Title: POLARIZED LIGHT SOURCE WITH HIGH LUMINANCE

Abstract: The present invention relates to a method of generating polarized light and a light source using a laser diode pumped oriented ceramic or crystalline material instead of phosphors or unoriented ceramics to produce polarized beams. The light source with oriented crystalline or ceramic converter materials emitting polarized light is well suited for standard liquid crystal display based digital projection as well as polarization-based stereoscopic 3D projection.
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POLARIZED LIGHT SOURCE WITH HIGH LUMINANCE

FIELD OF THE INVENTION

The invention relates to a solid-state light source for emitting polarized light and a method of generating polarized light for use in projection applications.

BACKGROUND OF THE INVENTION

Solid-state light sources are currently entering many different lighting applications and replace the traditional incandescent and gas discharge lamps. The term "solid state" refers commonly to light emitted by solid-state electroluminescence, as opposed to incandescent bulbs (which use thermal radiation) or fluorescent tubes. Compared to incandescent lighting, solid-state lighting creates visible light with reduced heat generation or parasitic energy dissipation. Most common "white" light emitting diodes (LEDs) convert blue light from a solid-state device to an (approximate) white light spectrum using photoluminescence, the same principle used in conventional fluorescent tubes. For projection applications, recently a hybrid laser-phosphor-LED solution has been presented, where the laser has been used for pumping a phosphor to produce the green (G) primary colour. The other primary colours, red (R) and blue (B), could be generated in a similar way. The beam emitted by the phosphor or ceramic can be used directly for high brightness (digital light processing (DLP) micro displays projection applications. However, for liquid crystal displays (LCD) and liquid crystal on silicone (LCOS) technology, polarized beams are needed.

However, due to statistical orientation of the phosphor powder particles, the beam will be unpolarized. Even applying ceramic material will emit unpolarized light due to its polycrystalline and unoriented character. As a consequence, polarization has to be recovered at the expense of brightness in complex optical setups.

Several applications benefit from polarized light: e.g. digital projection, and the newly arising polarization-based stereoscopic three-dimensional (3D) projection. 3D-displays are gaining importance in the markets of digital cinema and television (TV). The 3D-display technology relies in most cases on polarized light, which is realized by splitting the beam from lamps with the use of complex and expensive polarization optics. High
intensity gas discharge lamps, like for example ultra high performance (UHP) or Xenon-
lamps are currently used in these demanding applications, but suffer from polarization
recovery of the beam. Nevertheless, solid-state light sources are also highly desired as the
light source in this type of applications.

A setup of a RGB conversion module in projection applications using lasers
has for example been realized by a hybrid solution and consists of at least three components:
the exciting laser diodes, the converting phosphor and a LED. Blue color is used directly
from the laser diodes (λ=445nm), which also acts as excitation source for the green-
converting phosphor. The red color is emitted directly by a LED. However, this hybrid setup
is still limited in brightness, e.g. for LCD technology, and therefore not adapted to low
Étendue applications with low "spread out" light in area and angle and thus low volume in
the phase space. In principle, also the red and even the blue primary colour can be generated
in this way.

Polarized light emitting elements can be coupled directly into the display
without any additional losses caused by polarization recovery or filtering. This means that
there are basically no polarization losses to be expected, which makes polarized light
emitting elements a very attractive light source for these applications. Still some issues
remain and make the direct use of lasers in these applications difficult. First, suitable lasers
are not available at all required emission wavelengths. Secondly, even with the right lasers
available, safety and image quality issues (Speckle) remain as problems that have to be
solved using additional measures.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a solid-state light source for emitting
polarized light at high intensity.

This object is achieved by a light source as claimed in claim 1.

Accordingly, by using oriented converter materials instead of phosphors or
LEDs, several advantages can be realized. First, a higher efficiency leading to increased
brightness can be achieved because no polarization recovery optics and color separation
dichroics are needed. Secondly, laser enabled improved light engine design will allow for
smaller and cheaper systems due to a reduced number of illumination and projection optics.

