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(54) **Title**: LASER PROJECTOR WITH REDUCED SPECKLE EFFECT

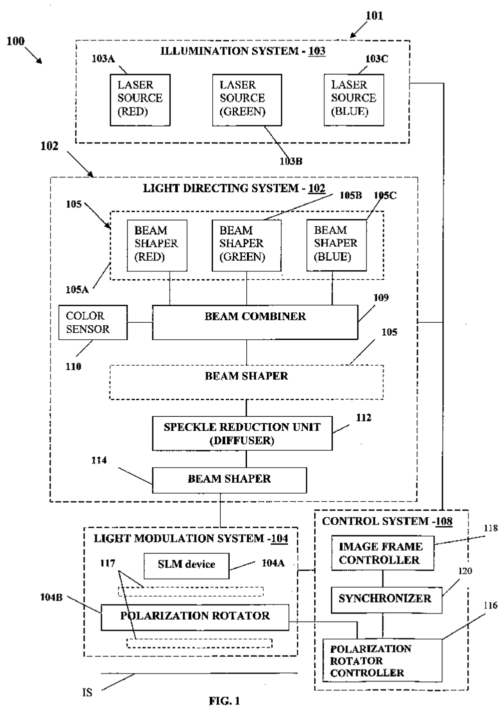

FIG. 1

(57) **Abstract**: A system is presented for use in an imaging system defining an imaging surface onto which sequentially acquired images are projected. The system comprises: a spatial light modulator (SLM) for receiving input linearly polarized light, and producing output polarized light modulated to have a spatial pattern corresponding to an image to be projected onto the imaging surface; and a de-speckling unit for processing said output polarized light while propagating towards the imaging surface to reduce speckle effect in the image as viewed on the imaging surface, the de-speckling unit comprising a polarization rotator assembly configured and operable to alternate polarization state of said output light between different polarization states with a predetermine rate.

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LASER PROJECTOR WITH REDUCED SPECKLE EFFECT

FIELD OF THE INVENTION

This invention is generally in the field of imaging/projecting techniques, and relates to a system and method for speckle reduction in a laser projector/imager. The invention is particularly useful for color laser projectors.

BACKGROUND OF THE INVENTION

The use of lasers as the source of illumination in an imaging/projection systems is advantageous because laser provides monochromatic light with low divergence thus enabling manufacturing of a very compact device. However, a laser source requires special beam shaping and speckle reduction techniques. The creation of a primary speckle pattern can be observed on the surface of a screen when a coherent beam of light passes through an optical system. The primary speckle pattern is caused by the random interference between different light beams of the projected coherent light thus reducing the image quality. Hence, reduction of the perceived amount of speckle is highly desirable.

Some techniques for the speckle reduction in the laser based optical systems are disclosed for example in International (PCT) Patent Publications Nos. WO 2006/024998 and WO 2009/051720. Also, some speckle reduction techniques suitable for use in micro-projectors or micro-displays are disclosed in WO 2009/040822 assigned to the assignee of the present application.

GENERAL DESCRIPTION

There is a need in the art in a speckle reduction technique for reducing the speckle effect in the image being projected onto an image plane, specifically for improving the image quality.

The present invention provides a novel light modulation system and an imaging/projecting system using the same, having reduced speckle effect. The present invention takes advantage of the known phenomena that two orthogonal polarizations of light create different speckle patterns.

The technique of the present invention utilizes controllable change of the state of polarization of light, modulated in accordance with an image to be projected/displayed, while propagating onto an imaging surface. The alternating polarization states are created at a certain rate relative to image frames such that the change of polarization is done at a rate sufficiently high for the human eye to average the different speckle patterns thus reducing the perceived speckle in the projected image.

Two orthogonal polarizations create speckle patterns that are uncorrelated. In this extreme case, averaging the two speckle patterns gives a reduction in speckle contrast by a factor equal to the reciprocal of the square root of 2. Speckle patterns that are created by two laser illuminations that are not orthogonal in polarization will not be entirely uncorrelated, and thus averaging the two speckle patterns will reduce the perceived speckle contrast by a lesser amount.

The invention is based on a further understanding of that in a projector utilizing a liquid crystal based spatial light modulator (SLM), light incident onto the SLM is to be linearly polarized, and accordingly speckle reduction by alternating the polarization state should be applied to light output of the SLM. Moreover, considering a color projector using such type of SLM, where different color channels are sequentially modulated by the same SLM (e.g. different lasers are turned ON and OFF sequentially) or different colors are modulated in parallel by different SLM units, the controllable change of polarization of the modulated light should be synchronized with the light modulation scheme (e.g. with the timing of the lasers). Generally speaking, the controllable change of polarization of the modulated light should be synchronized with the image frames (or sub-frames of different colors within the same frame).

Thus, according to one broad aspect of the invention, there is provided a system for use in an imaging system defining an imaging surface onto which sequentially acquired images are projected, the system comprises: a spatial light modulator (SLM) device for receiving input linearly polarized light, and producing output polarized light modulated to have a spatial pattern corresponding to an image to be projected onto the imaging surface; and a de-speckling unit for processing said output polarized light while propagating towards the imaging surface to reduce speckle effect in the image as viewed on the imaging surface, the de-speckling unit comprising a polarization rotator assembly configured and operable to alternate polarization state of said output light between different polarization states with a predetermine rate.

The SLM device is of a kind operable with polarized light, namely operable with polarized input to its pixel matrix, and utilizing an analyzer at the output of the pixel matrix. The analyzer may include a polarizer that blocks the "unwanted" light and transmits the desired light (the image), or may include a polarizing beam splitter (PBS) that spatially separates the desired light (the image) and the unwanted light. Such polarization-based SLM device is typically a liquid crystal based device, comprising an SLM unit formed by a liquid crystal pixel matrix enclosed between two substrates (typically silicon and glass substrates for LCoS type SLM or glass substrates for LCD type SLM), and the analyzer unit at the output of the pixel matrix (e.g. at the output of the SLM unit). Considering such type of SLM, the imaging system may include a polarizer located upstream of the SLM device, with respect to a direction of propagation of light towards the SLM, to produce said input polarized light; or the light source system is configured for producing polarized light.

