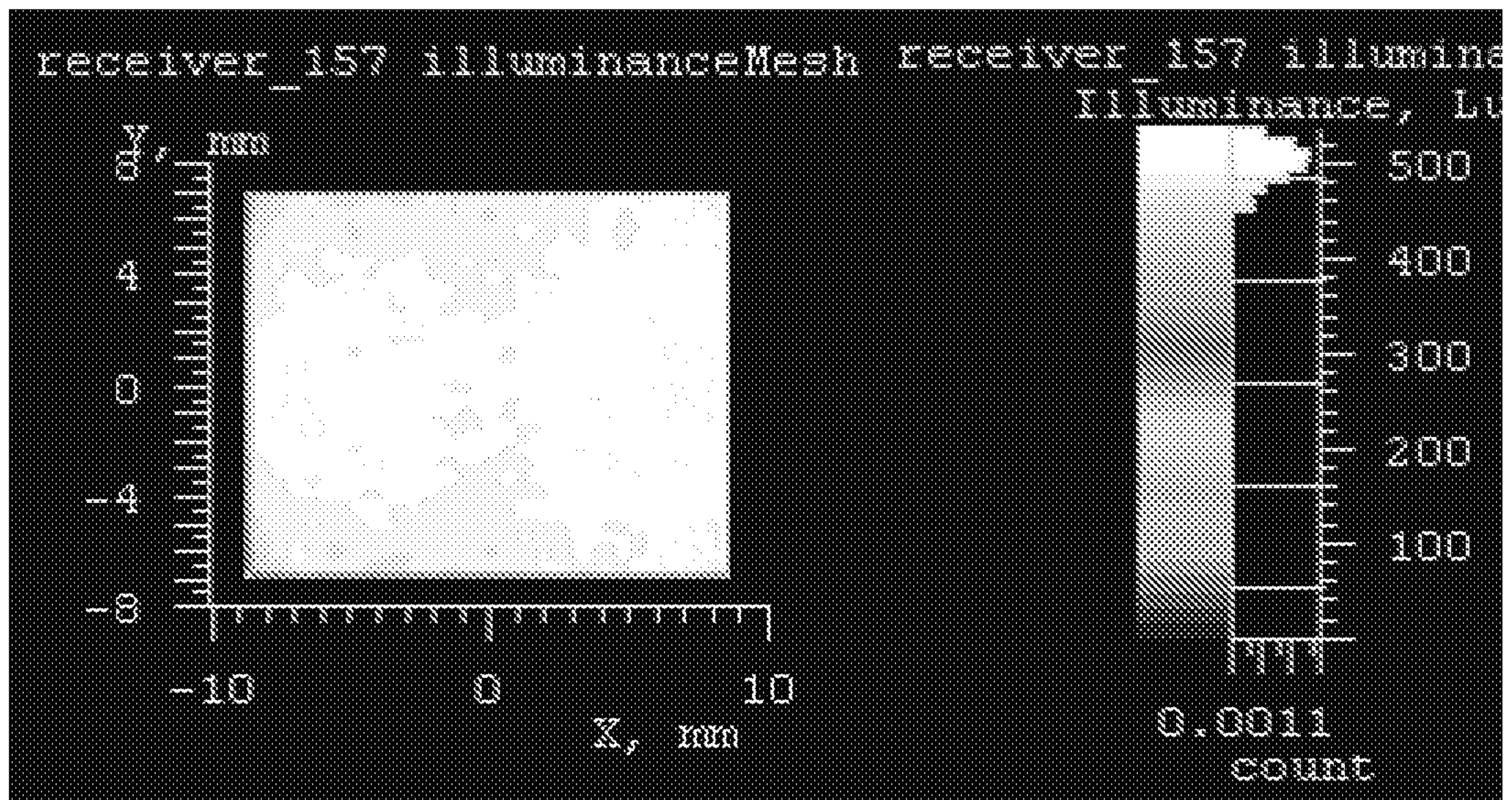


FIG. 6A

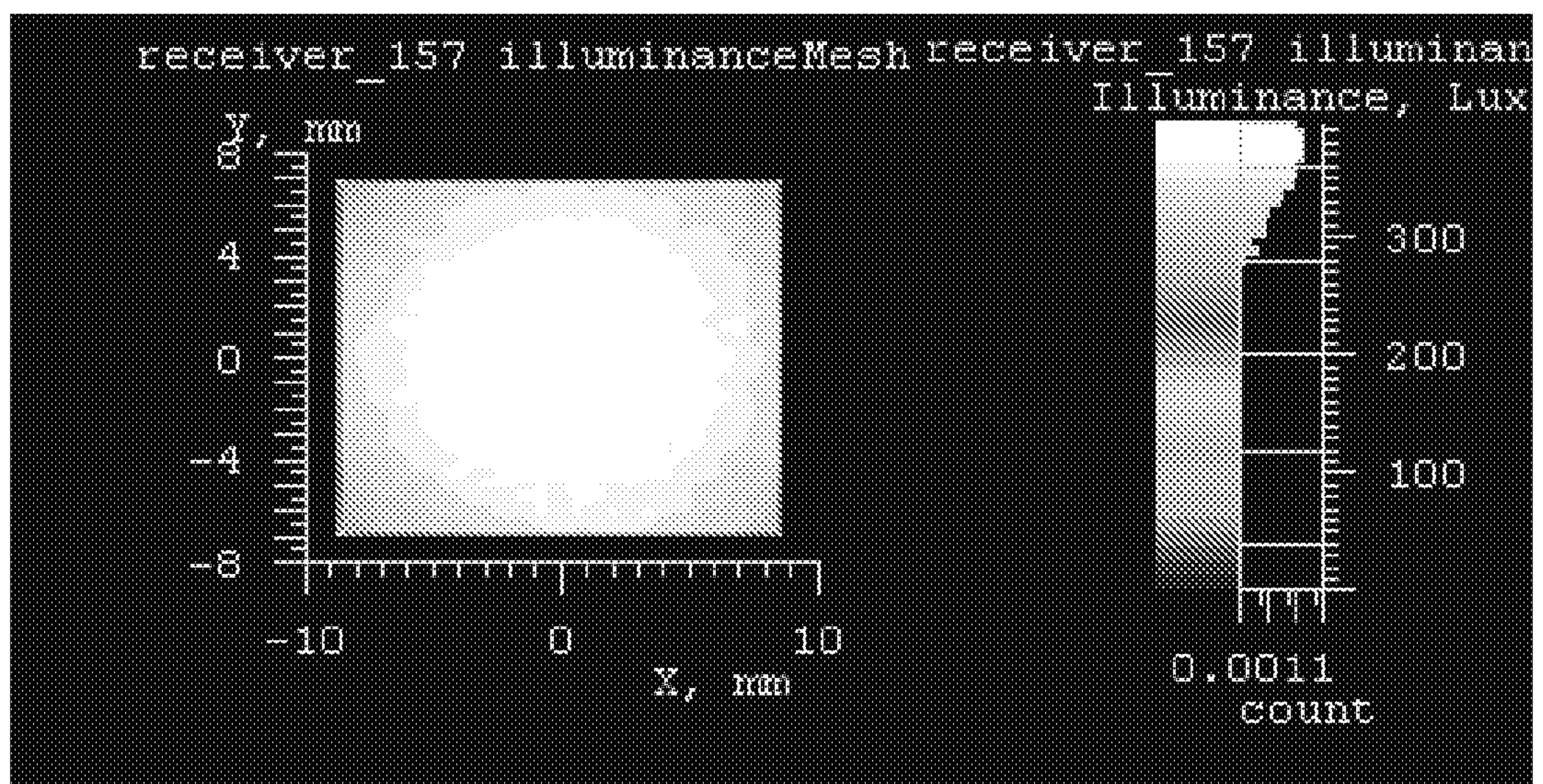