According to a first aspect, the beam generator may comprise a laser source
for generating a pumping laser beam. This provides the advantage that a highly efficient
point-shaped excitation of the oriented luminescent material can be achieved by the laser beam.

According to a second aspect which may be combined with the first aspect, the at least one conversion element may be adapted to generate the polarized beam at a wavelength different from the exciting wavelength of the light beam. Thereby, a polarized beam of a predetermined wavelength can be generated at high intensity.

According to a third aspect which can be combined with any one of the first and second aspects, the heat sink may be arranged as a moving element on which a plurality of conversion elements are arranged so that the light beam selectively illuminates the conversion elements when the moving element moves. Thereby, an improved heat dissipation can be achieved and the light source can be used for high power applications. The light beam is preferentially a focused light beam.

According to a fourth aspect which can be combined with any one of the first to third aspects, the moving element may be a spinning wheel and the conversion elements may be arranged at the circumference of the spinning wheel in such a manner that the orientation of the oriented luminescent material of all conversion elements is substantially parallel. Thereby, a converted output radiation with sinussoidally changing polarization can be achieved, which is useful for 3D applications.

According to a fifth aspect which can be combined with any one of the first to fourth aspects, the moving element may be a spinning wheel and the conversion elements may be arranged at the circumference of the spinning wheel in such a manner that the orientation of the oriented luminescent material of all conversion elements is substantially tangential or radial to the spinning wheel. Thereby, a converted output radiation with fixed polarization can be achieved.

According to a sixth aspect which can be combined with any one of the first to fifth aspects, the moving element may be a spinning wheel and the conversion elements may be arranged at the circumference of the spinning wheel in such a manner that the oriented luminescent material of the conversion elements has alternating radial and tangential orientation with respect to the spinning wheel. Thereby, a converted output radiation with digitally changing or switched polarization can be achieved, which may also be useful for 3D applications.

According to a seventh aspect which can be combined with any one of the first to sixth aspects, said conversion elements may be used in a reflection or transparent mode.
Thus, a flexible arrangement can be achieved by suitably selecting the mode of the conversion elements.

According to an eighth aspect which can be combined with any one of the first to seventh aspects, the oriented luminescent material may comprise an oriented ceramic or crystal. More specifically, the oriented luminescent material may comprise or may be selected from Pr:YLF, Nd:YLF, Ho:YLF, Yb:NaYF₄, Yb:Er:NaYF₄, Ho:NaYF₄, Tm:Er:NaYF₄, Pr,Yb:BaY₂F₈ or Pr:SrAl₂O₄. Thereby, the characteristics of the oriented luminescent material can be adapted to the desired application of the light source.

Further advantageous embodiments are defined below.

BRIEF DESCRIPTION OF THE DRAWINGS

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

In the drawings:

Fig. 1 shows a schematic setup of a light source for generating a polarized light beam with high luminance according to a first embodiment;

Fig. 2 shows a schematic arrangement of a dynamic application with tangential and radial alignment of segments according to a second embodiment;

Fig. 3 shows a schematic arrangement of a dynamic application with parallel orientation of segments according to a third embodiment;

Fig. 4 shows a schematic arrangement of a dynamic application with altering radial and tangential orientation of segments according to a fourth embodiment; and

Fig. 5 shows a schematic arrangement of a dynamic application for generating anti-parallel polarized beams according to a fifth embodiment.

DETAILED DESCRIPTION OF EMBODIMENTS

Various embodiments are now described based on a light source using a laser diode pumped oriented ceramic or crystalline material instead of phosphors or unoriented ceramics to produce at least one polarized beam. It is however noted that the present invention can be applied to any kind of light source in which oriented crystalline or ceramic converter materials can be used to emit polarized light.

In the proposed light source, oriented luminescent materials - of crystalline or ceramic nature - that are pumped by a laser source are used. They generate a polarized beam
at a wavelength different from the exciting laser wavelength. This provides various advantages in different setups and arrangements that are discussed in the following embodiments. Thereby, projection systems (e.g. LCD- and LCoS-projection systems) can be drastically simplified, since by using a setup like the proposed one, costly elements for polarization control can be omitted.