The predetermined rate of alternating the polarization state is preferably appropriately selected in accordance with a timing diagram of sequential acquisition of the images. Considering an imaging system configured for projecting color image, the images are constituted by sub-frames of different colors of a common image frame. In some embodiments, the polarization rotator assembly is configured and operable by a control signal to effect a change of the polarization state with a response time shorter than a duration of the sub-frame, the predetermine rate of the polarization rotation is such as to alternates the polarization of light several times during each sub-frame. In some other embodiments, wherein the polarization rotator assembly has a response time comparable with a duration of the sub-frame, the predetermine rate of the polarization rotation is such that the polarization of light in each sub-frame is alternating over consecutive images. In yet further embodiments, where the polarization rotator assembly has a response time comparable with a duration of the image frame, the predetermine rate of the polarization rotation is of about a video frame rate range selected to prevent a stroboscopic effect.

The system is associated with (is connectable to or comprises) a control system configured and operable to operate the polarization rotator to implement said alternating of the polarization state of the output light with the predetermine rate. The control system may include a polarization rotator controller utility, and a synchronizer utility. The polarization rotator controller utility is adapted to generate a control signal to the polarization rotator to apply the polarization rotation to light interacting therewith. The synchronizer utility operates for synchronizing the rate of the change of polarization state in accordance with a response time of the polarization rotator to said control signal, in relation to duration of the image frame. In some embodiments, the control system may be configured and operable to select an image frame during which the polarization rotation is to be effected.

The input light may comprise different light components of different colors, being spatially separated from one another or being components of a common combined light beam.

The polarization rotator may be an active device comprising an active medium responsive to a control signal by a change in its polarization direction. Such an active polarization rotator may comprise a liquid crystal cell. Alternatively, the polarization rotator may be a passive device, comprising different regions carrying media of different polarization directions, respectively. In this case, displacement of the polarization rotator with respect to an optical path of the output polarized light results in alternating locations of said different regions in said optical path.

The imaging system preferably comprises a projection lens unit (single lens or multiple optical elements) located in an optical path of the output light propagating from the SLM to the imaging surface. The polarization rotator may be placed in either one of the following locations: upstream of the projection lens unit, downstream of the projection lens unit, and inside the projection lens unit between optical elements of the projection lens unit.

The system preferably comprises an additional de-speckling unit accommodated upstream of the SLM with respect to a general direction of light propagation through the imaging system and configured and operable for reducing speckle effect in light interacting therewith. Such additional de-speckling unit may be configured and operable to induce interaction of light with a pattern continuously varying in space and time. This additional de-speckling unit may for example comprise a controllably movable diffuser.

The SLM may be configured and operable in a light transmission mode or a light reflection mode. In this connection, it should be understood that terms "upstream" and "downstream" of the SLM actually refer to locations relative to the SLM with respect to a general direction of light propagation. More specifically, location upstream of the SLM refers to a location in the optical path of light before interacting with the SLM pixel matrix, and location downstream of the SLM refers to a location in the optical path of light after being modulated by the SLM pixel matrix

According to another broad aspect of the invention, there is provided an imaging system defining an imaging surface onto which sequentially acquired images are projected, the system comprising: an illumination system producing light carrying multiple light channels, a first de-speckling unit for processing said input light to reduce speckle effect therein, a polarizer for receiving the input light output from the first de-speckling unit and producing input polarized light carrying said multiple light channels, a spatial light modulator (SLM) device for receiving said input light and producing output polarized light modulated to have a spatial pattern corresponding to an image to be projected onto the imaging surface, and a second de-speckling unit for processing said output polarized light while propagating towards the imaging surface to reduce speckle effect in the image as viewed on the imaging surface, the first de-speckling unit applying to light interacting therewith a pattern varying in space and time, and the second de-speckling unit applying varying polarization rotation to said output polarized light.

According to yet another broad aspect of the invention, there is provided a method for projecting an image onto an imaging surface, the method comprising: modulating input polarized light to create output polarized light having a spatial pattern indicative of an image to be projected on the imaging surface, continuously varying polarization state of the output light while directing said output light to the imaging surface, thereby reducing speckle effect in the image viewed in the imaging surface.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a block diagram of a projection system utilizing the principles of the invention for reduction of speckle in the projected image;

Figs. 2A, 2B and 2C show three examples respectively of the configuration of a light modulation system of the present invention suitable for use in an imaging/projection system, for example the system of Fig. 1;

Fig. 3 shows an example of a synchronization mechanism to synchronize the operation of a polarization rotator and a spatial light modulator for synchronizing the polarization rotation effect with the image frames.

DETAILED DESCRIPTION OF EMBODIMENTS

Reference is made to **Fig. 1** exemplifying, by way of a block diagram, a projection display system **100** utilizing a light modulation system of the present invention. The projection display system **100** includes an illumination system **101** producing input light (e.g. multiple light channels), a light directing system **102**, and a light modulation system **104** which is configured and operable for spatially modulating input light incident thereon in accordance with an image to be projected onto a screen/imaging surface **IS** in the image plane. In the present specific but not limiting example, the illumination system **101** includes a light source system **103** generating three light beams of different primary color wavelengths (in red, green and blue regions of the visible optical spectrum). This can be done using a broadband laser equipped with appropriately operable color filters, or using different lasers for different light channels. In this example, three laser sources **103A**, **103B** and **103C** are shown associated with red, green and blue light channels respectively. It should however be noted that the invention is not limited to the multi-color example, and, moreover, for the purposes of the color-projector embodiment of the invention, the laser sources **103A**, **103B** and **103C** actually constitute either laser emitters themselves or color filters, as the case may be, or a combination of both. The invention is also not limited to an imaging/projection system where multiple colors are all generated by laser sources. The light source system may include a combination of lasers and other type light sources (e.g. LED(s)). In this case, the speckle effect created by the coherent light source(s) will be reduced.

Also, in the present not limiting example, multiple light channels are associated with the common light modulation system **104**, e.g. operable in a time division mode for sequentially applying spatial light modulation for different color beams. The image projected onto the imaging surface is generally an integration of three primary colors. In some embodiments a so-called "color sequential projector" is used, meaning that at a given time the SLM modulates light interacting with the pixel matrix in accordance with data of one color, e.g. red, and thus at said given time (imaging session producing a sub0image of the multi0color image frame) only the red light beam is being modulated (e.g. only red light source is illuminating the SLM); the same for green and blue light beams sequentially. Generally, in Color Filter projectors, either a white light source or all three light sources illuminate the SLM typically all the time, and each image pixel is created by filters for three different primary colors located adjacent to each other (sub-pixels).