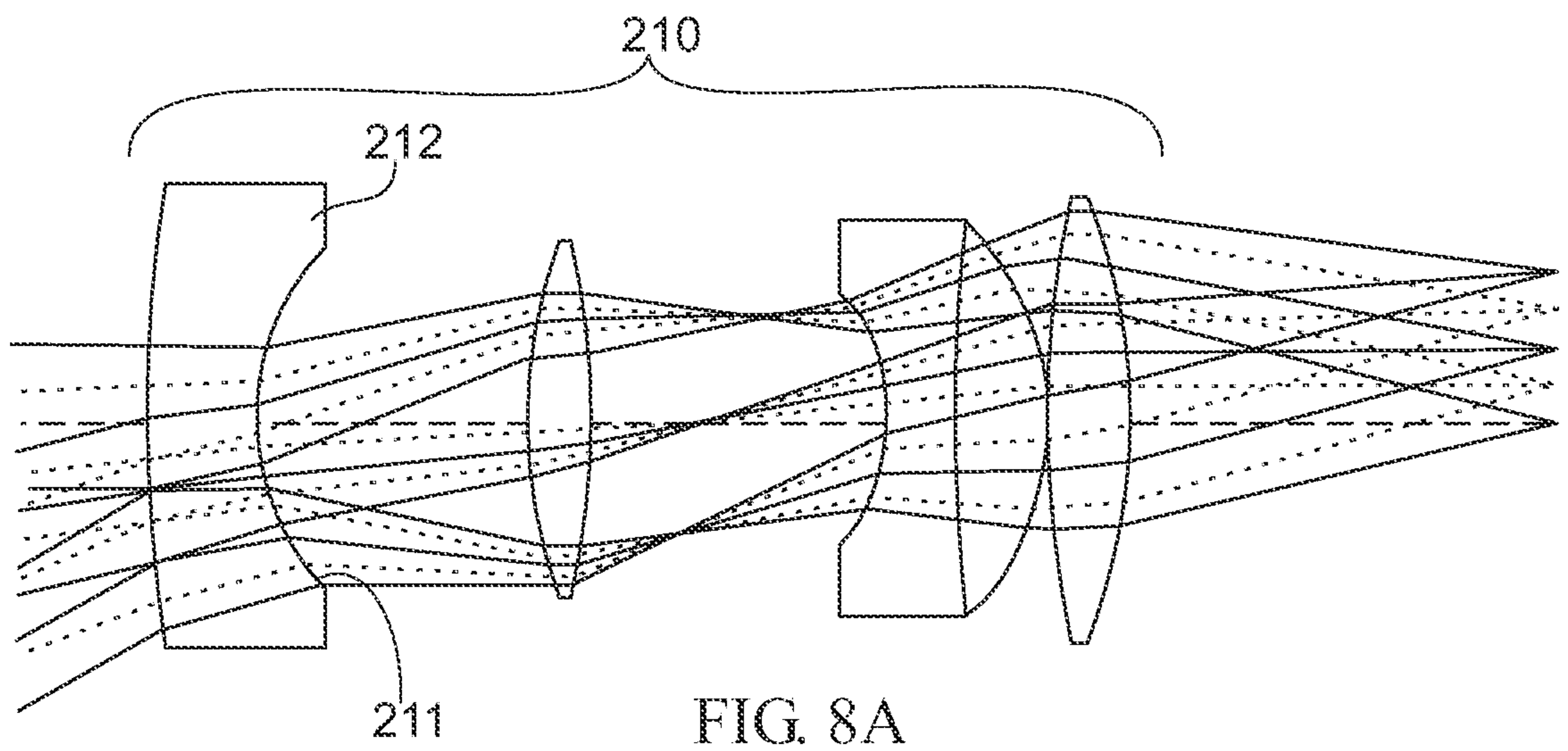
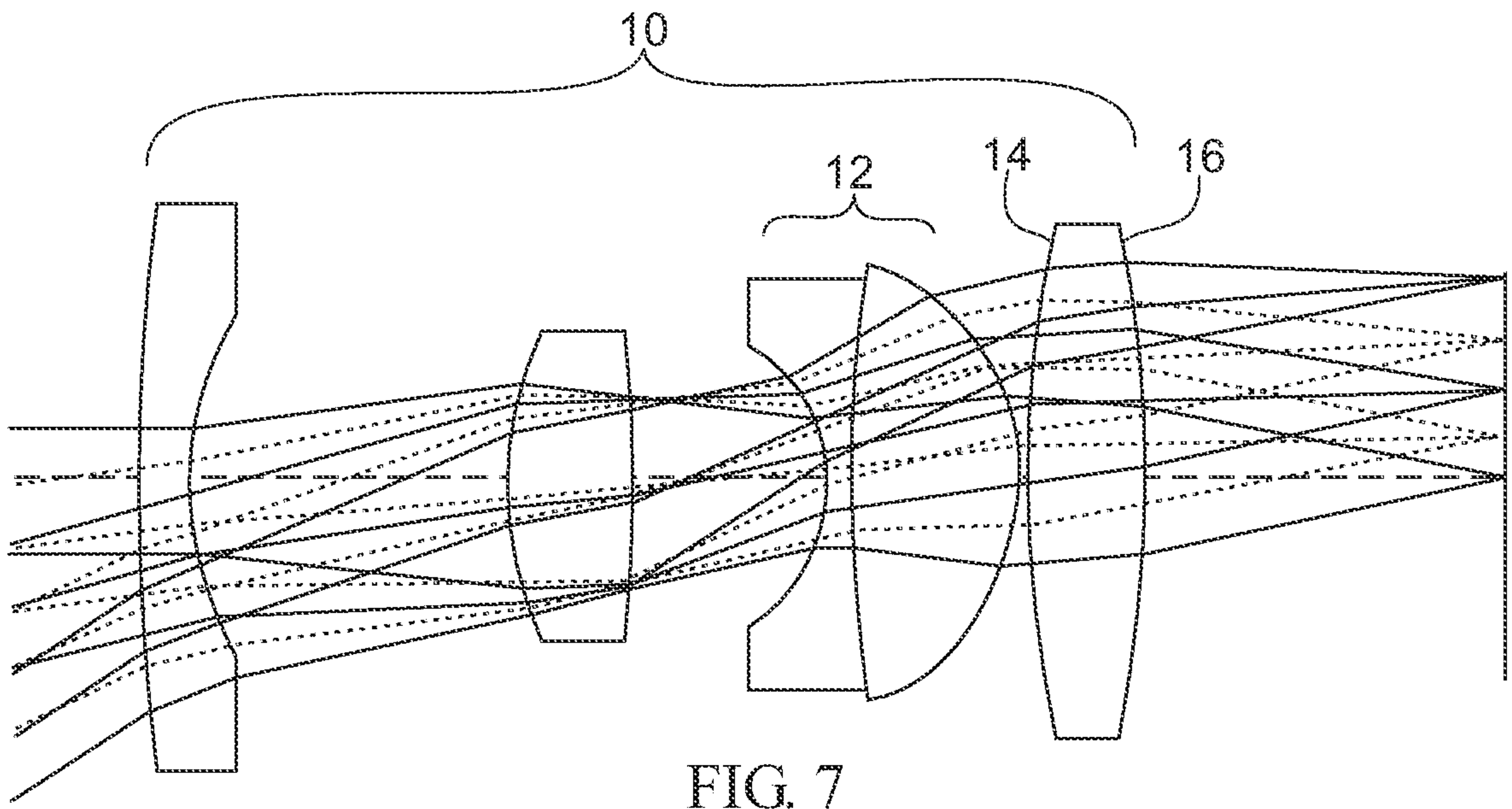


