PCT

WORLD INTELLECTUAL PROPE
International Bu

INTERNATIONAL APPLICATION PUBLISHED UNDER

WO 9605534A1

(51) International Patent Classification 6 :
G02B 27/28, H04N 9/31

A1

(11) International Publication Number: WO 96/05534

(43) International Publication Date: 22 February 1996 (22.02.96)

(21) International Application Number: PCT/IB95/00612

(22) International Filing Date: 4 August 1995 (04.08.95)

(30) Priority Data:
94202287.2 9 August 1994 (09.08.94) EP
(34) Countries for which the regional or international application was filed: AT et al.

(71) Applicant: PHILIPS ELECTRONICS N.V. [NL/NL]; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL).

(71) Applicant *(for SE only)*: PHILIPS NORDEN AB [SE/SE]; Kottbygatan 5, Kista, S-164 85 Stockholm (SE).

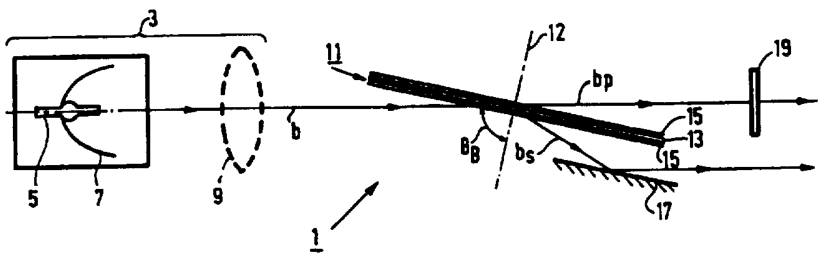
(72) Inventors: STROOMER, Martinus, Victor, Christiaan; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL). DE VAAN, Adrianus, Johannes, Stephanus, Maria; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL). WORTEL, Franciscus, Johannes, Maria; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL).

(74) Agent: FAESSEN, Louis, Marie, Hubertus; Internationaal Octrooibureau B.V., P.O. Box 220, NL-5600 AE Eindhoven (NL).

(81) Designated States: CN, JP, KR, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: ILLUMINATION SYSTEM FOR SUPPLYING A POLARIZED RADIATION BEAM, AND IMAGE PROJECTION DEVICE COMPRISING SUCH AN ILLUMINATION SYSTEM



(57) Abstract

The invention relates to an illumination system (1) for supplying a polarized radiation beam. To this end, the illumination system (1) successively comprises a radiation source unit (3) for supplying an illumination beam, a polarizing element (11) for splitting the radiation beam into two mutually perpendicularly and linearly polarized sub-beams and a polarization-rotating element (19) in one of the sub-beams. The polarizing element (11) is constituted by at least one optical transparent plate (13) having a refractive index n_0 with a first face and a second face, while at least one of these faces is provided with an optically thin layer (15) having a refractive index n_1 which is larger than n_0. A reflector (17) for reflecting this sub-beam in the same direction of propagation as that of the other sub-beam is arranged in the light path of at least one of the sub-beams. The chief ray of the beam incident on the plate (13), which beam has a narrow divergence, and the normal (12) on the plate (13) enclose an angle which is substantially equal to the Brewster angle which applies to the transition between the optically thin layer and a medium surrounding the polarizing element (11).

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria
AU	Australia
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
BY	Belarus
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CN	China
CS	Czechoslovakia
CZ	Czech Republic
DE	Germany
DK	Denmark
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgystan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakhstan
LI	Liechtenstein
LK	Sri Lanka
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SI	Slovenia
SK	Slovakia
SN	Senegal
TD	Chad
TG	Togo
TJ	Tajikistan
TT	Trinidad and Tobago
UA	Ukraine
US	United States of America
UZ	Uzbekistan
VN	Viet Nam

Illumination system for supplying a polarized radiation beam, and image projection device comprising such an illumination system.

The invention relates to an illumination system for supplying a polarized radiation beam, successively comprising a radiation source unit with a radiation source for supplying radiation and an optical system for concentrating the radiation to a beam, a polarization separator element for splitting the radiation beam into two linearly polarized sub-beams having mutually perpendicular directions of polarization, and a polarization-rotating element in one of the sub-beams.

The invention also relates to an image projection device comprising such an illumination system.

An illumination system of the type described in the opening paragraph is known from United States Patent US-A 5,184,248. The illumination system described in this Patent comprises a polarizing beam splitter which, in combination with a polarization-rotating element, substantially completely converts the unpolarized radiation beam from the radiation source into a radiation beam having a single linear direction of polarization. The beam splitter comprises two glass prisms between which a layer of birefringent material is present as a polarization-separating layer. The extraordinary refractive index of the birefringent material is equal to the refractive index of the material of the prisms, while the ordinary refractive index is smaller than that of the material of the prisms. A light beam entering *via* the first prism is split into an extraordinary light beam which does not see any refractive index difference on the birefringent layer and is consequently passed to the second prism, and an ordinary light beam which is totally reflected on the interface between the first prism and the birefringent layer. The two sub-beams thus formed leave the beam splitter as parallel beams which jointly form one beam having a circular cross-section. By providing a 90° polarization-rotating element on one of the exit faces of the beam splitter, it can be ensured that the two sub-beams have the same direction of polarization.

A drawback of the known illumination system is that the beam splitter used is relatively complicated and difficult to manufacture. This is caused by the special shape and high optical quality of the two glass bodies and by providing the polarization-separating layer between these bodies. Since a relatively high light intensity is desired in an image projection device and, consequently, the radiation source should be relatively powerful, there is a relatively great risk that the polarization-separating layer is damaged due to the high light intensity.

It is an object of the invention to provide an illumination system in which substantially the complete radiation beam from the source is converted into a beam having the same direction of polarization and in which the desired quantity of intensity does not affect the polarizing element. Moreover, this illumination system can be realised in a relatively simple manner.

To this end, the illumination system according to the invention is characterized in that the polarization separator comprises at least one polarizing element which is constituted by an optical transparent plate having a refractive index n_0 with a first face and a second face, while an optically thin layer having a refractive index n_1 which is larger than n_0 is provided on at least one of said faces, in that a reflector is arranged in the light path of at least one of the sub-beams for reflecting said sub-beam in the same direction of propagation as that of the other sub-beam, in that the radiation source unit supplies a radiation beam having a narrow divergence, and in that the chief ray of said beam and the normal on the plate enclose an angle Θ_B which is substantially equal to the Brewster angle which applies to the transition between the optically thin layer and a medium surrounding the polarization separator.

An optically transparent plate, at least one side of which is provided with a thin layer having a high refractive index is used as a polarizing element. When the chief ray of an unpolarized beam is incident on such a plate at an angle for which there is an optimum separation between the two mutually perpendicular, linearly polarized sub-beams, the p-polarized beam component and the s-polarized beam component, the one beam component (p) will be passed, whereas the other beam component (s) will be reflected. This angle is equal to the Brewster angle which applies to the transition between the optically thin layer and the medium surrounding the polarizing element, which medium is generally air.

A beam having a narrow divergence is understood to mean a beam whose border rays enclose an angle of substantially 5° maximum. At such a small beam divergence, an efficient polarization conversion is realised for the entire beam, because, due to the small angular deviation of the border rays with respect to the chief ray, not only the chief ray of the beam but also the border rays will be optimally subject to the effect of the polarizing element.

Said polarizing element is known *per se*, for example from the article "Polarizing beam splitters for infrared and millimeter waves using single-layer-coated dielectric slab or unbacked films" by R.M.A. Azzam in Applied Optics, vol. 25, no. 23, December 1986.