It should be understood that the invention is not limited to this specific example, and the principles of the invention may be used in any light modulation system in the imaging path of an imaging/projecting system.

The light directing system **102** includes a beam shaping unit **105**, and considering the example of multiple light channels, also includes a beam combiner **109**. The beam combiner **109** may include deflector(s) and wavelength-selective element(s), such as dichroic mirror(s) which are not specifically shown. The wavelength-selective elements may be implemented as dichroic coatings on a substrate surface, which may be configured as plate or cubic element. It should be noted, and also shown in the figure in dashed lines, that the beam shaping unit **105** may be located either upstream or downstream of the beam combiner **109**. Considering the upstream beam shaping unit **105**, it includes three separate beam shapers **105A, 105B** and **105C**. Alternatively, the multiple light channels are first combined by the beam combiner **109**, and then the combined multi-color light beam undergoes beam shaping by the beam shaper unit **105** associated with a pupil filling system.

The beam shaper may be configured as a dual micro-lens array (DMLA), namely a substrate having opposite surfaces thereof patterned to define two co-aligned lenslet arrays. This is disclosed in the International (PCT) publication WO 2009/040822 assigned to the assignee of the present application, which publication is incorporated herein by reference.

Preferably, the beam shaping unit **105** is located downstream of the beam combiner **109** and includes hexagonal microlens array (HexMLA), which is typically common for all light channels (the HMLA can be for one, two or three colors – depending on its location). This improves effective and uniform filling of the projector pupil, namely provides for matching between the exit pupil of the illumination system and the entrance pupil of a projection lens (at the output of the light modulation system). The light directing system **102** may include an additional polarizing beam splitter for the improvement of the polarization extinction ratio and, as a result, the system contrast. The use of additional polarizing beam splitter improves the polarization extinction ratio in the illumination beam. If the extinction ratio of one or more laser sources is the limiting factor for the system contrast, using such cleaning polarizing beam splitter provides improvement of the contrast of the projector as measured on the screen. The configuration and operation of such beam shaping unit is disclosed in co-pending US application Serial No. 12/731,860, which is incorporated herein by reference.

As further shown in the figure, the beam combiner **109** is preferably associated with an optical power sensor **110**. The latter is used to monitor and correct, if needed, the white balance due to the variation of the light source power for different colors, associated with temperature changes and long-term power decay. A beam combiner typically has an "active output" through which most of the combined energy is directed along a desired direction, and a "passive output" associated with the propagation of unavoidable "energy loss". Thus, as shown in the figure, the optical power sensor **110** may be oriented with respect to the beam combiner **109** such as to collect light at the passive output of the combiner **109**. The optical power sensor can be incorporated at any other place within the light directing system **102**. The optical power sensor **110** can be either a simple photo diode using the time sequential character of the projector to beforehand synchronize between the working light source and the photo diode measurement, or a color sensor that may include: three detectors having three (red, blue and green) filters respectively; and/or three detectors with grating; and/or three detectors with dispersive element (prism or other); and/or a spectrometer. Generally, the color sensor may be positioned in any point after combining the color beams. If a simple photo diode is used, then 3 different photodiode sensors can be positioned also before the beam combiner.

The light directing system **102** further includes a speckle reduction unit **112** followed by a further beam shaper **114**. This beam shaper **114** is configured as a beam homogenizer to provide spatially uniform illumination on a light input surface of the light modulation system **104**. This is also disclosed in US 12/731,860.

The light modulation system **104** of the present invention includes a spatial light modulator (SLM) **104A** and a de-speckling unit **104B** at the output of the spatial light modulator **104A**. The de-speckling unit **104B** is configured to eliminate or at least significantly reduce the speckle effect in the image being projected onto the projection surface. The de-speckling unit **104B** includes a polarization rotator device for controllably rotating polarization of the output image-modulated light.

Also provided in the system **100** is a control system **108** connectable (via wires or wireless signal transmission) to the light modulation system **104** and the illumination system **101**, and possibly the light directing system **102**. The control system **108** is typically a computer system including *inter alia* data input and output utilities, memory, processor, etc. which are not specifically shown and the operation of which need not be specifically described. Provided in the control system **108,** for the purposes of the present invention is a polarization rotator controller utility **116,** image frame controller utility **118** for controlling operation of the illumination system and/or SLM, and a synchronizer utility **120** for synchronizing the polarization rotation time scheme in accordance with that of the image frame.

The light modulation system **104** is configured such that modulated light output of the SLM pixel matrix has certain preferred polarization direction (e.g. is linearly polarized), e.g. the SLM device is a liquid crystal based spatial light modulator having a liquid crystal matrix and an analyzer at the output thereof. Accordingly, the system **100** is configured to provide linearly polarized input to the SLM pixel matrix, which can be implemented by either utilizing a polarized light source system, or using an additional polarizer upstream of a light modulating medium in the SLM being a part of the SLM device **104A**, or a part of the illumination system **101**, or a stand-alone element in between the illumination system and the SLM device.

As indicated above, in the case of liquid crystal based light modulation system, the light modulating system operates with an input polarized light and is associated with an output analyzer. The LC medium (pixel matrix) changes the polarization of light interacting therewith in a continuous manner between two extreme polarizations, typically orthogonal polarizations. The analyzer can be either a polarizer that blocks the unwanted light and transmits the desired light (the image) or a polarizing beam splitter (PBS) that spatially separates the desired light (the image) and the unwanted light. If an image pixel is to be produced with maximum brightness, the "on", then the polarization of the light coming out of the LC will be such that it is transmitted via the analyzer. If an image pixel is to be produced with minimum brightness, then the polarization of the light coming out of the LC will be such that it is blocked by the analyzer. When the desired pixel brightness is in between the maximum and minimum values, then the LC will change the polarization of the respective light component to provide a polarization that will be a combination of the two orthogonal polarizations, so that when the LC output passes through the analyzer any brightness level between maximum ("on") and minimum ("off") will be achieved. Considering the reflective type SLM unit, the same polarizing beam splitter can serve as an input polarizer for producing polarized input to the SLM and as an output analyzer.

The need for reducing a speckle effect in illuminating light (i.e. speckle reduction unit **112** applied before image-data modulation of light) is generally associated with a high degree of spatial coherence of laser light resulting in spots and grains on an image created at the input surface of the light modulator. The de-speckling unit **112** is configured for producing a light pattern varying in time and space, e.g. using diffuser(s). The latter may include pupil diffuser or fill diffuser. A displaceable (continuously) diffuser may be used (a voice coil diffuser, rotationally vibrating diffuser, rotating disc diffuser, and tubular rotating diffuser). Passage of the illuminating light through such time and space varying pattern reduces the speckle effect of illumination.