FIG. 6B



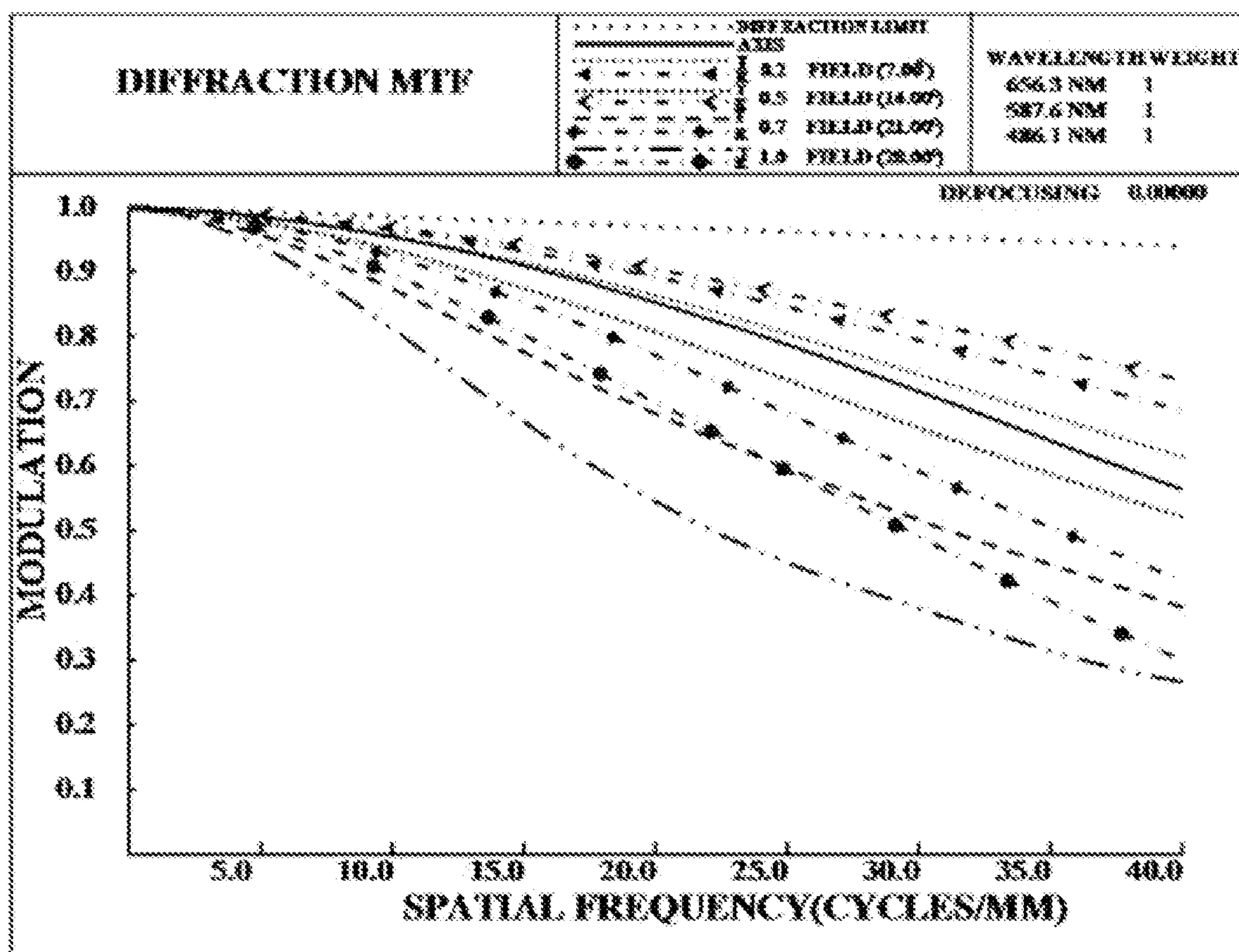


FIG. 8B

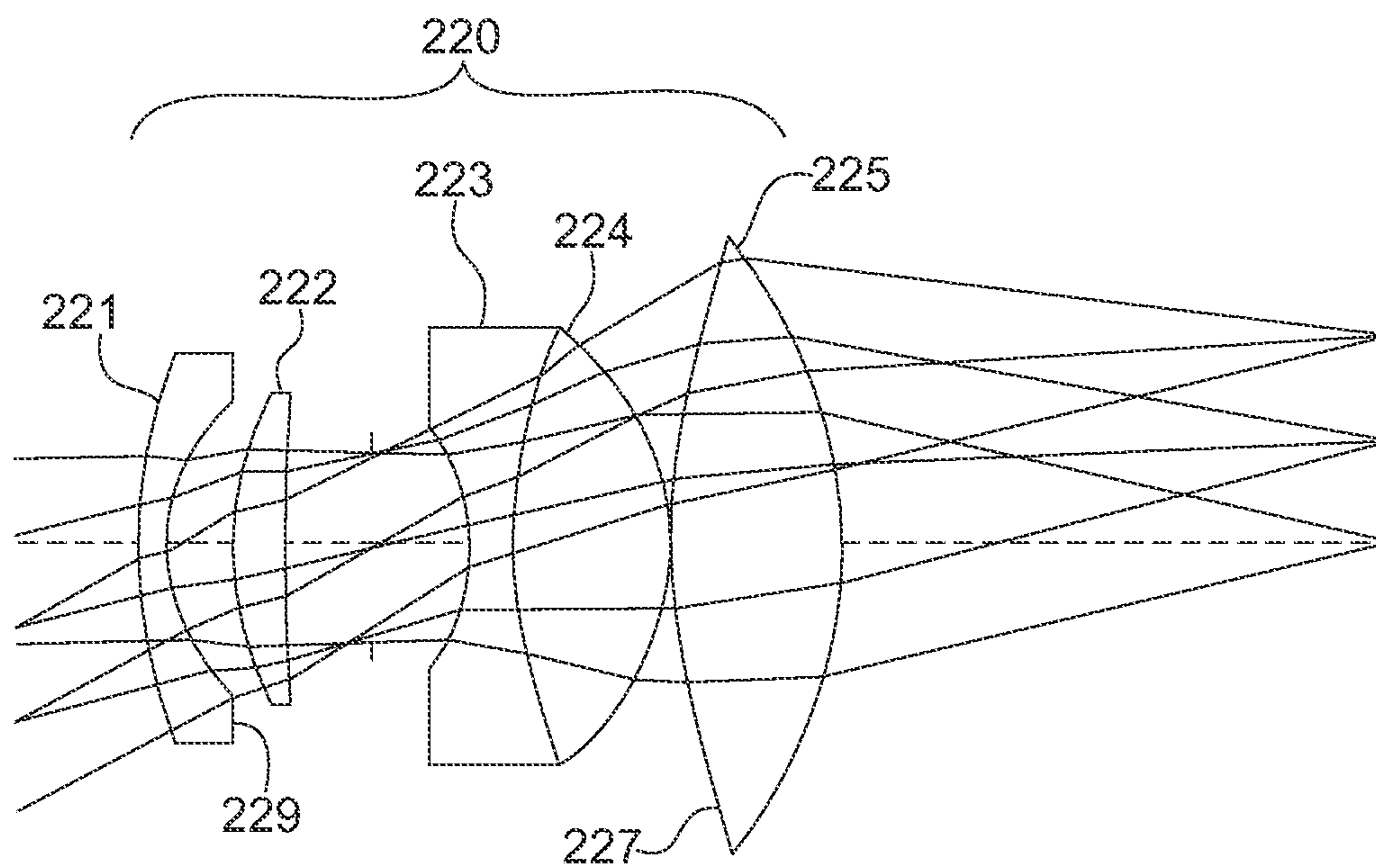


FIG. 9A

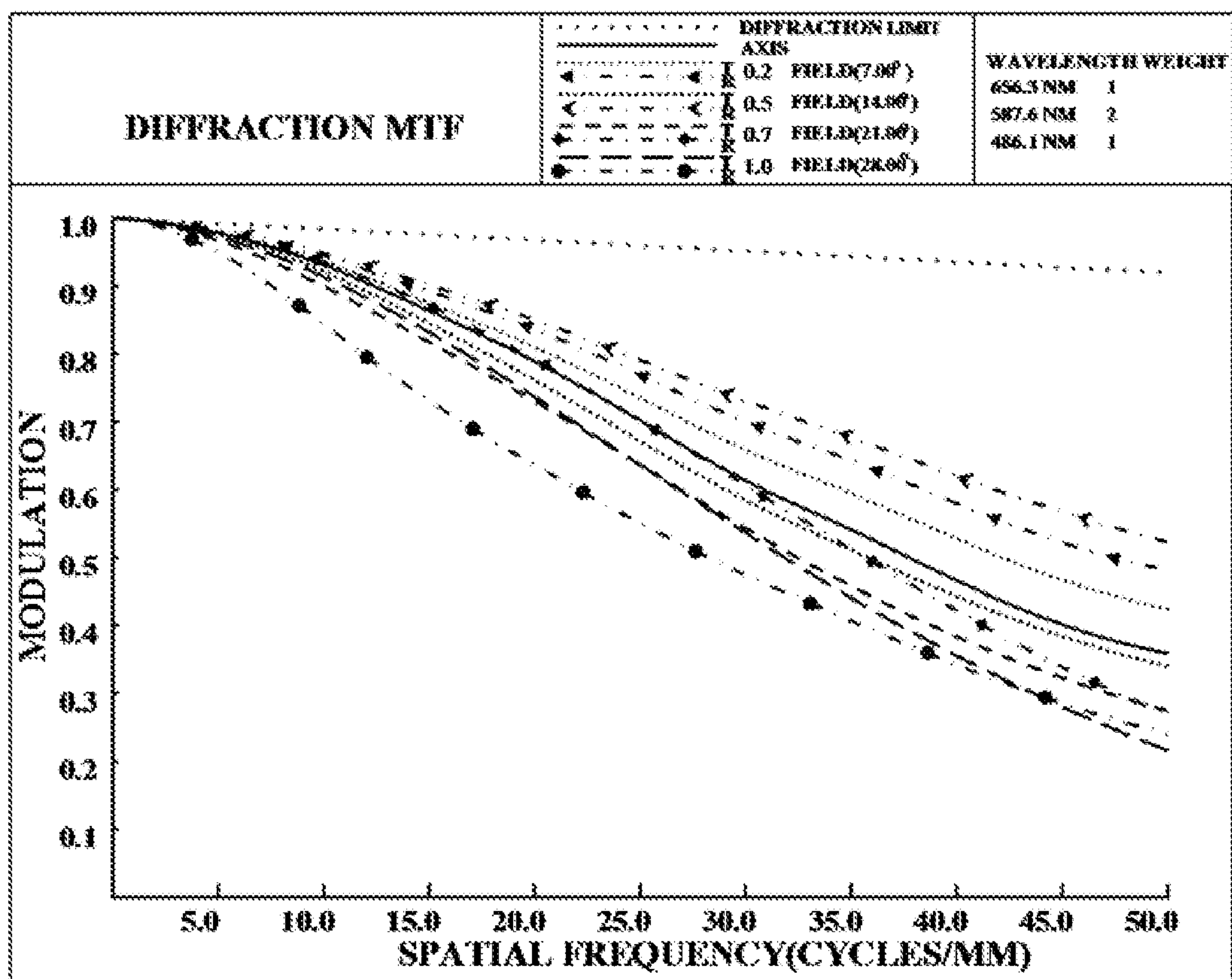