Fig. 1 shows a schematic setup of a light source for generating a polarized light beam with high luminance according to a first embodiment. A focussed laser beam 10 (pump radiation) is directed onto a piece of oriented crystalline or ceramic luminescent material 40 through a beam splitter 20 and illuminates the piece of luminescent material 40 from one side. The converted luminescent radiation 12 is collected from the same side by a reflector 30 (which is not restricted to the shape shown in Fig. 1) and a heat sink 50 is used to removes the heat generated in the luminescent material 40 from the other side. The beam splitter 20 provides a high transmission for the pump radiation of the focussed laser beam 10 from one side and a high reflection for the concerted luminescent radiation 12 from the other side.

The proper orientation of the polarization of the converted radiation 12 can be set by rotating the converting element (i.e. oriented luminescent material 40) with respect to the display (not shown) and pumping laser (not shown). Here, the converting oriented luminescent material 40 is fixed in position and the first embodiment is therefore called a static solution or application as opposed to the dynamic solution or application explained in the following embodiments. The static solution is quite suitable for lower power setups, where heat removal can be done via the heat sink 50 shown in Fig. 1. The heat sink 50 may be physically designed to increase the surface area in contact with the cooling fluid surrounding it, such as the air. Approach air velocity, choice of material, fin (or other protrusion) design and surface treatment are some of the design factors which influence the thermal resistance, i.e. thermal performance, of the heat sink 50. Thermal adhesive may be added to the base of the heatsink 50 to help its thermal performance. The heat sink 50 may be made of aluminum, copper, synthetic diamond, or composite materials, for example.

The beam splitter 20 may be based on a prism or a mirror. As an example, a half-silvered mirror may be used, which is a plate of glass with a thin coating of aluminium with the thickness of the aluminium coating such that part, typically half, of light incident at a 45-degree angle is transmitted, and the remainder reflected. Instead of a metallic coating, a dielectric optical coating may be used. Depending on the coating that is being used, reflection/transmission ratios may differ in function of the wavelength.
For higher powers and lumen levels, a so-called dynamic solution might be preferred. Here, the heat sink is arranged as a moving element on which a plurality of conversion elements are arranged so that the focussed light beam selectively illuminates the conversion elements when the moving element moves. This improves heat dissipation.

Fig. 2 shows a schematic arrangement of a dynamic application with tangential and radial alignment of conversion segments or conversion elements 42, 44 according to a second embodiment. The converting elements 42, 44 of oriented luminescent material are placed on a spinning wheel 50 having a heat sink function and optionally being made of a heat sink material and/or structure. In this way, the heat generated in the converting elements 42, 44 is spread over the wheel 50 and the average temperature of the converting element can be kept low. Even for dynamic solutions, like color wheels, the converting elements 42, 44 of oriented material segments can be used. The converting elements 42, 44 are attached to the wheel 50 in a proper way to emit a polarized beam. As can be gathered from Fig. 2, the alignment of the orientation of the luminescent material of the converting segments 42, 44 can be arranged radially (right part of Fig. 2) or tangentially (left part of Fig. 2) on the wheel 50. The spot size of a pumping beam 10 should match the size of the converting segments 42, 44. Thus a polarized beam with constant amplitude can be realized based on the excited converted radiation. Also different elements for the generation of different primary colours can be placed on the wheel 50. Both solutions are well-suited for LCD projection applications because the converted polarized beam can be coupled into a combiner without the need of any polarizer enabling higher brightness and lower cost. Even with a colour wheel the LCD technology can be used to save the polarizer and thus achieve higher brightness.

Fig. 3 shows a schematic arrangement of another dynamic application with parallel orientation of conversion elements 46, 48 according to a third embodiment. If the conversion elements 42, 44 on the wheel 50 are made out of one piece, or of several single elements arranged with parallel orientation (horizontal orientation in left part of Fig. 3 and vertical polarization on the right part of Fig. 3), the orientation of the conversion elements exposed to the excitation beam will change in an oscillatory manner, while the wheel 50 is turning. The response will be a beam of light with an oscillatory polarization, but constant intensity. This beam can be split into two beams with perpendicular polarization to each other. Such a light source will be very useful to realize a simplified and highly efficient light source for 3D stereoscopic projection systems.
As shown in Fig. 3, the polarization of the two beams alternates with time, along the spinning of the wheel 50. Additionally, circularly polarised light can be realized very easily by using a lambda/4-retarder though ghosting effects will not be observed any more.