The inventors have found that reduction of speckle effect by inducing the time and space varying pattern (by diffuser) into light before being modulated in accordance with the image to be projected is practically insufficient for the high image quality requirement, and additional speckle reduction is needed to be applied to the image-carrying light, namely light modulated in accordance with the image to be displayed. Moreover, considering the light modulation by an SLM operable with polarized light (such LC based SLM), the speckle reduction by polarization rotation cannot be applied to light upstream the SLM.

The polarization rotator **104B** located in the optical path of the image being projected is configured and operable to alternate the polarization of light passing therethrough, e.g. between two orthogonal polarization states, or between any number of arbitrary polarization states in the general case, giving a lesser amount of speckle reduction. Since two orthogonal polarization states produce two uncorrelated speckle patterns, this arrangement reduces speckle by a factor of the square root of 2 for the light field being imaged. Considering the common light modulation system for multiple colors, where the modulation of multiple colors is carried out in a time sequential mode, the control unit **108** is appropriately preprogrammed to synchronize the operation of the pixel arrangement of the SLM unit **104A** and the operation of the polarization rotator **104B**, such that the polarization rotator alternates the polarization of each color components (R,G,B) between the orthogonal polarization states. Depending on the response time of the polarization rotator **104B**, the polarization of each color can be altered once or more during each color sub-frame or in consecutive frames. Thus, reduction of speckle by a factor of the square root of 2 for each color can be obtained.

It should be understood, and is also mentioned above, that the SLM unit may be of a reflective (LCoS or DMD device) or transmitting type. In case an LCoS reflective type SLM is used, a polarization beams splitter is provided for splitting/combining light propagating towards the SLM and modulated light from the SLM. In this connection, it should be noted that if the LCoS based SLM is used which changes the polarization of light, the polarization rotator **104B** is located in the optical path of light output from the SLM. Whereas DMD based SLM is used, the operation of which is not influenced by the polarization of input light and which does not change the polarization of light interacting therewith, the polarization rotator may be placed in the optical path of either input or output of the SLM.

Reference is made to **Fig. 2A**, showing more specifically an example of the configuration of a light modulation system **104** of the present invention. Here, the reflective LCoS type SLM is used. To facilitate understanding the same reference numbers are used for exemplifying components that are common (at least functionally) in all the examples of the invention. Light field **L** from three light source unit **103** (e.g. light being combined in a common multi-component light beam) is linearly polarized (in s-polarization) and is directed onto an SLM unit **104A** via a polarized beam splitter **115** (and possibly other elements of the light directing system as described above). The polarized beam splitter **115** reflects the laser beams onto the SLM system **104**. The latter includes the SLM unit **104A** including an array of pixels, each one acting as an electrically controlled polarization rotator, an analyzer which in the present example of the reflective type SLM is constituted by the same polarizer beam splitter **115**, and a polarization rotator **104B** . The image is created by operating of selected pixels (in accordance with the image data from the control unit) to rotate polarization of light interacting with these pixels. The light output of each pixel is a combination of s-polarized and p-polarized light. The ratio between s- and p-polarization of light is determined by the desired image data. Where the p-polarized light passes through the polarizing beam splitter (PBS) **115**, the latter transmits the so-modulated light field **L'** (image) towards the polarization rotator **104B** to be then projected onto the imaging surface (not shown here). Light that is incident on pixels that are not rotating the polarization, is reflected from the SLM in its original s-polarization state and the beam splitter **115** reflects this light back towards the light source. An image is created by controllably operating (by the image data) selective pixels (LC cells) to rotate the polarization of light interacting therewith. Thus, the modulated light field that propagates from the SLM **104A** after the PBS **115** (from projection lens) towards the imaging surface is p-polarized. By introducing the polarization rotator **104B** (LC cell) and appropriately operating it (via its driver operated by a control signal from the control system) in the optical path of the modulated light coming out of the beam splitter **115**, the polarization of light that is projected on the imaging surface (screen) can be altered in time, creating different speckle patterns which the human eye averages thus reducing the perceived amount of speckle. Also shown in the figure is a projection lens **117** in the optical path of the modulated light output of the SLM. Although in the present example the polarization rotator **104B** is shown as being located downstream of the projection lens **117**, it may be located upstream thereof, i.e. between the SLM unit **104A** and the projection lens **117**, or can be incorporated into the projection lens unit **117** (being located in between optical elements of the projection lens unit).

Fig. 2B shows another example of the light modulation system **104** utilizing an LCoS type SLM device. Light field **L** from the illumination and light directing systems 101, 102 (e.g. light being combined in a common multi-component light beam) is linearly polarized (in p-polarization) and is directed onto an SLM unit **104A** via a polarized beam splitter **115** (and possibly other elements of the light directing system as described above). The polarized beam splitter **115** transmits the laser beams onto the SLM **104A**. The image is created by operating of selected pixels (in accordance with the image data from the control unit) to rotate polarization of light interacting with these pixels. The light output of each pixel is a combination of s-polarized and p-polarized light. The ratio between s- and p-polarization of light is determined by the desired image data. Where the s-polarized light is reflected by the polarizing beam splitter (PBS) **115**, the latter transmits the so-modulated light field **L'** (image) towards a polarization rotator **104B** to be then projected onto the imaging surface (not shown here).

Fig. 2C shows yet another example of the configuration of a light modulation system **104** of the present invention. This example differs from the above-described examples in that here an SLM device is a transmissive type SLM. The SLM system **104** includes an SLM device **104A** (an array of pixels, each one acting as an electrically controlled polarization rotator), an output analyzer **104C**, and a polarization rotator **104B**. The image is created by operating selected pixels (in accordance with the image data from the control unit) to rotate the polarization of light incident on said pixels. A light field **L** incident onto the array of pixels of the SLM unit has certain linear polarization (e.g. s-polarization), and modulated light field **L'** transmitted through the SLM is p-polarized and propagates towards a polarization rotator **104B** via the projection lens **117**. Thus, similarly to the above-described example, light **L** interacts with (passes through) the SLM **104A** and light **L'** output from the SLM (transmitted through the SLM) is polarized in a predetermined direction. Accordingly, by introducing the polarization rotator **104B** in the optical path of light **L'**, the polarization of light **L'** being projected onto the imaging surface can be altered in time thus creating different speckle patterns which reduce the perceived amount of speckle in the final image being viewed on the imaging surface.