FIG. 9B

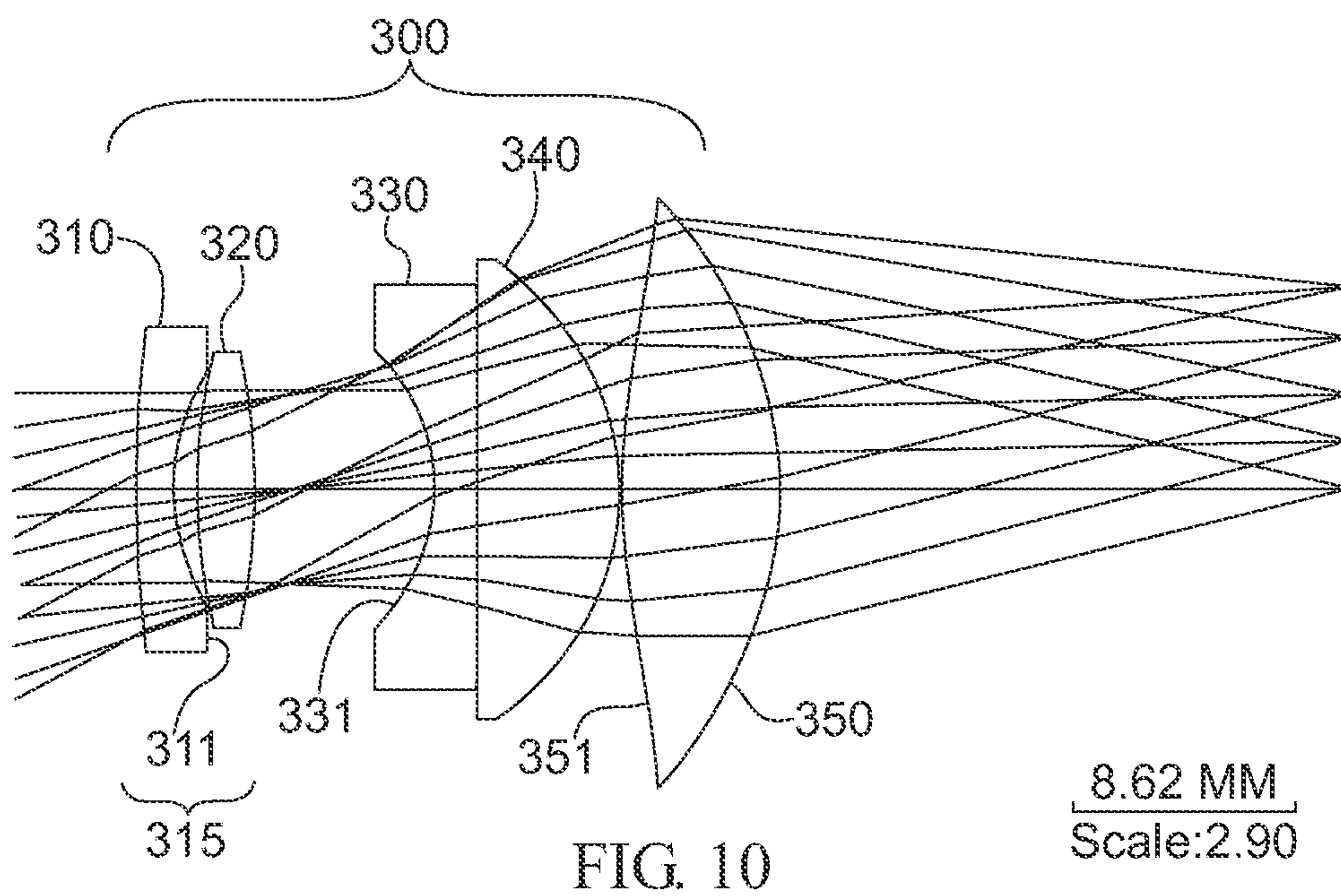


FIG. 10

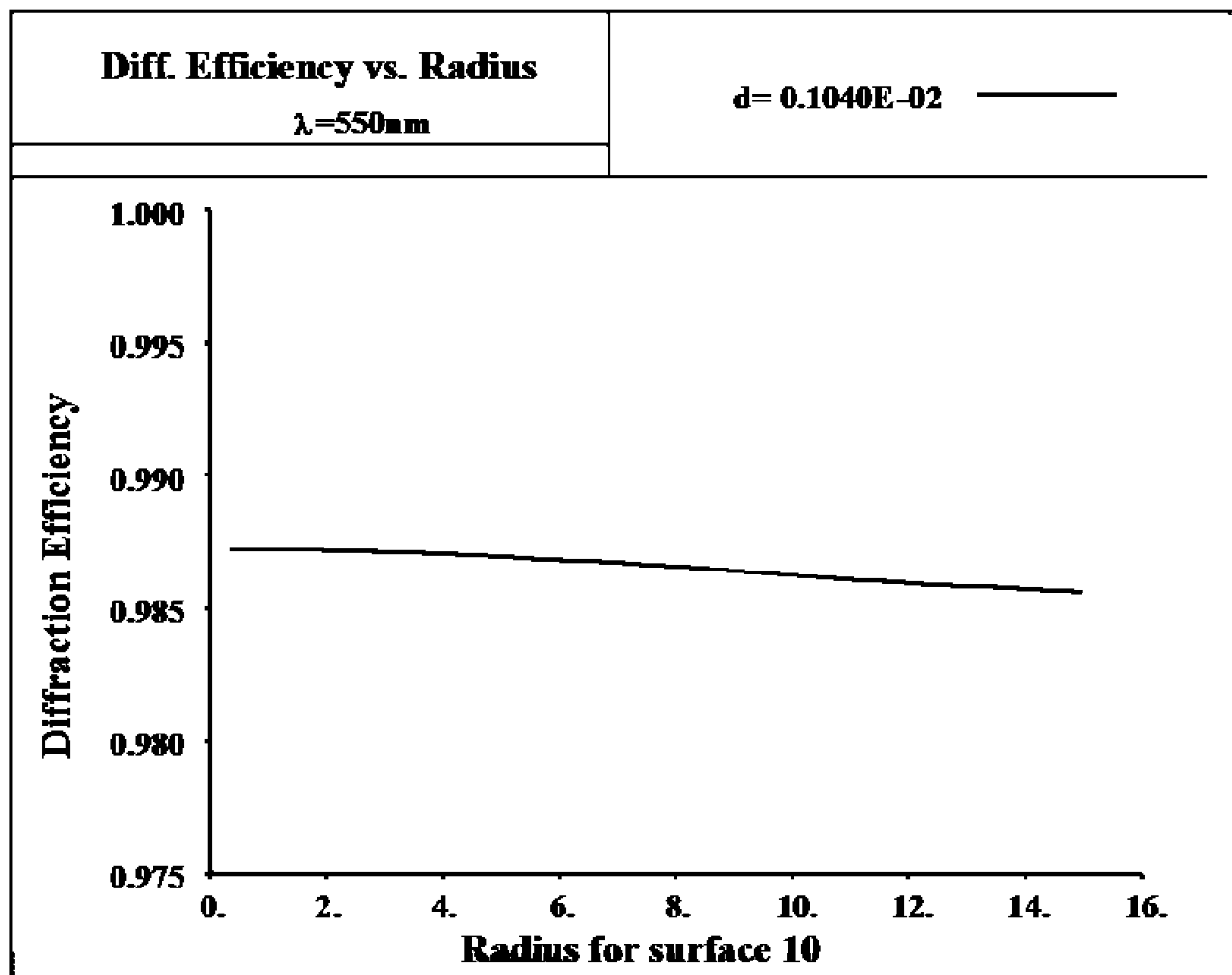


FIG. 11A