An advantage of the polarizing element used is that the support of the layers is an optically transparent plate on which a thin layer can be provided in a simple manner, for example by means of vapour deposition or immersion. Materials which are suitable for these layers are, for example titanium dioxide, cerium dioxide or zinc sulphide, which materials are resistant to high temperatures.

It is to be noted that an image projection device in which such a polarizing element is used as a prepolarizer is known from European Patent Application EP-A 0 518 111. However, in the device described in this Application only one of the two mutually perpendicularly polarized sub-beams is used for the image formation. In this manner, half of the intensity of the radiation beam supplied by the radiation source unit is thus lost. Moreover, no special measures are taken or suggested in said Patent Application as regards the divergence of the radiation beam, so that the polarization separation is not optimal for the entire incident radiation beam and, consequently, there will be loss of light.

In the illumination system according to the invention the beam component reflected by the reflector out of the beam from the radiation source unit is reflected in the same direction of propagation as that of the other beam component.

The polarization-rotating element ensures that the two components have the same direction of polarization so that substantially the entire beam from the radiation source unit is converted into a beam having the same linear state of polarization.

A preferred embodiment of the illumination system according to the invention is characterized in that the illumination system comprises at least two polarization separators whose normal on each polarization separator and the chief ray of the beam incident on the relevant polarization separator enclose an angle θ_B which is substantially equal to the Brewster angle which applies to the transition between the optically thin layer and the medium surrounding the polarization separator, the two polarization separators mutually enclosing an angle $\theta' = 180° - \theta_B$.

In this way, a more compact embodiment of the illumination system is obtained. A further advantage is that the chief ray of the polarized beam and the chief ray of the beam to be polarized are substantially in alignment, so that this embodiment of the illumination system can replace illumination systems in existing image projection devices without substantial adaptations.

An embodiment of the illumination system according to the invention is characterized in that the radiation source unit has a low throughput.

A beam having a narrow divergence is supplied, *inter alia*, by an illumination system having a low throughput. The term "throughput" characterizes the power of an optical system to transport radiation energy. This power is given by $E = A.\Omega$ in which A is the radiating surface and Ω is the spatial angle through which light is emitted, both measured at the location of the entrance aperture of the system in the centre of this aperture. In an optical system the throughput further down the system cannot be enlarged anymore but only reduced by blocking radiation, so that radiation will then be lost.

In image projection devices in which liquid crystal display panels are used in transmission, only 10% of the radiation incident on the panel is passed to the projection lens system, when a colour panel is used, and 30% of the radiation incident on a monochrome panel is passed. To have a sufficient light intensity per surface unit on the projection screen so as to reproduce an image having a relatively high brightness, the illumination beam should have a large intensity. Increasing the intensity of the lamp has only a limited advantage. In fact, lamps supplying a higher radiation energy also have a larger radiating surface. Consequently, the exit aperture of the radiation source unit will be larger. A reduction of the exit aperture means that a part of the radiation energy would be lost. It is therefore desirable to capture as much radiation energy from the radiation source as possible and concentrate it to a narrow beam.

The use of a radiation source unit having a low throughput in an optical system has the advantage that further down the system it is not necessary to use expensive optical elements having, for example large numerical apertures or large cross-sections.

A further embodiment of the illumination system according to the invention is characterized in that the radiation source unit comprises a lamp having a short arc length, which lamp is surrounded by a reflector.

A beam having a narrow divergence and an illumination system having a low throughput can be realised, *inter alia*, by making use of a lamp having a short arc length and being surrounded by a reflector.

An example of a suitable lamp is a xenon lamp. However, this lamp has a relatively short lifetime (approximately 350 hours) and may be subject to the risk of explosion. Another suitable lamp is a short-arc metal halide lamp. This lamp also has the drawback of a relatively short lifetime of several hundred hours.

A preferred embodiment of the illumination system according to the invention is characterized in that the radiation source is a high-pressure mercury discharge lamp comprising

a lamp vessel of quartz glass, having a region surrounding a discharge space;

tungsten electrodes arranged in the lamp vessel and separated from each other, which electrodes define a discharge path and are connected to current conductors extending from the lamp vessel to the exterior;

a filling of at least 0.2 mg Hg/mm^3, 10^{-6} - 10^{-4} μmol Hal/mm^3, in which Hal is one of the materials from the group of Cl, Br and I, and

a rare gas in the lamp vessel, while

the discharge space has a spheroidal shape with a dimension S in the direction of the discharge path and is equal to

$S(mm) = e \,.\, D_i$

in which e has a value between 1.0 and 1.8,

$D_i(mm) = f \,.\, [3.2 + 0.011(mm/W) \,.\, P(W)]$

in which D_i is the largest value for the diameter perpendicular to the discharge path,

f has a value between 0.9 and 1.1,

P is the power used at nominal operation, between 70 and 200 W,

the part of the lamp vessel surrounding the discharge space has a convex outer surface which, in a plane in which D_i is located, has a diameter D_o which is given by

$D_o(mm) \geq 3.2 + 0.055(mm/W) \,.\, P(W)$,

the length of the discharge path D_p is between 1.0 and 2.0 mm and the selected halogen is Br.

Said lamp has a short arc length in combination with a lifetime of several thousand hours and may therefore be used to great advantage as a radiation source in an illumination system according to the invention, in which a polarizing element is used which functions optimally when the incident beam has a narrow divergence.

It is to be noted that such a lamp is known *per se* from European Patent Application EP-A 0 576 071 in the name of the Applicant.

The invention further relates to an image projection device comprising an illumination system for supplying a polarized radiation beam, at least one image display panel arranged in the path of this beam for generating an image to be projected, and a projection lens system for projecting the image on a projection screen. This device is characterized in that the illumination system is an illumination system as described hereinbefore.

A preferred embodiment of the image projection device according to the invention is characterized in that an optical integrator is arranged in the light path between the polarizing element and the image display panel.

An optical integrator is known *per se* from, for example United States Patent US-A 5,098,184 in the name of the Applicant. By arranging such an optical integrator in the light path between the polarizing element and the image display panel, *inter alia*, a uniform light distribution across the light beam can be realised so that the homogeneity of the image formed is enhanced.

However, an optical integrator can be used to great advantage in an illumination system according to the invention. Since the linearly polarized beam supplied by the polarizing element consists of the combination of two separate sub-beams, each of which has covered a different path between the radiation source and the location where they are combined to a single beam again, the intensity distribution across the composite beam will not be constant. Due to the presence of the integrator, the intensity is spread across the total beam in such a way that a uniform distribution is obtained at the area of the image display panel, which enhances the homogeneity of the image to be formed.

A further embodiment of the image projection device according to the invention is characterized in that the optical integrator successively comprises a first lens plate provided with a plurality of first lenses which, in a plane perpendicular to the principal axis of the polarized beam, have a uniform width in a first direction and a uniform height in a second direction perpendicular to the first direction, and a second lens plate provided with a plurality of second lenses, which plurality is proportional to the plurality of first lenses, the first lens plate dividing a radiation beam incident thereon into a plurality of sub-beams proportional to the plurality of first lenses, which sub-beams have their waist in the plane of the second lenses and whose chief rays are directed towards the centres of the associated second lenses, the second lenses imaging the radiation spots formed on the first lens plate in a superimposed manner on the image display panel to be illuminated or on a plane conjugated therewith, and in that the aspect ratio of the first lenses corresponds to that of the image display panel.

