Abstract: An optical device for relaying polychromatic light is disclosed. The device comprises: an input optical element formed in a planar substrate for receiving and redirecting the light for propagation of the light in a lateral direction within the substrate; and an output optical element formed in the substrate for receiving light propagating within the substrate and coupling the light out of the substrate. The device further comprises a reflector assembly at least partially coating opposite surfaces of the substrate for substantially reflecting light rays impinging on the reflector assembly at an angle within a first angular range, and substantially transmitting light rays of the polychromatic light impinging on the reflector assembly at an angle within a second angular range. In some embodiments of the present invention the input optical element and the output optical element are diffraction gratings having a periodic profile shaped such that at least one portion of the light is dominantly coupled into a diffraction order m satisfying $|m| > 1$.
OPTICAL DEVICE FOR RELAYING POLYCHROMATIC LIGHT

RELATED APPLICATION/S
This application claims the benefit of priority from U.S. Patent Application Nos. 61/006,242 filed January 2, 2008, and 61/129,392 filed June 23, 2008, the contents of which are hereby incorporated by reference.

FIELD AND BACKGROUND OF THE INVENTION
The present invention, in some embodiments thereof, relates to optics and, more particularly, but not exclusively, to an optical relay device for relaying polychromatic light and to wearable/portable display systems.

Miniaturization of electronic devices has always been a continuing objective in the field of electronics. Electronic devices are often equipped with some form of a display, which is visible to a user. As these devices reduce in size, there is an increase need for manufacturing compact displays, which are compatible with small size electronic devices. Besides having small dimensions, such displays should not sacrifice image quality, and be available at low cost. By definition the above characteristics are conflicting and many attempts have been made to provide some balanced solution.

An electronic display may provide a real image, the size of which is determined by the physical size of the display device, or a virtual image, the size of which may extend the dimensions of the display device.

A real image is defined as an image, projected on or displayed by a viewing surface positioned at the location of the image, and observed by an unaided human eye (to the extent that the viewer does not require corrective glasses). Examples of real image displays include a cathode ray tube (CRT), a liquid crystal display (LCD), an organic light emitting diode array (OLED), or any screen-projected displays. A real image could be viewed normally from a distance of about at least 25 cm, the minimal distance at which the human eye can utilize focus onto an object. Unless a person is long-sighted, he may not be able to view a sharp image at a closer distance.

By contrast to a real image, a virtual image is defined as an image, which is not projected onto or emitted from a viewing surface, and no light ray connects the image and an observer. A virtual image can only be seen through an optic element, for
example a typical virtual image can be obtained from an object placed in front of a converging lens, between the lens and its focal point. Light rays, which are reflected from an individual point on the object, diverge when passing through the lens, thus no two rays share two endpoints. An observer, viewing from the other side of the lens would perceive an image, which is located behind the object, hence enlarged. A virtual image of an object, positioned at the focal plane of a lens, is said to be projected to infinity. A virtual image display system, which includes a miniature display panel and a lens, can enable viewing of a small size, but high content display, from a distance much smaller than 25 cm. Such a display system can provide a viewing capability which is equivalent to a high content, large size real image display system, viewed from much larger distance.

Also known is the use of holographic optical elements in portable virtual image displays. Holographic optical elements serve as an imaging lens and a combiner where a two-dimensional, quasi-monochromatic display is imaged to infinity and reflected into the eye of an observer.

U.S. Patent No. 4,711,512 to Upatnieks describes a diffractive planar optics head-up display configured to transmit collimated light wavefronts of an image, as well as to allow light rays coming through the aircraft windscreen to pass and be viewed by the pilot. The light wavefronts enter an elongated optical element located within the aircraft cockpit through a first diffractive element, are diffracted into total internal reflection within the optical element, and are diffracted out of the optical element by means of a second diffractive element into the direction of the pilot's eye while retaining the collimation.

U.S. Patent Nos. 5,966,223 and 5,682,255 to Friesem et al. describes a holographic optical device similar to that of Upatnieks, with the additional aspect that the first diffractive optical element acts further as the collimating element that collimates the waves emitted by each data point in a display source and corrects for field aberrations over the entire field-of-view.

U.S. Patent No. 6,757,105 to Niv et al., the contents of which are hereby incorporated by reference, provides a diffractive optical element for optimizing a field-of-view for a multicolor spectrum. The optical element includes a light-transmissive substrate and a linear grating formed therein. Niv et al. teach how to select the pitch of
the linear grating and the refraction index of the light-transmissive substrate so as to trap a light beam having a predetermined spectrum and characterized by a predetermined field of view to propagate within the light-transmissive substrate via total internal reflection. Niv et al. also disclose an optical device incorporating the aforementioned diffractive optical element for transmitting light in general and images in particular into the eye of the user.