Fig. 4 shows a schematic arrangement of a dynamic application with altering radial and tangential orientation of conversion elements 42, 44 according to a fourth embodiment. If the conversion elements 42, 44 on the wheel 50 are arranged with alternating radial and tangential orientation a beam with digitally alternating polarization can be realized, where the polarization directly switches between vertical and horizontal polarization. In combination with a synchronized display, two frames with perpendicular polarization to each other can be projected simultaneously. Such a light source can be very useful to realize a simplified and highly efficient light source for 3D stereoscopic projection systems.

Fig. 5 shows a schematic arrangement of a dynamic application for generating parallel and orthogonal polarized beams according to a fifth embodiment. A side view of the rotating wheel 50 of the schematic arrangement of the fifth embodiment is shown in the left part of Fig. 5 and a diagram with signal waveforms of the normalized intensity $i_n$ of the converted output beams with parallel (p) and orthogonal (o) polarization after respective beam splitters 22 and 24 is shown in the right part of Fig. 5.

In the fifth embodiment, the excitation beam is directed onto conversion elements (not shown in Fig. 5) of radially or tangentially oriented luminescent material provided on a rotating wheel 50. Thus, when the wheel 50 rotates the polarization of the excited converted radiation continuously changes its orientation in a sinusoidal or oscillating manner. A first beam splitter 20 splits the converted radiation 12 into the upper direction of Fig. 5 towards second and third beam splitters 22, 24. At the second beam splitter 22 orthogonally polarized radiation is split to obtain a first converted output beam 14 with orthogonal polarization while parallelly or vertically oriented radiation is transmitted through said second beam splitter 22 and enters the third beam splitter 24 where it is split to obtain a second converted output beam 16 with parallel polarization.

As can be gathered from the diagram in the right part of Fig. 5, both output beams 14 and 16 have an oscillating or sinusoidal intensity of opposite polarity due to the oscillating or sinusoidal polarity of the converted radiation 12 generated by the conversion elements.

There are several combinations of excitation laser wavelengths and oriented luminescent materials that can be used advantageously. Two examples are mentioned here
without limiting the choice of possible materials. First of all, praseodym-doped yttrium-lithium-fluoride (Pr:YLF) excited with blue laser radiation from the wavelength range between 440-485nm. This material can be produced as an oriented ceramic or with the well-known crystal growth techniques as a well-ordered single crystal. Excitation of this material leads to polarized emission at different wavelengths, which is well-known from spectroscopic experiments. Another example uses infrared laser radiation at about 980nm wavelength and excites, e.g., sodium yttrium fluoride doped with rare earth materials (Erbium (Er), Ytterbium (Yb)), i.e., Er,Yb:NaYF₄. This material can emit at green and red wavelengths and can also be produced as a single crystal or an oriented ceramic. Suitable materials are for example Pr:YLF, Nd:YLF, Ho:YLF, Yb:NaYF₄, Yb:Er:NaYF₄, Ho:NaYF₄, Tm:Er:NaYF₄, Pr,Yb:BaY₂F₈, Pr:SrAl₂O₄:Pr.

As proposed in the above embodiments, oriented ceramics or crystals are used as luminescent converters to generate polarized light for projection applications. They can be used as luminescent converter in static applications or in dynamic applications (e.g. by using a (colour) wheel with tangential or radial alignment). If a colour wheel with parallel alignment of the converter orientation or with alternating 90° orientation is used, polarized light for 3D stereoscopic projection technology can be generated. The converting elements can be used in reflection or in transparent mode, which means that the converted radiation is obtained with or without reflection at the converting elements.