The optical integrator is preferably implemented in this way. Since the aspect ratio of the lenses of the first lens plate corresponds to that of the image display panel, the total cross-section of the illumination beam, which is composed of sub-beams originating from a pair of associated lenses of the lens plates, is adapted to that of the panel so that a large part of the radiation from the radiation source is incident on the panel. By adapting the shape of the beam as satisfactorily as possible to the shape of the image display panel, it can be ensured that a minimum quantity of light falls beside the panel. Since the radiation spots formed on the lenses of the first plate are imaged in a superimposed manner on the plane of the image display panel by means of the second lens plates and the lens placed behind said plate, the radiation distribution of the beam at the area of this panel has the desired extent of uniformity.

A further embodiment of the image projection device according to the invention is characterized in that the lenses of at least one lens plate are aspherical.

An aspherical lens is understood to mean a lens whose fundamental shape is spherical but whose real shape deviates slightly so as to correct for spherical aberrations of the fundamental shape. The imaging quality can be enhanced by making use of aspherical lenses.

A further embodiment of the image projection device according to the invention is characterized in that the plurality of second lenses is equal to twice the plurality of first lenses.

This is preferably the case when the radiation source image formed by the reflector does not coincide with this radiation source.

A further embodiment of the image projection device according to the invention is characterized in that the image display panel is a DMD panel and in that the projection screen is a polarizing screen whose direction of polarization corresponds to the direction of polarization of the illumination beam supplied by the combination of the polarizing element and the polarization-rotating element.

The image display panel, or the three image display panels for colour image projection, may be implemented with liquid crystalline material. For such panels the incident radiation should be polarized because the image information to be projected is supplied by modulating the state of polarization of the beam incident on the panel in accordance with the image information. The modulated radiation beam is subsequently projected on an image projection screen *via* a projection lens system.

The state of polarization desired for the incident beam may be linear or circular, dependent on the used polarizer and analyser which form part of the image display panel. If a "circular" image display panel is used, *i.e.* a panel modulating the circular state of polarization of a radiation beam, for example a $\lambda/4$ plate should be arranged between the described illumination system and the image display panel so as to convert the linear state of polarization supplied by the illumination system into a circular state of polarization.

Instead of a liquid crystal display panel (LCD panel) as an image display panel, a DMD (Digital Micromirrored Device) panel may alternatively be used. An example of a known application of a DMD panel in a video projection system is described in United States Patent US-A 4,638,309.

A DMD is a semiconductor element which is made of a single silicon wafer and comprises a matrix of deformable mirror elements. Each mirror element may be tilted in conformity with a voltage applied thereto, which voltage represents the image information to be displayed. In this way, radiation incident on the matrix of mirror elements is reflected at different angles into or out of the projection system. Subsequently, the radiation reflected into the system is concentrated to a beam by means of an optical system and converted into a projected image *via* a projection lens system. The image information to be reproduced is thus derived from the angles at which the incident radiation is reflected by the mirror elements, rather than from the modulation of the state of polarization presented to the panel. When a linearly polarized beam is presented to a DMD panel, the state of polarization will not change due to the supply of image information, in other words due to the reflection on the mirror elements. If a polarizing image projection screen is then used for the projection, and if the direction of polarization of this screen corresponds to that of the beam supplied by the combination of the polarizing element and the polarization-rotating element, then substantially 50% of the ambient light will be blocked by the screen, while substantially all signal light is transmitted towards the viewers. Consequently, a projected image having a considerably higher contrast is obtained.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

In the drawings

Figs. 1a and 1b are diagrammatic representations of two embodiments of an illumination system according to the invention;

Fig. 2 shows the operating principle of two stacked polarizing elements;

Fig. 3 is a diagrammatic representation of an embodiment of an illumination system having a low throughput;

Fig. 4 is a diagrammatic representation of a radiation source having a short arc length suitable for a radiation source unit for use in an illumination system according to the invention;

Fig. 5 is a diagrammatic representation of an embodiment of an image projection device according to the invention; and

Fig. 6 is a diagrammatic representation of a third embodiment of an illumination system according to the invention.

Figs. 1a and 1b show two embodiments of an illumination system 1 according to the invention. Such an illumination system 1 may be used, for example in an image projection device which is provided with at least one image display panel for illuminating the image display panel.

The illumination system 1 includes a radiation source unit 3 which comprises a lamp 5 and a reflector 7. The lamp 5 emits light in the direction of the object to be illuminated, for example an image display panel, and in the backward direction. The reflector 7 ensures that the backwards emitted light is collected and is still sent into the direction of the object. The reflector 7 may be, for example self-collimating. If this is not the case, an extra collimating lens 9 will be required for concentrating the light emitted by the lamp 5 to a parallel beam b. This parallel beam b, only the chief ray of which is shown, is subsequently incident on a polarizing element 11.

The polarizing element 11 comprises an optically transparent plate 13 having a refractive index n_0, at least one side of which is provided with an optically thin layer 15 having a refractive index n_1, for which it holds that $n_1 > n_0$. Such an element, which is provided with an optically thin layer at both sides, is known *per se* from the article "Polarizing beam splitters for infrared and millimeter waves using single-layer-coated dielectric slab or unbacked films" by R.M.A. Azzam in Applied Optics, vol. 25, no. 23, December 1986. The optically thin layer may comprise, for example TiO_2, CeO_2 or ZnS_2. Such a polarizing element can be manufactured in a relatively simple manner by vapour deposition or immersion. Moreover, said materials are resistant to very high temperatures.

When an illumination beam is incident on such a polarizing element 11, with the chief ray of the beam b and the normal 12 on the element 11 enclosing an angle for which light which is s-polarized will be reflected from the beam b as beam b_s, while light which is p-polarized will be transmitted as beam b_p, two mutually perpendicular, linearly polarized sub-beams will be formed. This angle is substantially equal to the Brewster angle for the transition between air and the optically thin layer provided on the transparent plate. For this angle, the reflection of the s-polarized light is substantially 80%, while the reflection of p-polarized light is only approximately 2%. The value of the Brewster angle for the transition between air and the optically thin layer is determined by the refractive index n_1 of the thin optical layer 15 provided on the transparent plate 13, in accordance with the formula $tg\ \Theta_B = n_1$. If the polarizing element is present in a medium other than air, the Brewster angle will also be dependent on the refractive index of this medium.

Moreover, a reflecting element 17 is provided so as to send the sub-beam reflected out of the original beam b into the direction of propagation of this beam b again. In this way, two parallel sub-beams are formed which are mutually perpendicularly and linearly polarized. By providing a polarization-rotating element 19 in one of these two sub-beams, for example in the form of a $\lambda/2$ plate or a liquid crystalline layer having a molecular ordering, which element rotates the direction of polarization through 90°, the two directions of polarization can be rendered equal to each other. In this way, substantially the entire beam from the radiation source unit 3 is converted into a linearly polarized beam having a single direction of polarization.

If a circularly polarized beam is desired, a $\lambda/4$ plate may be arranged between the assembly of the polarizing element 11 and the polarization-rotating element 19 and the object to be illuminated. Consequently, the linearly polarized beam can be converted into a circularly polarized beam. This may be necessary, for example if an image display panel is used which operates with circularly polarized light.

Fig. 1a shows an embodiment of the illumination system 1 in which the s-polarized beam component is reflected by the reflecting element 17 in the direction parallel to that of the original beam, while this is the case for the p-polarized component in Fig. 1b. Dependent on the desired final polarization, p or s, of the beam to be sent to an image display panel, the polarization-rotating element 19 is arranged in either the s or the p-polarized sub-beam. In both Figures 1a and 1b the beam supplied by the illumination system 1 is s-polarized.