In the examples of Figs. 2A-2C, the polarization rotator **104B** is associated with its driver which operates the polarization rotator in accordance with a control signal coming from the control system to vary the polarization state of light interacting with the polarization rotator. It should be understood that generally the polarization rotator **104B** may be an "active" device or a "passive" device. An active polarization rotator is a device having a polarization affecting medium, such as a liquid crystal cell, shiftable (by an electric signal) between its different operative states differently affecting the polarization of light passing therethrough. A passive polarization rotator has two (or more) regions each of a certain fixed polarization direction, such that shifting the relative location of the passive polarization rotator with respect to an axis of propagation of incident light selectively places the different regions in the optical path of said light. This may for example be a disk-like element carrying two or more different polarization rotating regions, rotation of the disk with a certain speed alternates the locations of these polarization rotating regions in the optical path of the modulated light.

In some embodiments of the invention, the polarization rotator **104B** is Liquid Crystal (LC) cell. Such LC cell includes a layer of liquid crystal located between two cover plates (typically glass plates) and an electrode arrangement appropriately attached to the LC layer for applying voltage thereon. By controlling the voltage applied to the liquid crystal, the polarization of light going through the LC cell (or in some embodiments, reflected therefrom), the device can be altered and rotated. According to some embodiments, the cover plates are coated with antireflection coating to maximize the device' transmission. A quarter wave plate (QWP) can be added to the device, to change elliptical polarization to linear.

Changing the state of polarization of a light field incident on an imaging/projecting surface changes the created speckle pattern. Considering that this change of polarization state is implemented at a sufficiently high rate (e.g. from about 100 microseconds to about 10 milliseconds), the human eye would average the different speckle patterns and the perceived speckle would be reduced. Two orthogonal polarizations may create uncorrelated speckle pattern. In this case, averaging the two speckle patterns reduces the speckle contrast by a factor equal to the reciprocal of the square root of 2. Speckle patterns that are created by two laser illuminations that are not orthogonal in polarization are not entirely uncorrelated, and thus averaging the two speckle patterns reduces the perceived speckle contrast by a lesser amount.

As indicated above, a Liquid Crystal based SLM (with an appropriate analyzer) typically acts as a polarizer. Therefore, in a laser projector utilizing such an SLM, light incident on the SLM is linearly polarized in a preferred orientation relative to the SLM active plane (that of the pixel arrangement formed by LC cells) in order to achieve maximal power efficiency. Accordingly, in order to change (e.g. alternate) the polarization of light being projected and to achieve speckle reduction, polarization rotation may be applied to modulated light output of the SLM. Moreover, in color sequential laser projector, where different color lasers (or alternatively different spectral filters associated with a broadband laser) are turned ON and OFF sequentially, the operation of the polarization rotator **104B** may be synchronized with the timing of the lasers or with the timing of the image frames. The light modulation system **104** of the present invention may be used laser projectors based on color filter display, where the operation of the polarization rotator **104B** or other liquid crystal cell may be synchronized with the image frames. The operation of the polarization rotator **104B** is preferably synchronized with the timings and duration of the image frames (or sub-frames) such that, for each color, the power of light incident on the screen is equally divided between the orthogonal polarizations.

Reference is made to **Fig. 3** exemplifying a synchronization mechanism that may be used to synchronize the operation of the polarization rotator **104B** with the image frames. Four graphs **A**, **B**, **C** and **D** are shown, where graph **A** corresponds to the timely activation of the red, green and blue lasers, where each video frame, typically at the rate of 60 frames per second, is divided into three color sub-frames that contain the red, green and blue data of the frame, being displayed sequentially, and graphs **B**, **C** and **D** show three different examples of a timing diagram of the polarization rotator operation. Graph **B** corresponds to the timing diagram for the case where the polarization rotator has a response time much shorter than the sub-frame duration. In this case, the polarization rotator alternates the polarization of light several times during each sub-frame, thereby resulting in different patterns of speckles during each sub-frame, which reduces the perceived speckle. Graph **C** shows the timing diagram for the case the polarization rotator has a response time comparable with the duration of the sub-frame, e.g. of the order of about 5 milliseconds. In this case, the polarization rotator cannot change the polarization during a single sub-frame. Accordingly, the polarization rotator is synchronized with the projection system such that the polarization of each color is alternating over the consecutive frames. In case the speckle contrast of color sub-frames varies from color to color, it might be preferable to switch the polarization states during that color sub-frame which has the lowest speckle contrast. Since the eye is most sensitive to green light and the least sensitive to blue light, then alternating the polarization after the green sub-frame and during the blue sub-frame would have the best result in terms of reducing speckle contrast. Graph **D** is another example of the timing diagram in the case the polarization rotator has a response time comparable with the frame duration or slower. In that case, the polarization rotator will alternate between its two states twice during the human eye integration time. Where the motivation is to achieve maximum difference between the two polarization states during each eye integration time, assuming eye integration time is about 0.1 sec, then the polarization rotator will alternate between two states every about 0.05sec.

The LC cell based polarization rotator of the present invention can use various liquid crystal materials. Some of them, such as pi-cell, have short rise and fall times of a few milliseconds, which allow using the above exemplified chart **B** control. Some other types, such as TN liquid crystals, have rise and fall times comparable to the sub-frame duration, which is about 5.5 milliseconds in case of 60Hz frame rate; in this case charts **C** and **D** can be used.

Thus, the present invention provides a simple and effective solution for improving the quality of an image being projected onto the imaging surface. It should be understood that various modifications and changes can be applied to the embodiments of the invention as hereinbefore exemplified without departing from its scope defined in and by the appended claims.

CLAIMS:

1. A system for use in an imaging system defining an imaging surface onto which sequentially acquired images are projected, the system comprises: a spatial light modulator (SLM) for receiving input linearly polarized light, and producing output polarized light modulated to have a spatial pattern corresponding to an image to be projected onto the imaging surface; and a de-speckling unit for processing said output polarized light while propagating towards the imaging surface to reduce speckle effect in the image as viewed on the imaging surface, the de-speckling unit comprising a polarization rotator assembly configured and operable to alternate polarization state of said output light between different polarization states with a predetermine rate.