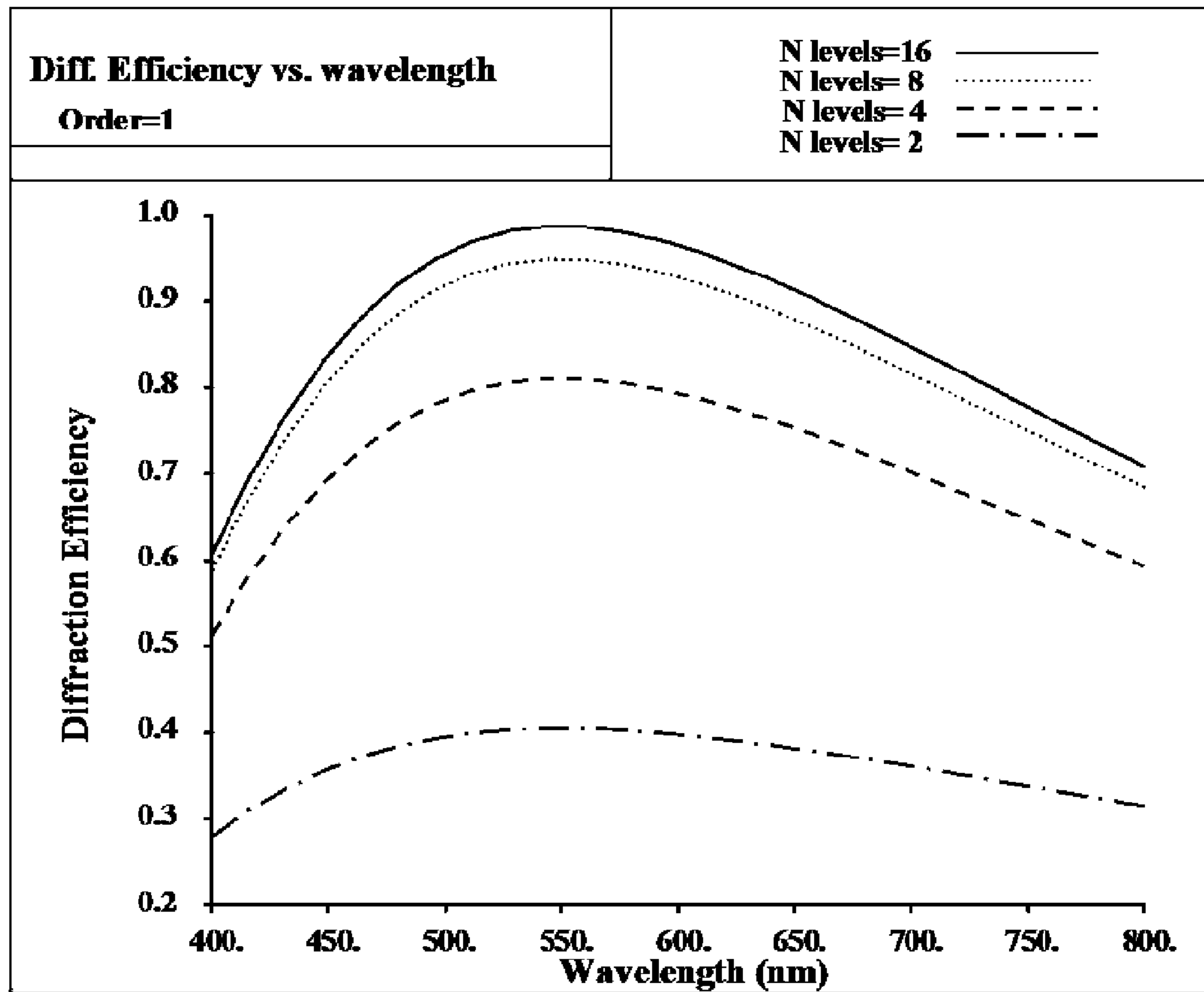


FIG. 11B

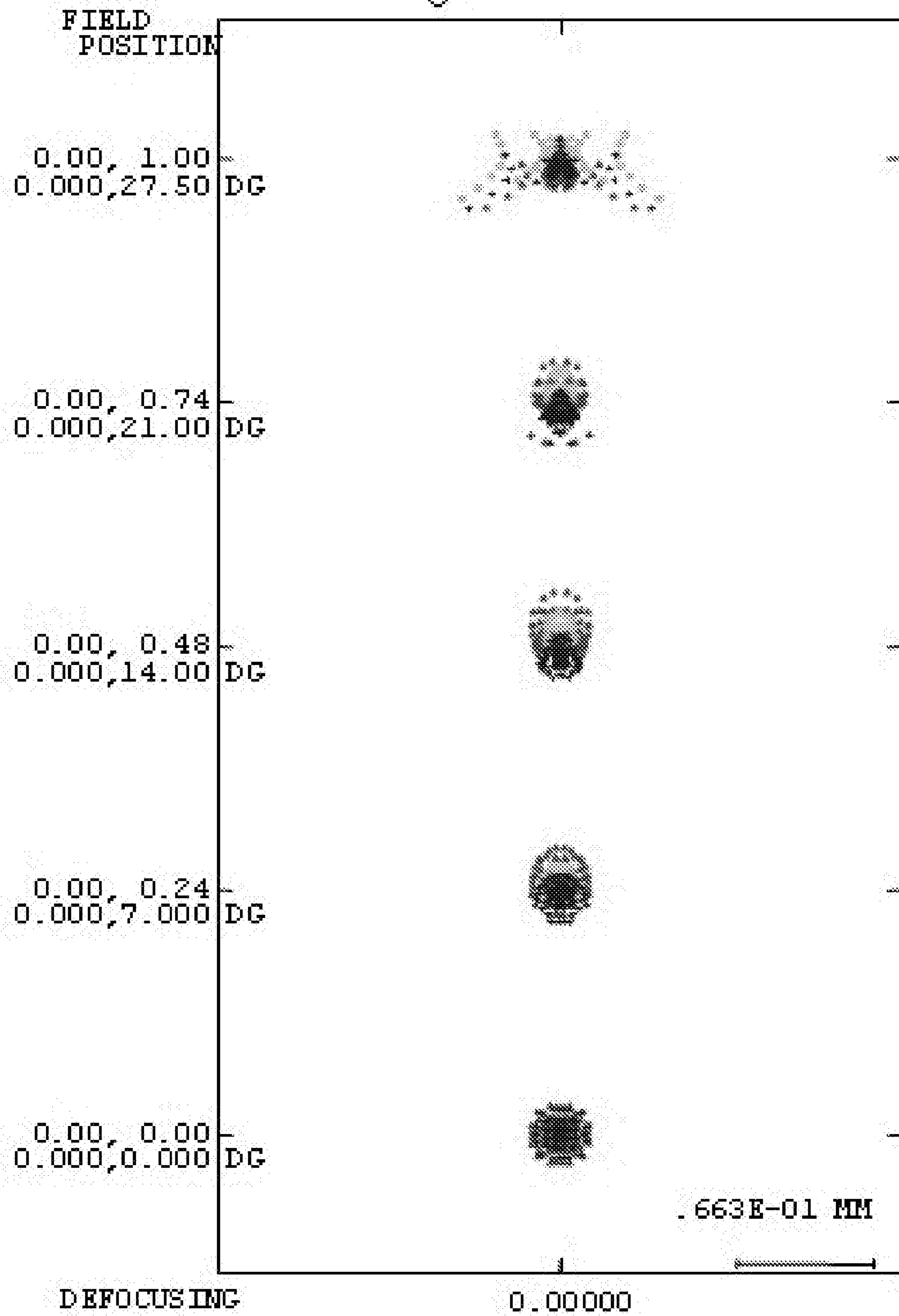


FIG. 12A

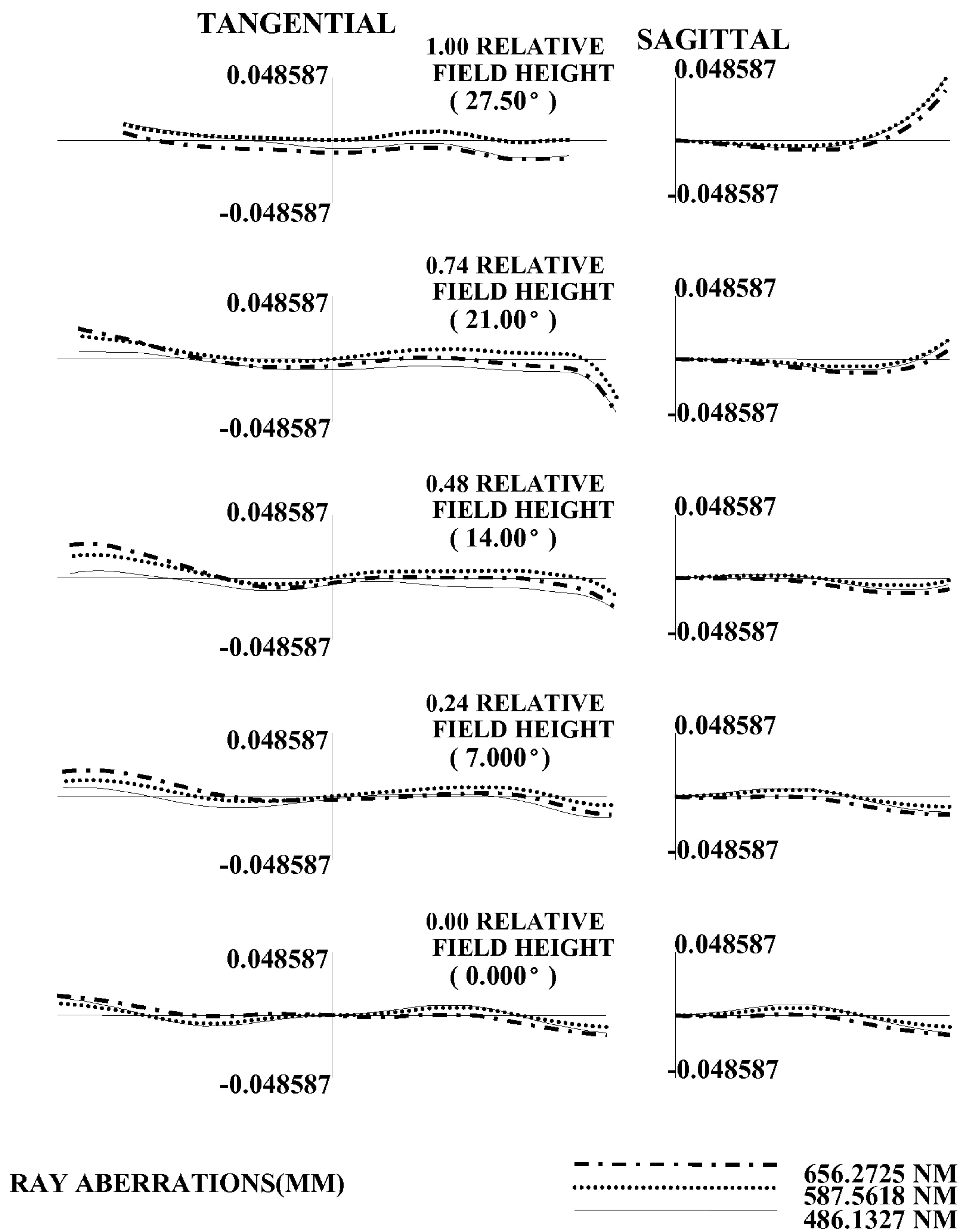