By providing both the first side and the second side of the transparent plate with an optically thin layer, the polarization-separating effect may be enhanced. For example, the reflection for the s-polarized beam component may be very high, *viz.* approximately 80%, and the reflection for the p-polarized beam component may be very low, *viz.* approximately 2%. Then only a small quantity of s-polarized light, together with the p-polarized beam component will be passed by the polarizing element.

Fig. 6 shows an alternative embodiment of the illumination system shown in Figs. 1a and 1b. The incident beam is considered to consist of two parallel sub-beams b_1

and b_2. Each of these sub-beams accommodates a polarization separator comprising a polarizing element 111, 111', in which the chief ray of a sub-beam and the normal 112, 112' on the polarizing element in this sub-beam enclose an angle θ_B. θ_B is the angle for which s-polarized light from the relevant sub-beam is reflected, while p-polarized light will be passed. The two polarizing elements 111 and 111' mutually enclose an angle of $\theta' = 180° - 2\theta_B$. Each polarizing element 111, 111' comprises a transparent plate 113, 113' having one or two optically thin layers 115, 115'.

The polarizing elements 111, 111' reflect the s-polarized component of each sub-beam towards a reflecting element 117, 117', which element deflects the s-polarized sub-beams in the direction parallel to the original beam. The p-polarized component will be passed by the polarizing elements 111, 111'.

If s-polarized light is desired, the p-polarized sub-beam may be provided with a polarization-rotating element 19, for example a $\lambda/2$ plate or a liquid crystalline layer having a molecular ordering, so that the p-polarized beam is converted into an s-polarized beam.

If p-polarized light is desired, the light passed by the polarizing elements will have the suitable direction of polarization right away, and a polarization rotator (not shown) is to be arranged in each s-polarized beam.

The embodiment shown in Fig. 6 has the advantage that it is more compact than the embodiments shown in Figs. 1a and 1b. The embodiment described above has the further advantage that the chief ray of the polarized beam is located at the same height as the chief ray of the beam to be polarized. Consequently, the illumination system according to the invention is optional and can replace illumination systems in existing image projection devices without substantial adaptations.

The polarization separation may be further optimized, both for the embodiments shown in Figs. 1a and 1b, and for those shown in Figs. 6a and 6b, by stacking a plurality of polarizing elements. Fig. 2 shows the operating principle of a polarization separator of the type shown in Fig. 1a with two polarizing elements 11, 11'. At least a part of the s-polarized portion b_s' of the beam b which, together with the p-polarized component b_p is passed by the first polarizing element 11, will be reflected on the second element 11'. The transmission of s-polarized light will decrease with an increasing number of polarizing elements.

Each polarization separator as shown in Figs. 2b and 6 may also comprise a plurality of stacked polarizing elements consisting of an optically transparent plate having one or two optically thin layers.

As already described hereinbefore, the beam to be polarized should be incident on the polarizing element at a given angle with respect to the normal in order that polarization separation occurs. To realise an efficient polarization separation of the complete light beam, both the chief ray and the border rays of the beam should be incident on the polarizing element at or substantially at this angle of incidence. This can be achieved with a radiation source unit whose light beam has a narrow divergence, in other words, a light beam whose border rays enclose a relatively small angle with the chief ray.

A radiation source unit supplying a light beam having a narrow divergence is, for example a radiation source unit having a low throughput.

The term "throughput" characterizes the power of an optical system to transport radiation energy. This power is defined by $E = A \cdot \Omega$, in which A is the radiating surface and Ω is the spatial angle through which light is emitted, both measured at the location of the entrance aperture of the system in the centre of this aperture. In an optical system the throughput further down the system cannot be enlarged anymore but only reduced by blocking radiation, so that radiation will then be lost.

An illumination system including a radiation source unit having a low throughput is known, for example from United States Patent US-A 5,046,837 and is shown diagrammatically in Fig. 3. In the illumination system 1 shown in this Figure, two condensor lenses 18 and 22 are arranged at the front side of the radiation source 5. This radiation source 5 with its centre M_s is, for example a metal halide lamp which is elongated and has a length-width ratio of, for example 2:1. The longitudinal direction of the lamp is perpendicular to the optical axis OO'. The radiation collected by the condensors is concentrated in two sub-beams b_1 and b_2 which are reflected to the principal axis by first reflectors 24, 26. Second reflectors 28, 30 constituting a roof mirror are arranged at both sides of the principal axis OO' at a position where the beams would intersect each other and where the beam cross-sections are already small. These reflectors deflect the beams in the direction of the principal axis. The beams have their waist in the exit plane 32 of the illumination system 1. Two secondary radiation sources 34, 36 having small radiating surface can be imaged in this plane.

In this way, two lamp images are formed within a circular area whose radius is smaller than twice the radius of the described circle of the radiating lamp surface, so that the lamp radiation which is collected by the condensors is concentrated to a beam having a small cross-section.

The condensors 18, 22 should have a large numerical aperture so as to collect sufficient light from the radiation source and may be constituted, for example by single lens elements having aspherical surfaces, so that these are sufficiently corrected for the envisaged object.

The requirements imposed on the lens elements 18 and 22 may be alleviated if additional lens elements such as the elements 38 or 40 and possibly more lens elements are associated with the elements 18 and 22. The additional lens elements may supply a part of the required correction for the lens elements 18 and 22 and may be, for example aspherical.

Here again, a concave reflector 7 is preferably arranged behind the radiation source 5, which reflector reflects the radiation emitted by the rear side of the source 5 to the condensors so that this radiation can contribute to the intensity of the beams b_1 and b_2 and thus enhances the efficiency of the illumination system.

For further details and embodiments of the radiation source unit 1 shown in Fig. 3 reference is made to the afore-mentioned United States Patent US-A 5,046,837.

A better alternative for a radiation source unit supplying an illumination beam having a narrow divergence or a low throughput is a unit comprising a lamp having a short arc length and being surrounded by a reflector. Examples of such lamps are a xenon lamp and a short-arc metal halide lamp. However, both lamps have the drawback of a relatively short lifetime. Moreover, a xenon lamp is also subject to the risk of explosion.

A lamp having a short arc length which is safe and has a considerably longer lifetime (several thousand hours) and is thus very suitable for use in combination with a polarizing element as described above in the illumination system according to the present invention is the UHP (Ultra High Pressure) lamp. This lamp is known *per se* from the afore-mentioned European Patent Application EP-A 0 576 071.

Fig. 4 shows an embodiment of such a lamp. The lamp 3 has a lamp vessel 51 of quartz, a part 53 of which surrounds a discharge space 55. The lamp vessel 51 accommodates two separated tungsten electrodes 57. The two electrodes 57 define a discharge path 59 and are connected to current conductors 61 which extend beyond the lamp vessel 51. The lamp vessel 51 is filled with at least 0.2 mg Hg/mm^3, 10^{-6} - 10^{-4} μmol Hal/mm^3, in which Hal is one of the materials Cl, Br or I, and further with a rare gas in the discharge space. The discharge space 55 has a spherical shape and a dimension S in the direction of the discharge path 59, defined by $S(mm) = e \, . \, D_i$, in which e has a value between 1.0 and 1.8, $D_i(mm) = f \, . \, [3.2 + 0.011(mm/W) \, . \, P(W)]$, in which D_i is the largest value for the diameter perpendicular to the discharge path 55, f has a value between 0.9 and 1.1, P is the power used at nominal operation, which power is between 70 and 200 W. The part 53 of the lamp vessel 51 surrounding the discharge space 55 has a convex outer surface 63 which, in a plane in which D_i is located has a diameter D_0 which is defined by D_0(mm) $\geq$ 3.2 + 0.055(mm/W) . P(W). The length D_p of the discharge path 59 is between 1.0 and 2.0 mm and the selected halogen is Br. For further details relating to the lamp described, reference is made to said European Patent Application.