2. A system according to Claim 1, wherein said predetermined rate of alternating the polarization state is selected in accordance with a timing diagram of sequential acquisition of said images.

3. A system according to Claim 2, wherein said images are sub-frames of different colors of a common image frame.

4. A system according to Claim 3, wherein the polarization rotator assembly is configured to respond to a control signal to effect a change of the polarization state with a response time shorter than a duration of the sub-frame, the predetermine rate of the polarization rotation is such as to alternates the polarization of light several times during each sub-frame.

5. A system according to Claim 3, wherein the polarization rotator assembly is configured to respond to a control signal to effect a change of the polarization state with a response time comparable with a duration of the sub-frame, the predetermine rate of the polarization rotation is such that the polarization of light in each sub-frame is alternating over consecutive images.

6. A system according to Claim 3, the polarization rotator assembly is configured to respond to a control signal to effect a change of the polarization state with a response time comparable with a duration of the image frame, the predetermine rate of the polarization rotation is of about a video frame rate range selected to prevent a stroboscopic effect.

7. A system according to any one of the preceding Claims, comprising a control system configured and operable to operate the polarization rotator to implement said alternating of the polarization state of said output light with the predetermine rate.

8. A system according to Claim 7, wherein the control system comprises: a polarization rotator controller utility to generate a control signal to the polarization rotator to apply the polarization rotation to light interacting therewith; and a synchronizer utility for synchronizing the rate of the change of polarization state in accordance with a response time of the polarization rotator to said control signal in relation to a duration of the image frame.

9. A system according to Claim 8, wherein the control system is configured and operable to select an image frame during which the polarization rotation is to be effected.

10. A system according to any one of the preceding Claims, wherein said input light comprises different light components of different colors being spatially separated from one another or being components of a common combined light beam.

11. A system according to any one of the preceding Claims, wherein the SLM is a liquid crystal based SLM comprising a liquid crystal pixel matrix.

12. A system according to Claim 11, comprising a polarizer located upstream of the SLM with respect to a direction of propagation of light towards the SLM to produce said input polarized light.

13. A system according to any one of the preceding Claims, wherein said polarization rotator is an active device comprising an active medium responsive to a control signal by a change in its polarization direction.

14. A system according to Claim 13, wherein said polarization rotator comprises a liquid crystal cell.

15. A system according to any one of Claims 1 to 12, wherein the polarization rotator is a passive device comprising different regions carrying media of different polarization directions, respectively, displacement of the polarization rotator with respect to an optical path of said output polarized light resulting in alternating locations of said different regions in said optical path.

16. A system according to any one of the preceding Claims, comprising a projection lens unit in an optical path of said output light propagating to the imaging surface, said polarization rotator being located in either one of the following: upstream of the projection lens unit, downstream of the projection lens unit, and inside the projection lens unit between optical elements of the projection lens unit.

17. A system according to any one of the preceding Claims, comprising an additional de-speckling unit accommodated upstream of the SLM with respect to a general direction of light propagation through the imaging system and configured and operable for reducing speckle effect in light interacting therewith.

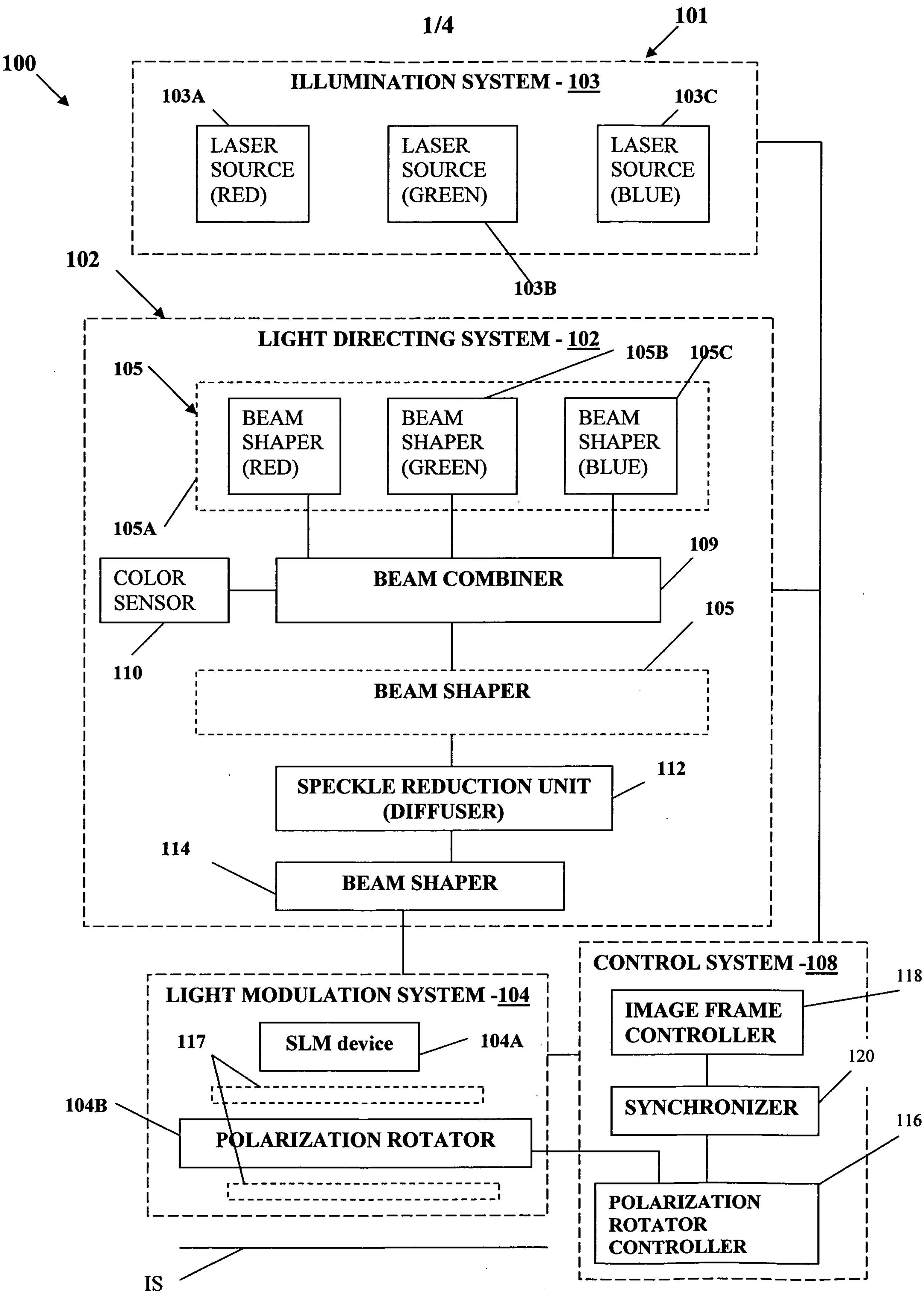
18. A system according to Claim 17, wherein said additional de-speckling unit is configured and operable to induce interaction of light with a pattern continuously varying in space and time.