To summarize, method of generating polarized light and a light source using a laser diode pumped oriented ceramic or crystalline material instead of phosphors or unoriented ceramics to produce polarized beams has been described. The light source with oriented crystalline or ceramic converter materials emitting polarized light is well suited for standard liquid crystal display based digital projection as well as polarization-based stereoscopic 3D projection.

While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments and can be used for various types of light sources where an incident light or light beam is to be converted to another wavelength and/or polarized, which can be focussed or not. The heat sink of the dynamic applications is not limited to the shape of a wheel. Any shape and any location of the conversion elements can be used to obtain a desired fixed or changing polarization when the heat sink moves. Other variations to the disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a
study of the drawings, the disclosure, and the appended claims. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting the scope.
CLAIMS:

1. A light source comprising:
   a) a beam generator for generating a light beam (10);
   b) at least one conversion element (40; 42, 44; 46, 48) made of oriented luminescent material excited by said light beam (10) to generate a polarized beam (12); and
   c) a heat sink (50) for dissipating heat generated in said at least one conversion element (40; 42, 44; 46, 48).

2. The light source according to claim 1, wherein said beam generator comprises a laser source for generating a pumping laser beam (10).

3. The light source according to claim 1, wherein said at least one conversion element (40; 42, 44; 46, 48) is adapted to generate said polarized beam (12) at a wavelength different from the exciting wavelength of said light beam (10).

4. The light source according to claim 1, wherein said heat sink (50) is arranged as a moving element on which a plurality of conversion elements (42, 44; 46, 48) is arranged so that said light beam (10) selectively illuminates said conversion elements (42, 44; 46, 48) when the moving element moves.

5. The light source according to claim 4, where said moving element is a spinning wheel and said conversion elements (46, 48) are arranged at the circumference of said spinning wheel in such a manner that the orientation of said oriented luminescent material of all conversion elements (46, 48) is substantially parallel.

6. The light source according to claim 4, where said moving element is a spinning wheel and said conversion elements (42, 44) are arranged at the circumference of said spinning wheel in such a manner that the orientation of said oriented luminescent material of all conversion elements (42, 44) is substantially tangential or radial to said spinning wheel.
7. The light source according to claim 4, where said moving element is a spinning wheel and said conversion elements (42, 44) are arranged at the circumference of said spinning wheel in such a manner that said oriented luminescent material of said conversion elements (42, 44) has alternating radial and tangential orientation with respect to said spinning wheel.

8. The light source according to claim 1, wherein said conversion elements (40; 42, 44; 46, 48) are used in a reflection or transparent mode.

9. The light source according to claim 1, wherein said oriented luminescent material comprises an oriented ceramic or crystal.

10. The light source according to claim 9, wherein said oriented luminescent material comprises Pr:YLF, Nd:YLF, Ho:YLF, Yb:NaYF₄, Yb:Er:NaYF₄, Ho:NaYF₄, Tm:Er:NaYF₄, Pr,Yb:BaY₂F₈ or Pr:SrAl₂O₄.

11. A method for generating a polarized light beam, said method comprising:
   a) generating a light beam (10); and
   b) exciting an oriented luminescent material by said light beam (10) to generate a polarized beam (12); wherein said oriented luminescent material is arranged on a heat sink (50) to dissipate heat generated in said oriented luminescent material.

12. The method of claim 11, wherein said heat sink (50) is configured as a moving element, wherein conversion elements (42, 44; 46, 48) made of said oriented luminescent material are arranged on said moving element, and wherein said moving element is moved such that said conversion elements (42, 44; 46, 48) are selectively excited by said light beam.
Fig. 5
**INTERNATIONAL SEARCH REPORT**

**International application No**
PCT/IB2012/05550O

**A. CLASSIFICATION OF SUBJECT MATTER**

INV. G02B27/28 C09K11/08

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
G02B C09K HOIS H01L

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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**X** Further documents are listed in the continuation of Box C. **X** See patent family annex.

- "A" document defining the general state of the art which is not considered to be of particular relevance
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- "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)
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**Date of the actual completion of the international search**
29 January 2013

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## International Search Report

### Information on patent family members

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