Such a lamp with a reflector at its rear side constitutes a radiation source unit which supplies a beam of the desired small divergence. This lamp may also be incorporated in the system shown in Fig. 3, so that a radiation source unit having a low throughput and a narrow divergence is obtained.

Fig. 5 shows an embodiment of an image projection device 20 comprising an illumination system 1 according to the invention of the type shown in Fig. 1a and an image display panel 21 for supplying the image information in accordance with an image to be projected with the radiation beam. Arranged behind the image display panel 21 is a projection lens system 23 for projecting the image generated by the panel in a magnified form on a projection screen 25.

The illumination system 1 may be alternatively an illumination system of the type shown in Fig. 1b, 3 or 6.

The image display panel may be, for example a liquid crystal display panel. Such a panel comprises a layer of liquid crystalline material which is enclosed between two optically transparent plates. A drive electrode is provided on each of these plates. These electrodes may be divided into a large number of rows and columns so that a large number of pixels is defined in the image display panel. The different pixels can be driven by driving the matrix electrodes. Thus, at the desired positions a local electric field can be applied across the liquid crystalline material. Such an electric field causes a variation of the effective refractive index of the material so that the light passing through a given pixel undergoes or does not undergo a rotation of the direction of polarization, dependent on the presence or absence of an electric field at the location of the relevant pixel.

Instead of this passively driven image display panel, an actively driven panel may alternatively be used. In the last-mentioned image display panel one of the supporting plates comprises an electrode, while the semiconductor drive electronics are provided on the other plate. Each of the pixels is now driven by its own active drive element such as, for example a thin-film transistor. Both types of direct-drive image display panels are described in, for example European Patent Application EP 0 266 184.

For such an image display panel the incident beam should be polarized, because the image information is supplied by modulation of the direction of polarization. A voltage is applied to each pixel of the image display panel, which voltage corresponds to the image information present at that location. Per pixel, the direction of polarization of the radiation incident on the relevant pixel is thus modulated in conformity with the image information to be displayed by said pixel. The illumination system according to the invention provides the possibility of supplying a polarized beam to the image display panel for which substantially the complete intensity of the radiation beam supplied by the radiation source is utilized.

If the image projection device is a colour image projection device, the device comprises three image display panels, one for each of the primary colours red, green and blue and also a plurality of dichroic mirrors which split the linearly polarized beam into a red, a green and a blue beam each incident on an associated panel. The beams modulated by these panels are subsequently recombined by a further set of dichroic mirrors to one beam which is imaged by the projection lens system as an image on the projection screen.

It is alternatively possible to use a single colour image display panel in a colour image projection device. Then, a matrix of dichroic mirrors arranged in front of the pixels is preferably used, as described in, for example United States Patent US-A 5,029,986 for the image display panel of a direct-vision image display device.

The image display panel may also be a DMD (Digital Micromirrored Device) panel instead of an LCD (Liquid Crystal Display) panel. A DMD is a semiconductor element which is made of a single silicon wafer and comprises a matrix of deformable mirror elements. Each mirror element may be tilted in conformity with a voltage applied thereto. In this way, radiation incident on the matrix of mirror elements is reflected at different angles into or out of the projection system. Subsequently, the radiation reflected into the system is concentrated to a beam by means of an optical system and converted into a projected image *via* a projection lens system. The operation of such a panel is not based on modulation of the state of polarization of the incident radiation, but the image information to be reproduced is derived from the angles at which the incident radiation is reflected by the mirror elements.

When a linearly polarized beam is presented to a DMD panel, the state of polarization will not change due to the supply of the image information, in other words due to setting the reflection angles of the mirror elements. This means that the beam provided with image information still has the same state of polarization as the beam which is supplied by the combination of the polarizing element 11 and the polarization-rotating element 19.

Here it is proposed to use a polarizing image projection screen 25 as an image projection screen whose direction of polarization corresponds to that of the beam supplied by the combination of the polarizing element 11 and the polarization-rotating element 19. A polarizing image projection screen is a screen which reflects only radiation having a given direction of polarization towards the viewer if a front projection screen is used, or transmits radiation if a rear projection screen is used. Radiation having a different direction of polarization is blocked for the viewer. Substantially 50% of ambient light which is slightly unpolarized will be blocked, while substantially all signal light having a direction of polarization in conformity with that of the screen will reach the viewer. In this way, an image having a considerably enhanced contrast can be obtained. An example of a polarizing projection screen provided with a circular polarizer is described in the non-prepublished Belgian Patent Application BE 09301042 in the name of the Applicant. An example of a polarizing projection screen comprising a linear polarizer is described in European Patent Specification EP-B 0 295 913.

Moreover, an optical integrator 27 may be arranged between the illumination system 1 and the image display panel 21. Such an integrator 27 is known from, for example United States Patent US-A 5,098,184.

The optical integrator 27 comprises a first lens plate 29 and a second lens plate 31. For example, the lamp-facing side of the first plate 29 is provided with a matrix of lenses 33 and the other side 35 is preferably plane. For the sake of simplicity, only four lenses are shown. Actually, the plate 29 comprises, for example 8 x 6 lenses. The side 37 of the source 3 facing the second lens plate 31 is, for example plane, while the side remote from the source carries a matrix of lenses 35. The number of rows and columns of lenses of the two plates 29 and 31 corresponds. This is preferably the case if an image of the radiation source, which is formed by the reflector 7 arranged behind the radiation source 5, coincides with the radiation source. When the image of the radiation source through the reflector and the radiation source itself coincide, it is assumed that the lamp is transparent to its own light. If this is not the case, hence if the lamp image is located next to the lamp, the second lens plate 31 preferably has twice as many lenses as the first lens plate 29.

The lenses 33 of the first lens plate 29 divide the incident beam into a number of sub-beams corresponding to the number of lenses 33 and ensure that these sub-beams have their waist in the plane of the lenses 35 of the second lens plate 31. For imaging the source 3 on the corresponding lenses 35 by means of the different lenses 33, a different portion of the incident beam is used each time. The lenses 35 have such a power in such a direction that they image the radiation spot formed on the corresponding lens 33 on the image display panel. It is thereby achieved that the illumination beam has a satisfactorily uniform intensity distribution.

In order that a minimum quantity of intensity is lost, the shape of the cross-section of the illumination beam is preferably adapted to the shape of the image display panel. Image display panels which are used for displaying conventional video images have an aspect ratio b:h = 4:3. When the lenses 33 have the same aspect ratio, it is achieved that, apart from optical losses, all radiation from the combination of polarizing and polarization-rotating element will illuminate the image display panel and the illumination system will have a high efficiency.

Lenses 39 and 41 ensuring that all integrator lens images in the plane of the image display panel 21 are satisfactorily superimposed and that the image display panel is satisfactorily imaged on the projection screen may be arranged behind the second lens plate 31.

The use of the known optical integrator in an illumination system according to the present invention has an extra advantage. Since the linearly polarized beam which will illuminate the image display panel is a combination of two sub-beams, each of which has covered a different path between the radiation source unit 3 and the location where they are combined to a single beam, the intensity distribution across this beam will not be constant. However, by using an integrator system, it will be possible to distribute the intensity uniformly across the total light beam.