19. A system according to claim 18, wherein said additional de-speckling unit comprises a controllably moving diffuser.

20. A system according to any one of the preceding Claims, wherein the SLM is configured and operable in a light transmission mode or a light reflection mode.

21. An imaging system defining an imaging surface onto which sequentially acquired images are projected, the system comprising: an illumination system producing light carrying multiple light channels, a first de-speckling unit for processing said input light to reduce speckle effect therein, a polarizer for receiving the input light output from the first de-speckling unit and producing input polarized light carrying said multiple light channels, a spatial light modulator (SLM) for receiving said input light, and producing output polarized light modulated to have a spatial pattern corresponding to an image to be projected onto the imaging surface, and a second de-speckling unit for processing said output polarized light while propagating towards the imaging surface to reduce speckle effect in the image as viewed on the imaging surface, the first de-speckling unit applying to light interacting therewith a pattern varying in space and time, and the second de-speckling unit applying varying polarization rotation to said output polarized light.

22. A method for projecting an image onto an imaging surface, the method comprising: modulating input polarized light to create output polarized light having a spatial pattern indicative of an image to be projected on the imaging surface, continuously varying polarization state of the output light while directing said output light to the imaging surface, thereby reducing speckle effect in the image viewed in the imaging surface.


101
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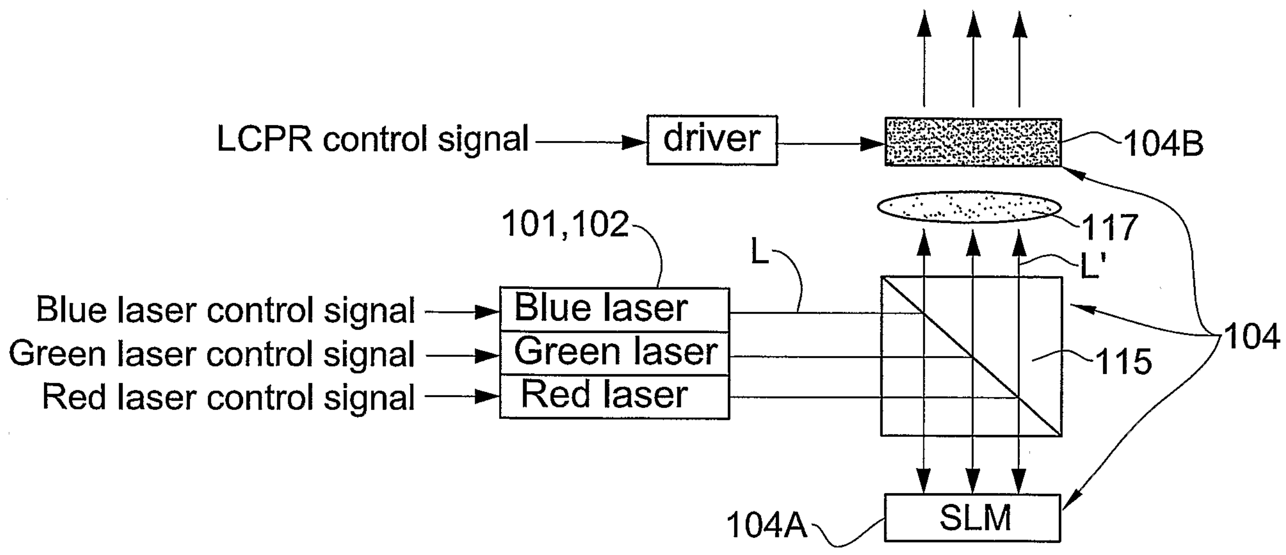
103A
103C
LASER SOURCE (RED)
LASER SOURCE (GREEN)
LASER SOURCE (BLUE)
103B
102
LIGHT DIRECTING SYSTEM - 102
105
105B
105C
BEAM SHAPER (RED)
BEAM SHAPER (GREEN)
BEAM SHAPER (BLUE)
105A
109
COLOR SENSOR
BEAM COMBINER
110
105
BEAM SHAPER
112
SPECKLE REDUCTION UNIT (DIFFUSER)
114
BEAM SHAPER
CONTROL SYSTEM -108
118
LIGHT MODULATION SYSTEM -104
IMAGE FRAME CONTROLLER
117
SLM device
104A
120
SYNCHRONIZER
104B
POLARIZATION ROTATOR
116
POLARIZATION ROTATOR CONTROLLER
IS

FIG. 1


LCPR control signal
driver
104B
117
101,102
L
L'
Blue laser control signal
Green laser control signal
Red laser control signal
Blue laser
Green laser
Red laser
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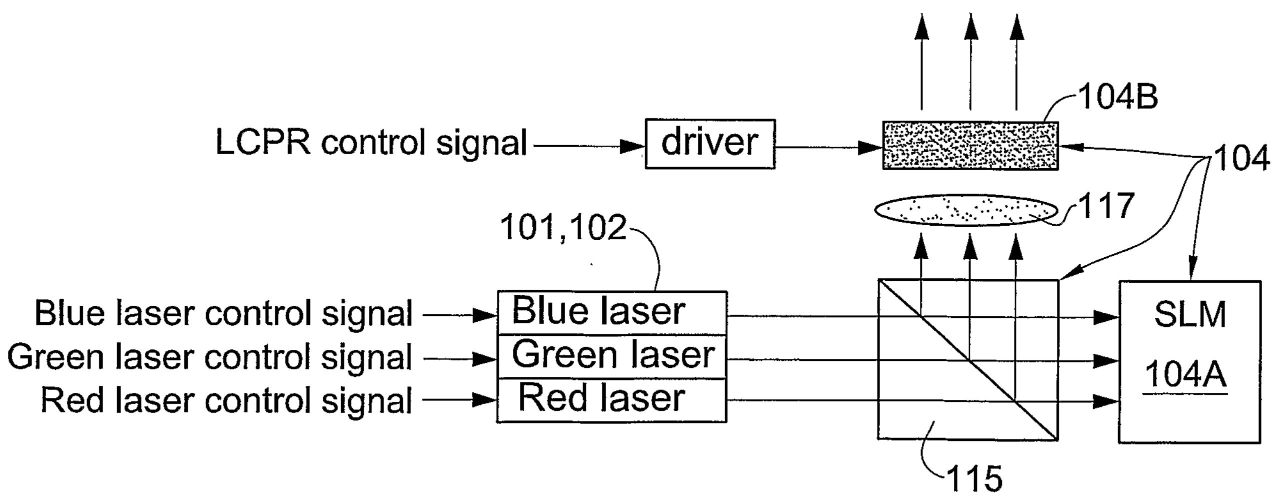
104A
SLM