FIG. 12B

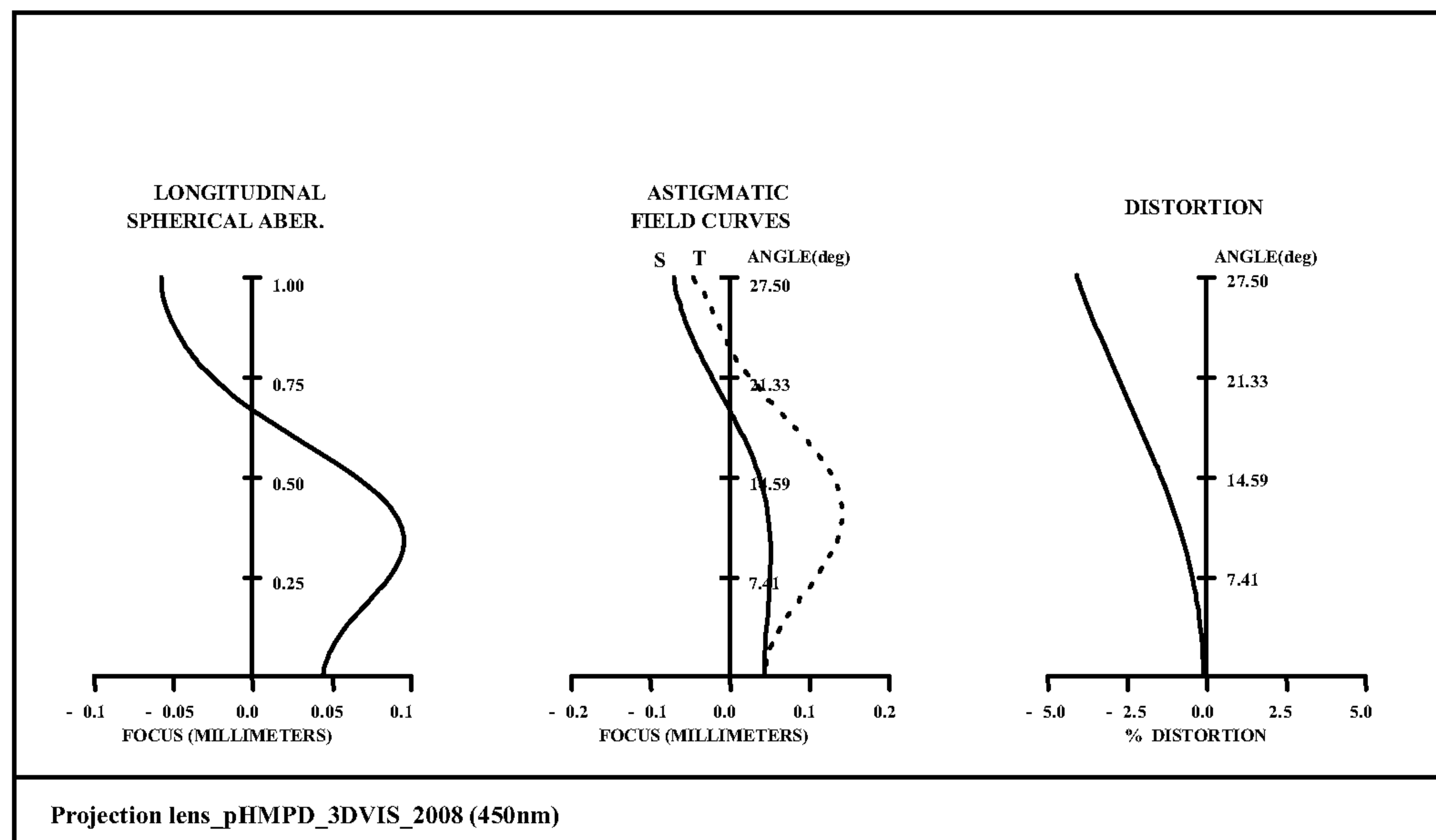


FIG. 12C

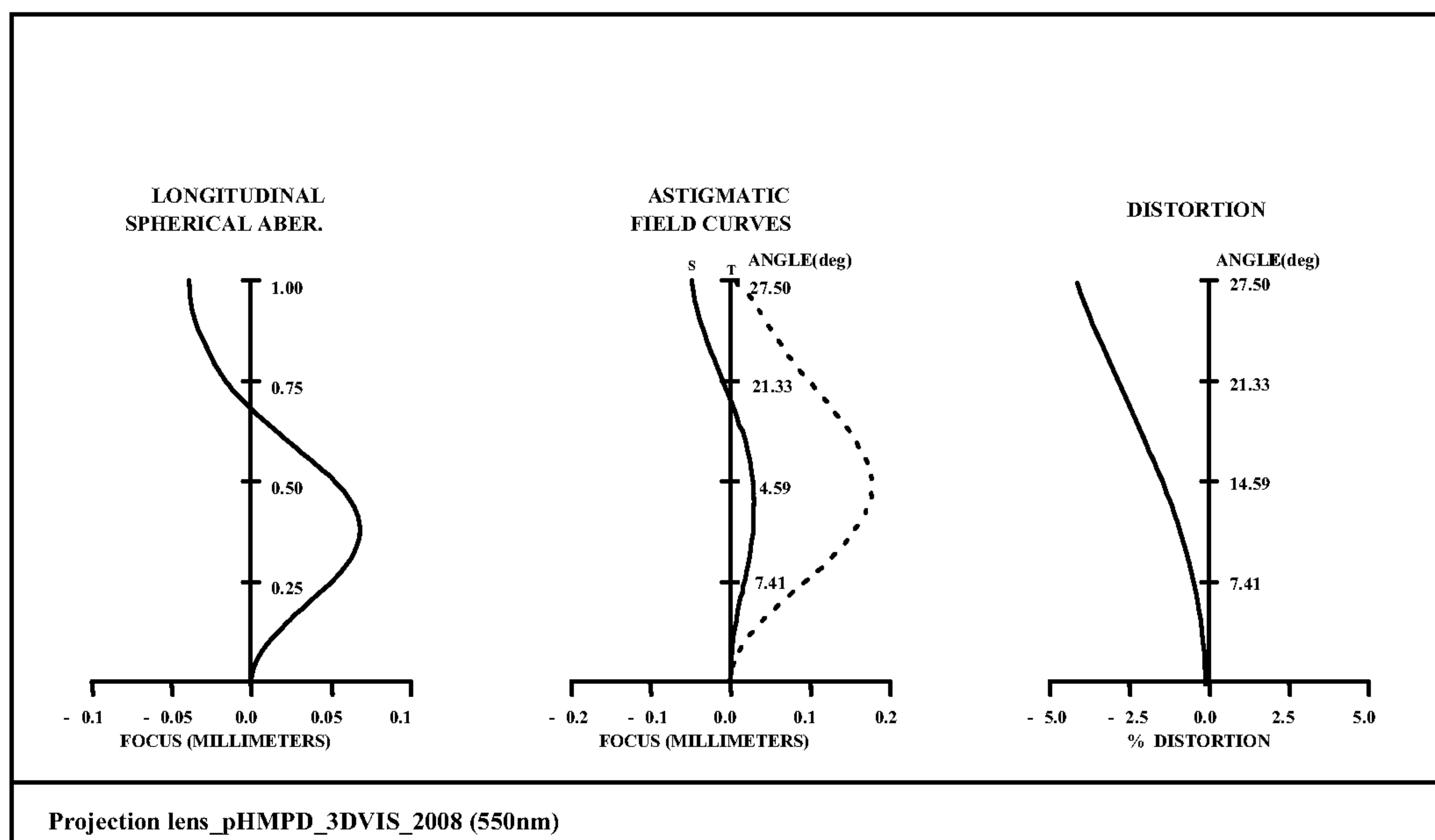


FIG. 12D

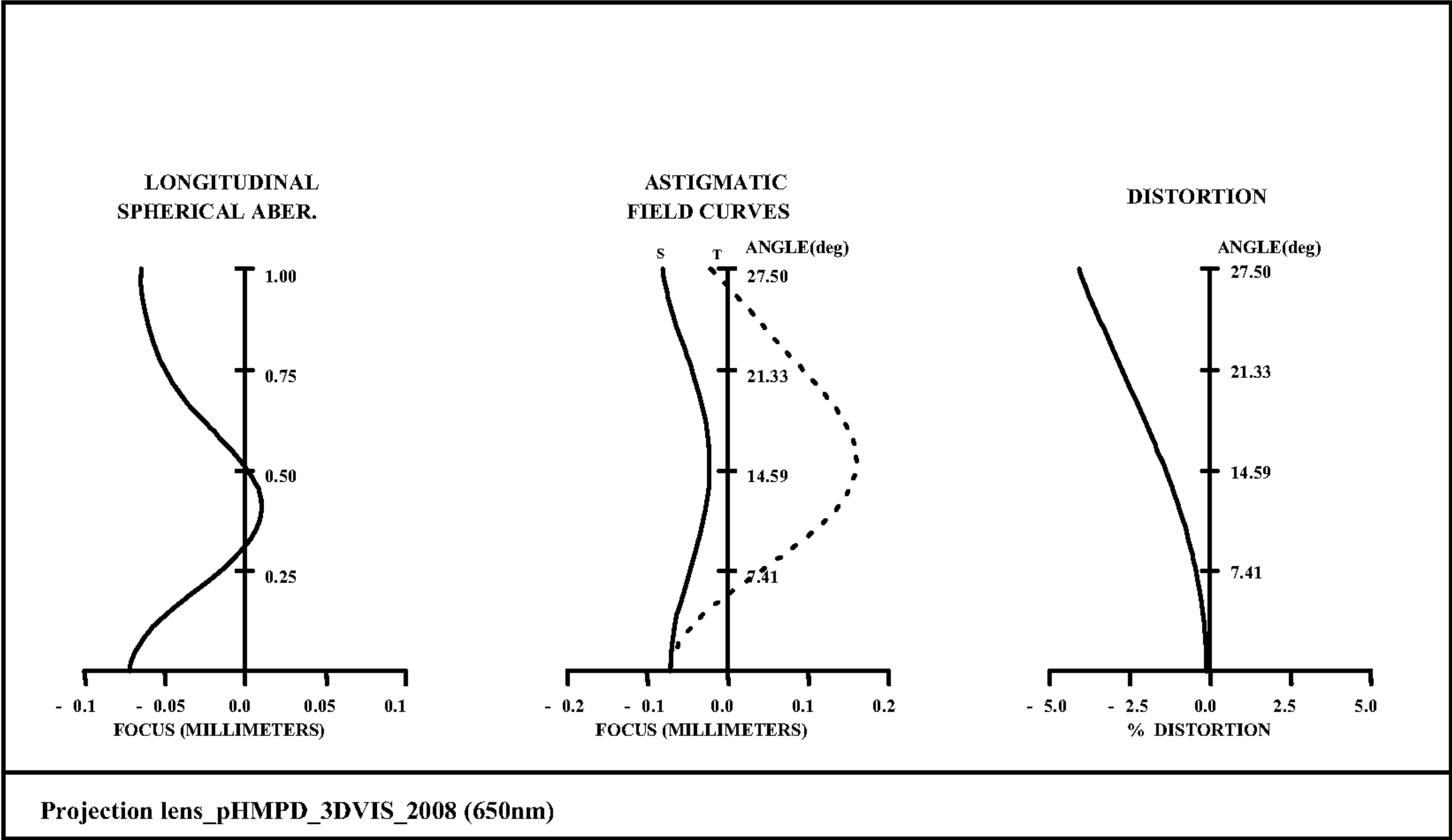