At least one of the lenses of at least one of the lens plates may be aspherical. An aspherical lens is understood to mean a lens whose fundamental shape is spherical but whose real shape has small deviations so as to correct for the spherical aberrations of the fundamental shape. The system efficiency can be enhanced by making use of aspherical lenses in a lens plate.

CLAIMS:

1. An illumination system for supplying a polarized radiation beam, successively comprising a radiation source unit with a radiation source for supplying radiation and an optical system for concentrating the radiation to a beam, a polarization separator for splitting the radiation beam into two linearly polarized sub-beams having mutually perpendicular directions of polarization, and a polarization-rotating element in one of the sub-beams, characterized in that the polarization separator comprises at least one polarizing element which is constituted by an optical transparent plate having a refractive index n_0 with a first face and a second face, at least one of said faces being provided with an optically thin layer having a refractive index n_1 which is larger than n_0, in that a reflector is arranged in the light path of at least one of the sub-beams for reflecting said sub-beam in the same direction of propagation as that of the other sub-beam, in that the radiation source unit supplies a radiation beam having a narrow divergence, and in that the chief ray of said beam and the normal on the plate enclose an angle Θ_B which is substantially equal to the Brewster angle which applies to the transition between the optically thin layer and a medium surrounding the polarization separator.

2. An illumination system as claimed in Claim 1, characterized in that the illumination system comprises at least two polarization separators whose normal on each polarization separator and the chief ray of the beam incident on the relevant polarization separator enclose an angle θ_B which is substantially equal to the Brewster angle which applies to the transition between the optically thin layer and the medium surrounding the polarization separator, the two polarization separators mutually enclosing an angle $\theta' = 180° - \theta_B$.

3. An illumination system as claimed in Claim 1 or 2, characterized in that the radiation source unit has a low throughput.

4. An illumination system as claimed in Claim 1, 2 or 3, characterized in that the radiation source unit comprises a lamp having a short arc length, which lamp is surrounded by a reflector.

5. An illumination system as claimed in Claim 4, characterized in that the radiation source is a high-pressure mercury discharge lamp comprising

a lamp vessel of quartz glass, having a region surrounding a discharge space;

tungsten electrodes arranged in the lamp vessel and separated from each other, which electrodes define a discharge path and are connected to current conductors extending from the lamp vessel to the exterior;

a filling of at least 0.2 mg Hg/mm^3, 10^{-6} - 10^{-4} μmol Hal/mm^3, in which Hal is one of the materials from the group of Cl, Br and I, and

a rare gas in the lamp vessel, while

the discharge space has a spheroidal shape with a dimension S in the direction of the discharge path and is equal to

$S(mm) = e \,.\, D_i$

in which e has a value between 1.0 and 1.8,

$D_i(mm) = f \,.\, [3.2 + 0.011(mm/W) \,.\, P(W)]$

in which D_i is the largest value for the diameter perpendicular to the discharge path,

f has a value between 0.9 and 1.1,

P is the power used at nominal operation, between 70 and 200 W,

the part of the lamp vessel surrounding the discharge space has a convex outer surface which, in a plane in which D_i is located, has a diameter D_o which is given by

$D_o(mm) \geq 3.2 + 0.055(mm/W) \,.\, P(W)$,

the length of the discharge path D_p is between 1.0 and 2.0 mm and the selected halogen is Br.

6. An image projection device comprising an illumination system for supplying a polarized radiation beam, at least one image display panel arranged in the path of said beam for generating an image to be projected, and a projection lens system for projecting the image on a projection screen, characterized in that the illumination system is an illumination system as claimed in Claim 1, 2, 3, 4 or 5.

7. An image projection device as claimed in Claim 6, characterized in that an optical integrator is arranged in the light path between the polarizing element and the image display panel.

8. An image projection device as claimed in Claim 7, characterized in that the optical integrator successively comprises a first lens plate provided with a plurality of first lenses which, in a plane perpendicular to the principal axis of the polarized beam, have a uniform width in a first direction and a uniform height in a second direction perpendicular to the first direction, and a second lens plate provided with a plurality of second lenses, which plurality is proportional to the plurality of first lenses, the first lens plate dividing a radiation beam incident thereon into a plurality of sub-beams proportional to the plurality of

first lenses, which sub-beams have their waist in the plane of the second lenses and whose chief rays are directed towards the centres of the associated second lenses, the second lenses imaging the radiation spots formed on the first lens plate in a superimposed manner on the image display panel to be illuminated or on a plane conjugated therewith, and in that the aspect ratio of the first lenses corresponds to that of the image display panel.

9. An image projection device as claimed in Claim 8, characterized in that the lenses of at least one lens plate are aspherical.

10. An image projection device as claimed in Claim 8 or 9, characterized in that the plurality of second lenses is equal to twice the plurality of first lenses.

11. An image projection device as claimed in any one of Claims 6 to 10, characterized in that the image display panel is a DMD panel and in that the projection screen is a polarizing screen whose direction of polarization corresponds to the direction of polarization of the illumination beam supplied by the combination of the polarizing element and the polarization-rotating element.