FIG. 2A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Blue laser
Green laser
Red laser
SLM
104A
115

FIG. 2B

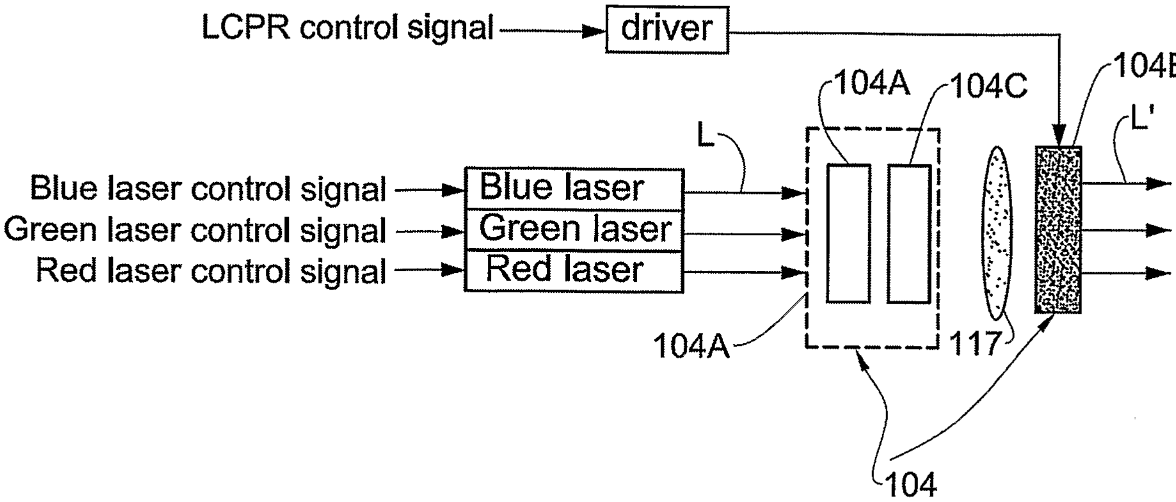
LCPR control signal
driver
104A
104C
104B
L
L'
Blue laser control signal
Green laser control signal
Red laser control signal
Blue laser
Green laser
Red laser
104A
117
104

FIG. 2C

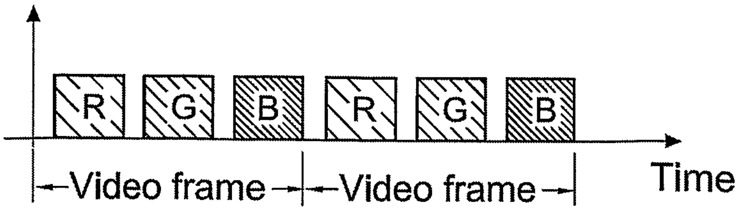

FIG. 3A

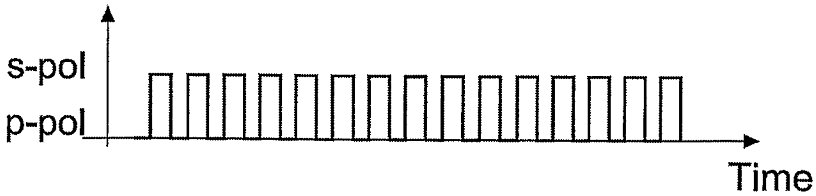

FIG. 3B

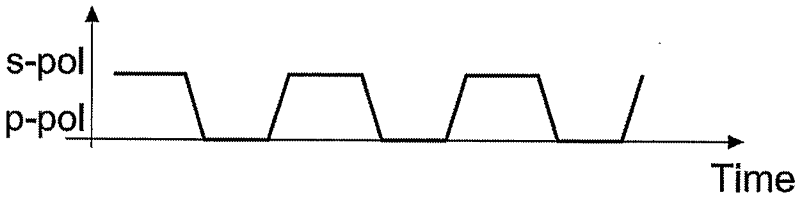

FIG. 3C

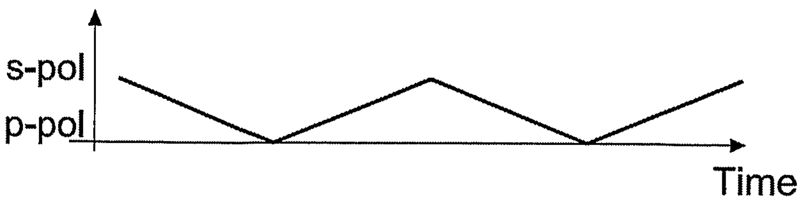

FIG. 3D

INTERNATIONAL SEARCH REPORT

International application No
PCT/IL2010/000335

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B27/48 H04N9/31
ADD.

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)
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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2009/096999 A1 (FRAHM ROBERT E [US] ET AL) 16 April 2009 (2009-04-16) the whole document but in particular pars. 27 and 43	1-22
X	WO 01/57581 A2 (SILICON LIGHT MACHINES INC [US]) 9 August 2001 (2001-08-09) the whole document but in particular page 15 and Figure 16	1-22
A	US 7 370 973 B2 (SAKAGUCHI RYUICHI [JP] ET AL) 13 May 2008 (2008-05-13) the whole document but in particular col. 5 and 6	1-22

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
6 August 2010	13/08/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lubach, Ernst

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/IL2010/000335

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US 7 193 765 B2 (CHRISTENSEN ROBERT R [US] ET AL) 20 March 2007 (2007-03-20) the whole document	1-22

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
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