FIG. 12E

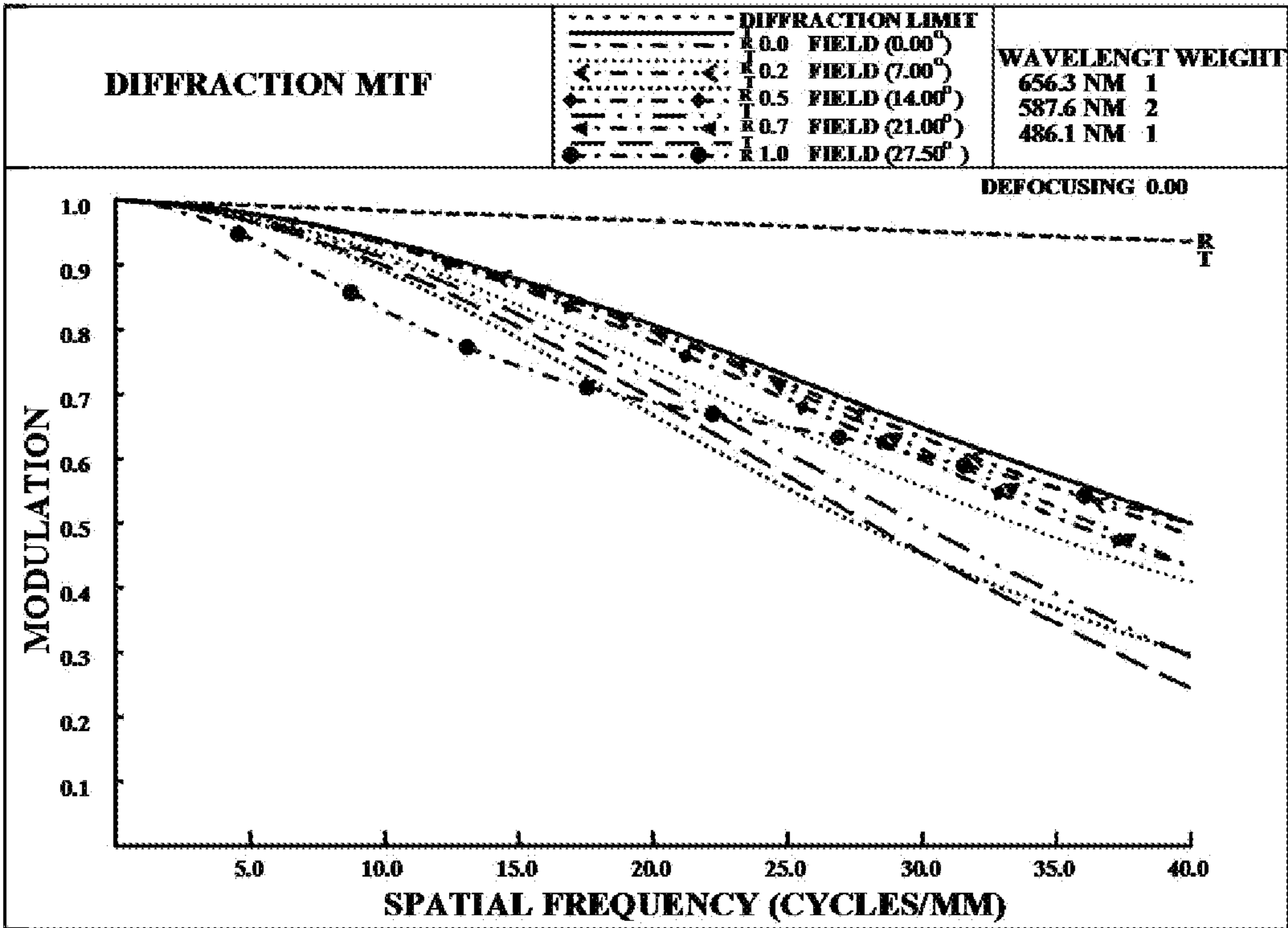


FIG. 12F

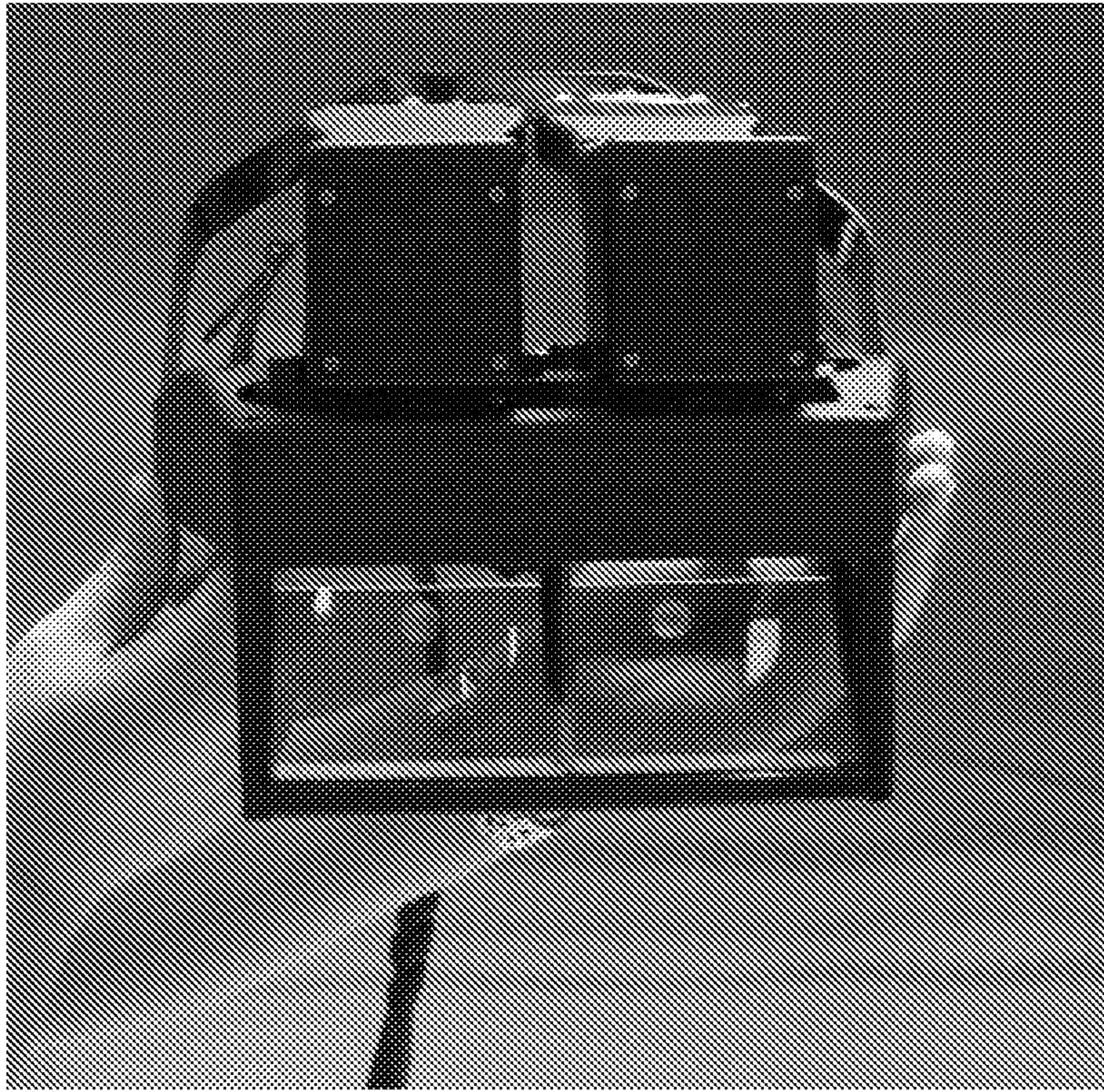


FIG. 13A