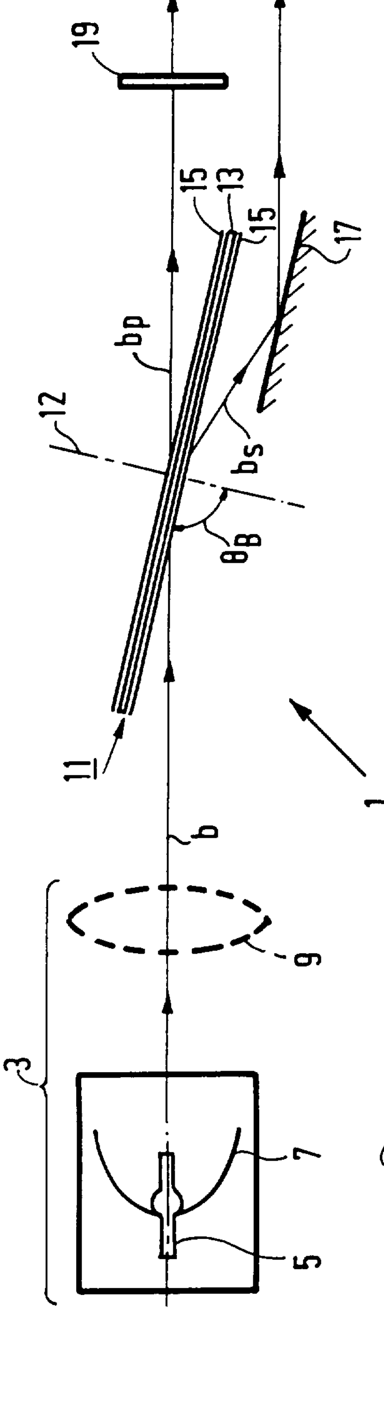


FIG.1a

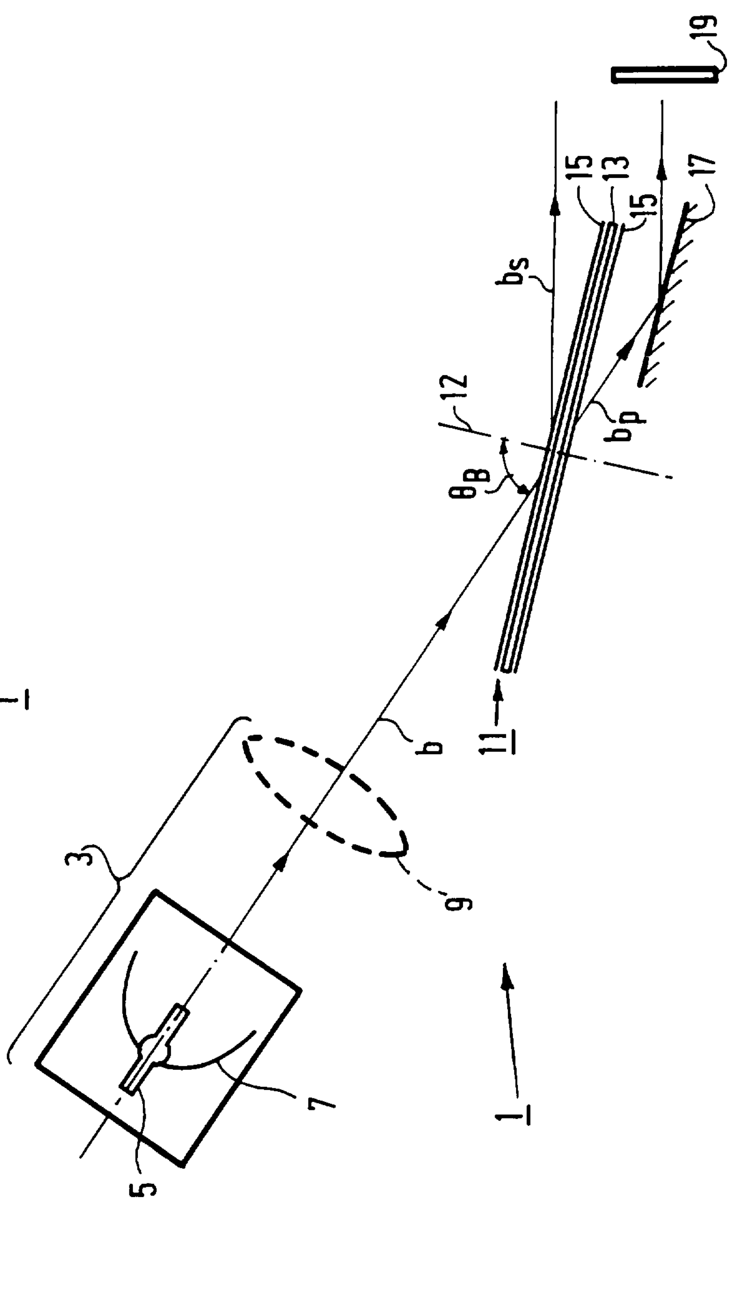


FIG.1b

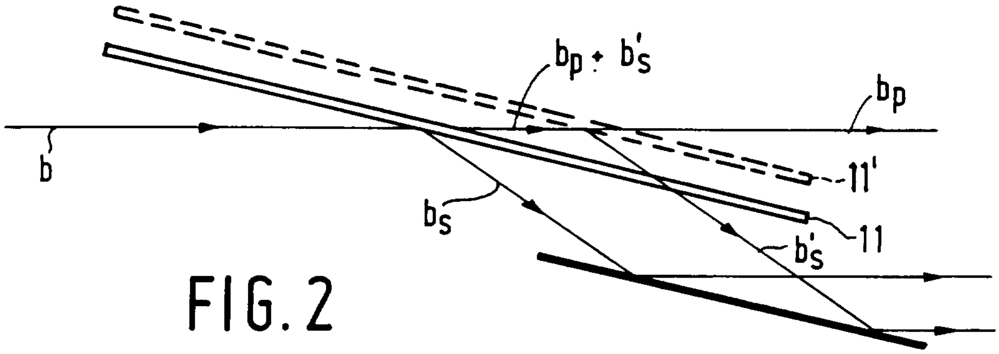


FIG.2

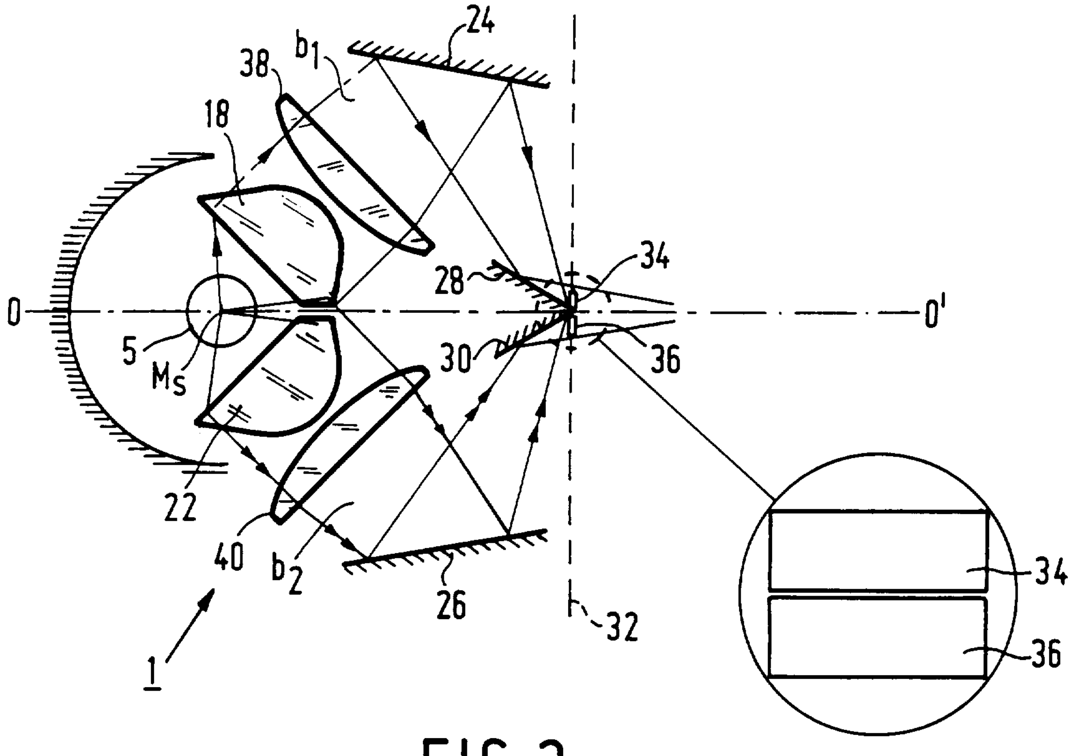


FIG.3

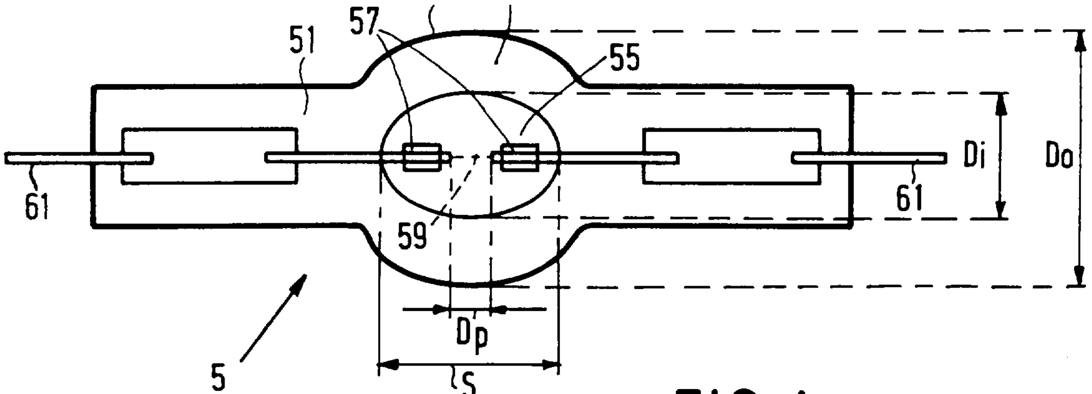


FIG.4

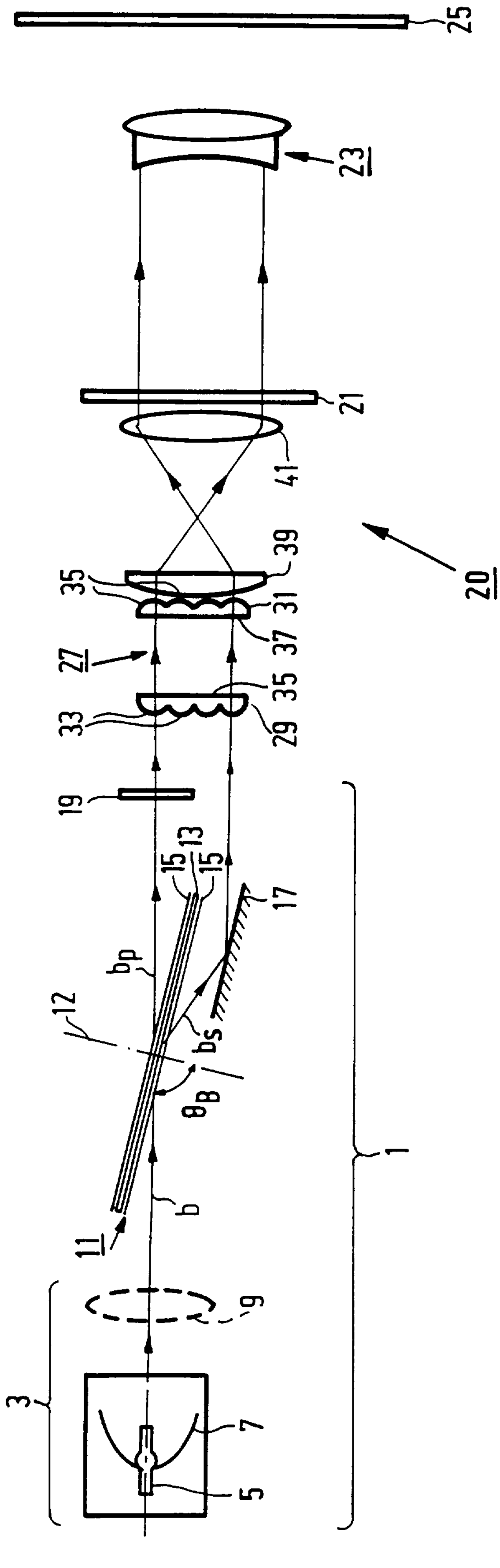

25
23
21
41
20
39
35
31
37
27
35
33
29
19
15
13
15
17
b_p
12
b_s
θ_B
b
11
9
3
7
5
1

FIG.5

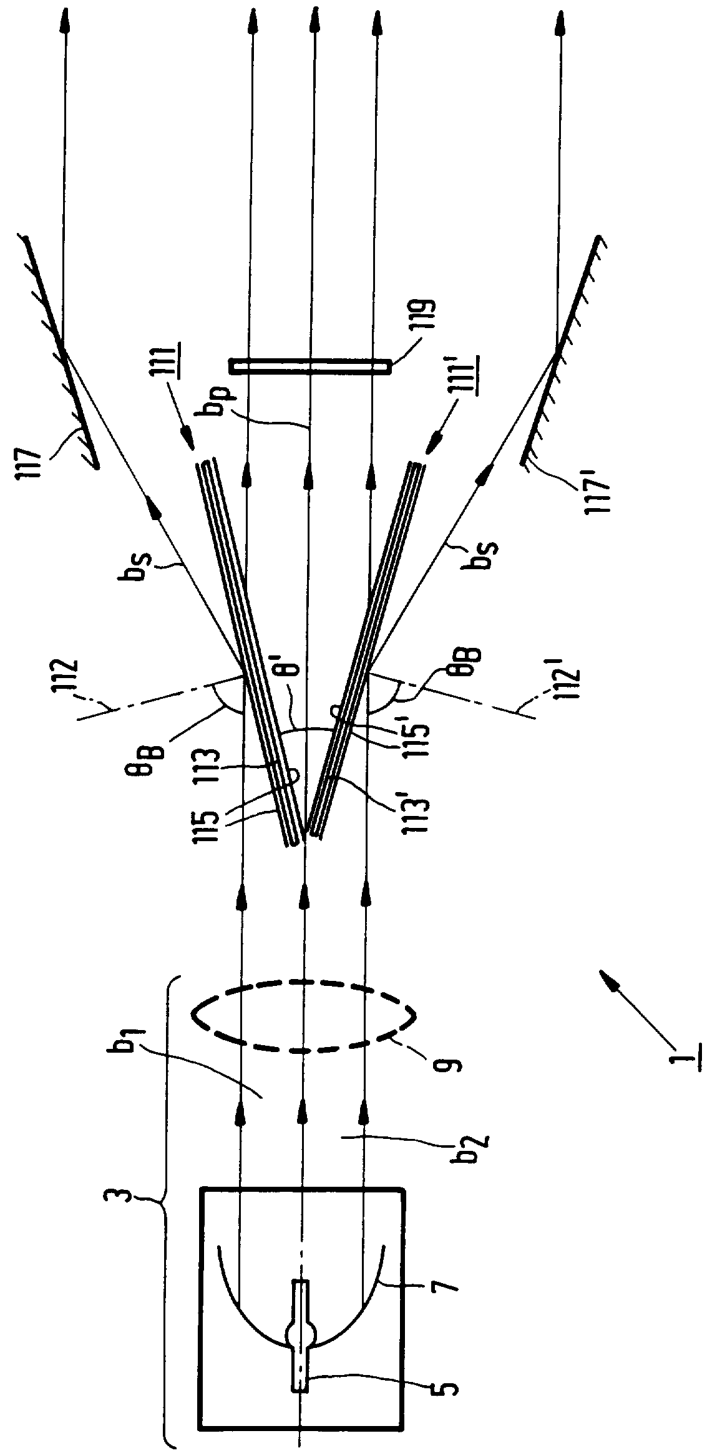

117
111
119
111'
117'
b_p
b_s
b_s
112
112'
θ_B
θ_B
θ'
113
115
115'
113'
b_1
b_2
9
3
7
5
1

FIG.6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB 95/00612

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: G02B 27/28, H04N 9/31
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: G02B, H04N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

ORBIT: WPAT, USPM, JAPIO

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0518111 A1 (MATSUSHITA ELECTRIC INDUSTRIAL CO., LTD.), 16 December 1992 (16.12.92) --	1-11
A	Patent Abstracts of Japan, Vol 14,No 258, P-1055, abstract of JP, A, 2-69715 (SEIKO EPSON CORP), 8 March 1990 (08.03.90) --	1-11
A	Patent Abstracts of Japan, Vol 14,No 249, P-1053, abstract of JP, A, 2-64613 (SEIKO EPSON CORP), 5 March 1990 (05.03.90) --	1-11
A	EP 0508413 A2 (CANON KABUSHIKI KAISHA), 14 October 1992 (14.10.92) --	1-11

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" erlier document but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- "Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
2 January 1996	04.01.96

Name and mailing address of the ISA/	Authorized officer
Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Bertil Dahl Telephone No. +46 8 782 25 00

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IB 95/00612

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP-A1- 0518111	16/12/92	JP-A- 5157915	25/06/93
		US-A- 5357370	18/10/94
EP-A2- 0508413	14/10/92	JP-A- 4310903	02/11/92