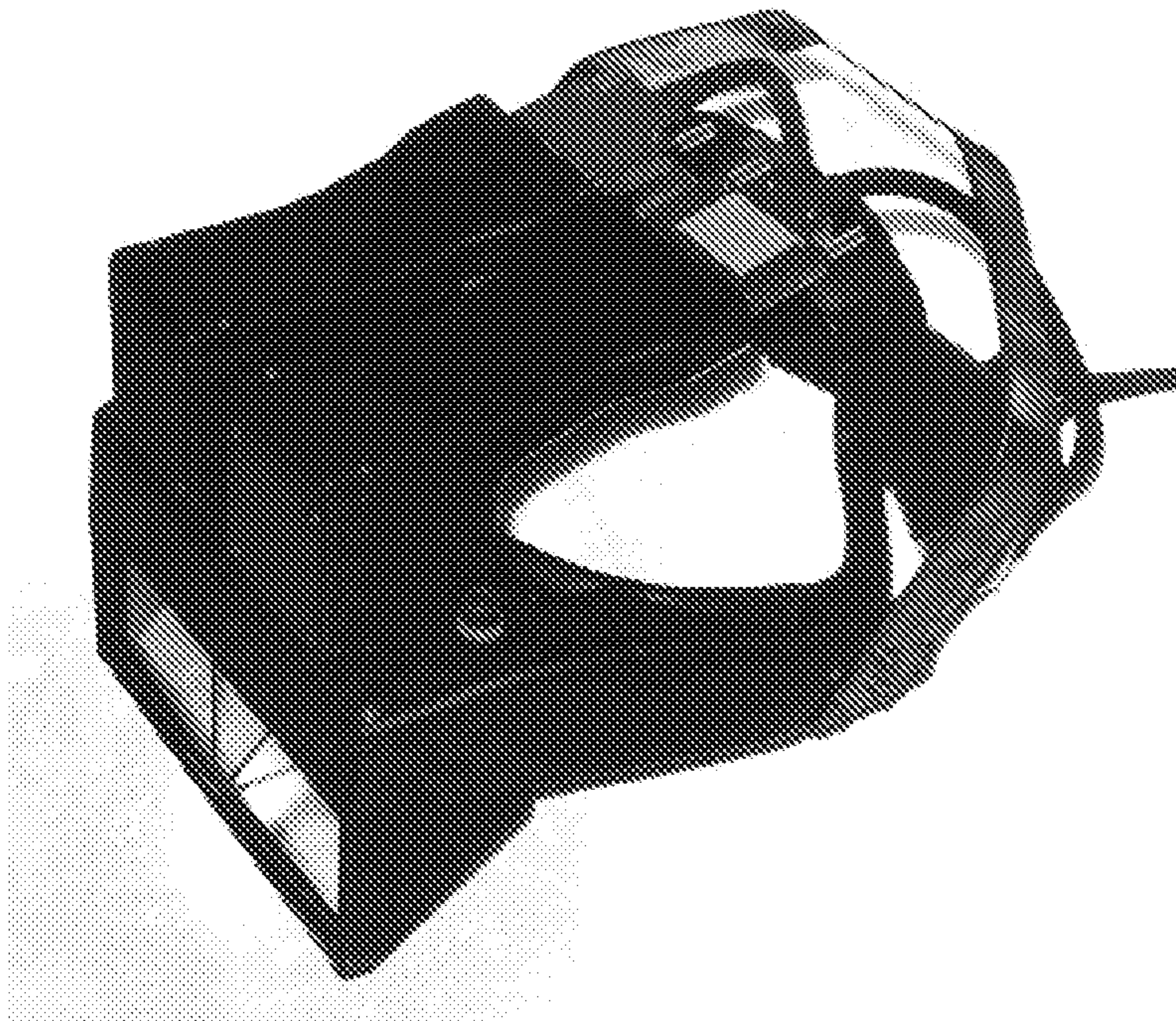


FIG. 13B

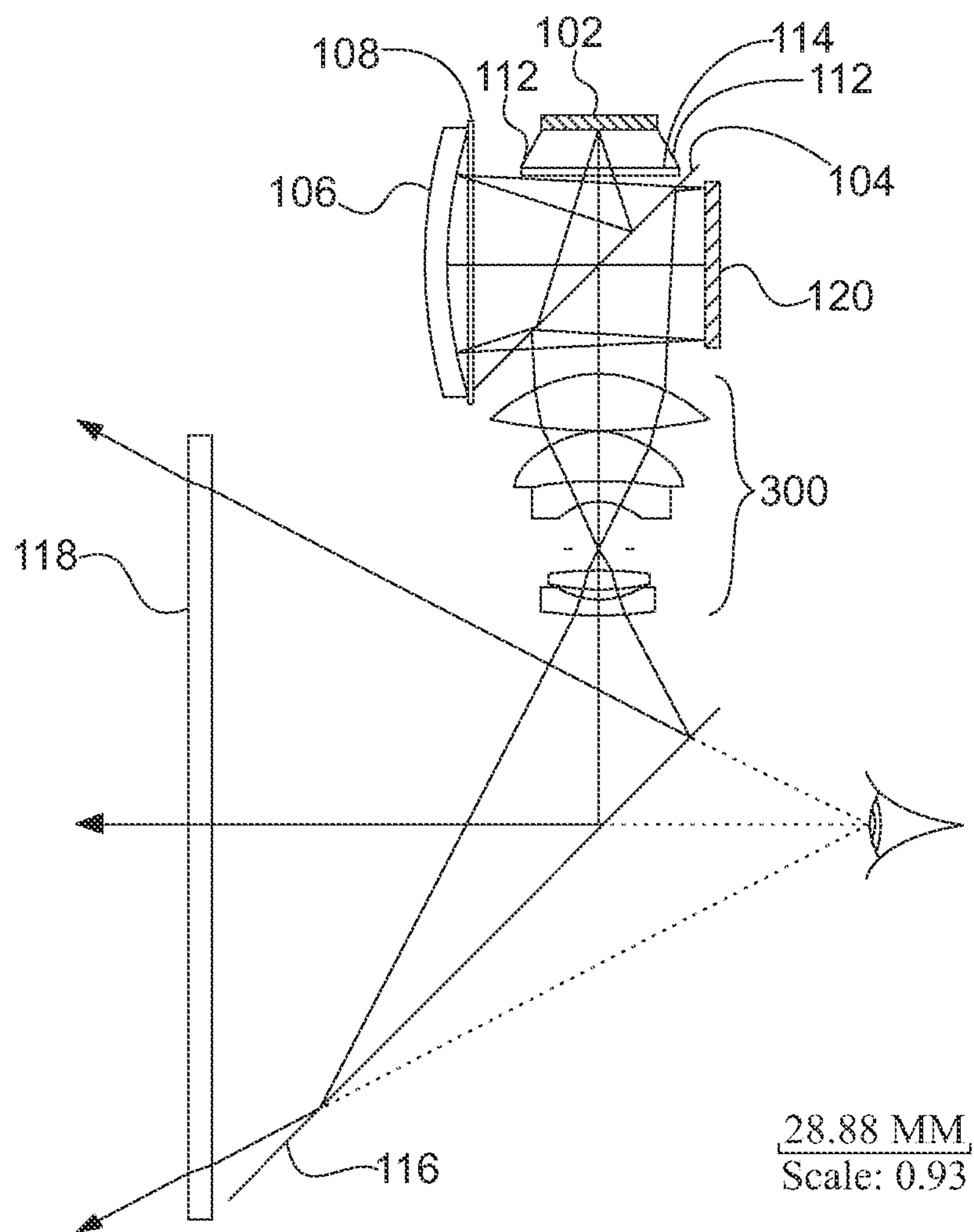


FIG. 14

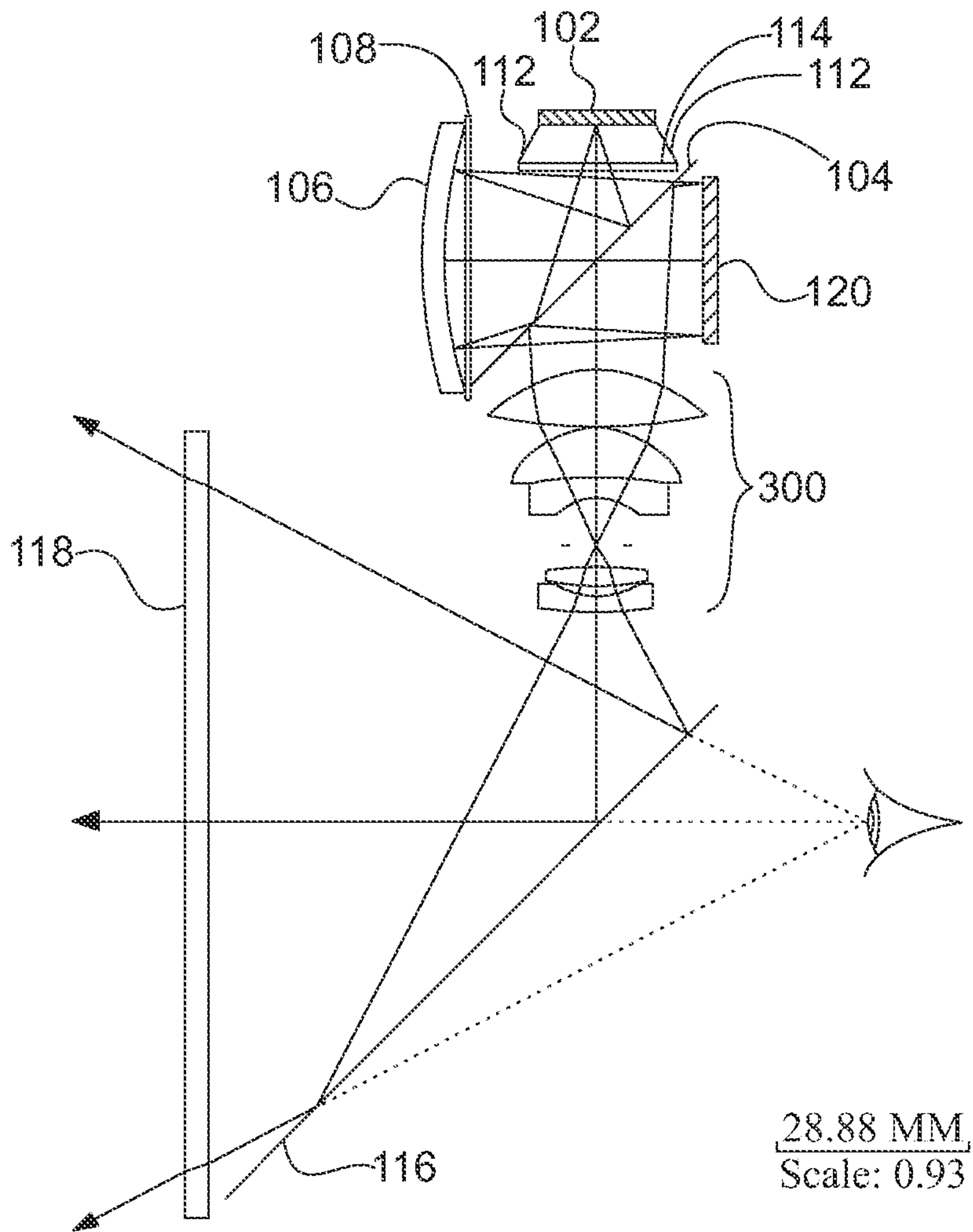


FIG. 14