A binocular device which employs several diffractive optical elements is disclosed in U.S. Published Application Nos. 20060018014 and 20060018019, and in International Patent Application, Publication No. WO 2006/008734, -the contents of which are hereby incorporated by reference. An optical relay is formed of a light transmissive substrate, an input diffractive optical element and two output diffractive optical elements. Collimated light is diffracted into the optical relay by the input diffractive optical element, propagates in the substrate via total internal reflection and coupled out of the optical relay by two output diffractive optical elements. The input and output diffractive optical elements preserve relative angles of the light rays to allow transmission of images with minimal or no distortions. The output elements are spaced apart such that light diffracted by one element is directed to one eye of the viewer and light diffracted by the other element is directed to the other eye of the viewer. The binocular design of these references significantly improves the field-of-view.

The diffraction and transmission efficiency of light depends on the wavelength (color) of the light. The above virtual image devices are designed to have a maximal diffraction and transmission efficiency for a particular color, while compromising with lower diffraction and transmission efficiencies of other colors. U.S. Published Application No. 20060221448 attempts to provide a solution to this problem using a Multi-plane optical apparatus. The apparatus comprises two or three light transmissive substrates each transmitting a different portion of the spectrum. The transmission efficiency of each light transmissive substrate is tailored to the respective spectral range.

Additional background art includes U.S. Patent Nos. 6,805,490 and 7,206,107.

SUMMARY OF THE INVENTION

According to an aspect of some embodiments of the present invention there is provided an optical relay device, for relaying polychromatic light. The device
comprises: an input optical element formed in a planar substrate for receiving and redirecting the light for propagation of the light in a lateral direction within the substrate; and an output optical element formed in the substrate for receiving light propagating within the substrate and coupling the light out of the substrate. The device further comprises a reflector assembly at least partially coating opposite surfaces of the substrate for substantially reflecting light rays impinging on the reflector assembly at an angle within a first angular range, and substantially transmitting light rays of the polychromatic light impinging on the reflector assembly at an angle within a second angular range being different from the second angular range.

According to an aspect of some embodiments of the present invention there is provided an optical relay device for relaying polychromatic light. The device comprises an input optical element formed in a substrate for receiving and redirecting the light for propagation of the light in a lateral direction within the substrate; and an output optical element formed in the substrate for receiving light propagating within the substrate and coupling the light out of the substrate. In some embodiments of the present invention the input optical element and the output optical element are diffraction gratings having a periodic profile shaped such that at least one portion of the light is dominantly coupled into a diffraction order \( m \) satisfying \( |m| > 1 \).

According to an aspect of some embodiments of the present invention there is provided a system for generating and transmitting an image. The system comprises the optical relay device, and an image generating system for providing the optical relay device with collimated light constituting the image.

According to an aspect of some embodiments of the present invention there is provided a method of viewing an image using the optical relay device. The method comprises transmitting a light beam constituting the image to the input optical element and viewing the image through the output optical element.

According to some embodiments of the present invention the output optical element is a left eye output optical element for receiving light propagating leftward within the substrate and outcoupling the light in a direction of a left eye of a viewer, and the device further comprises a right eye output optical element for receiving light propagating rightward within the substrate and outcoupling the light in a direction of a right eye of the viewer.
According to some embodiments of the present invention at least one of the input and the output optical elements is a reflective optical element coated by a reflective coat.

According to an aspect of some embodiments of the present invention there is provided a system for generating and transmitting an image. The system comprises an image generating system for generating a collimated polychromatic light beam constituting an image spanned over an angular range of at least 25 degrees, and an optical relay device, having a single substrate at least partially coated with a reflector assembly. The optical relay device relays the polychromatic light beam within the single substrate via internal reflections and/or reflections off the reflector assembly. The polychromatic light beam is relayed to provide each of a left eye and a right eye of a user with a view of the angular range by its entirety.

According to some embodiments of the present invention at least a few light rays of the polychromatic light propagate within the substrate at a propagation angle which is smaller than axritical angle.

According to some embodiments of the present invention the reflector assembly comprises a plurality of layers arranged such that adjacent layers of the plurality of layers have different refractive indices.

According to some embodiments of the invention the plurality of layers form an alternating sequence of refractive indices.

According to some embodiments of the invention the plurality of layers comprises at least 32 layers.

According to some embodiments of the present invention the reflector assembly is constituted for selectively transmitting or reflecting of any light ray having a wavelength ranging from about 440 nm to about 650 nm in a manner such that: if an incidence angle of the light ray is less than 15 degrees, then the reflector assembly allows transmission of the light ray therethrough; and if the incidence angle of the light ray is at least 20 degrees, then the reflector assembly reflects the light ray.

According to some embodiments of the present invention the input optical element and the output optical element are diffraction gratings having a periodic profile shaped such that all diffraction orders m satisfying |m| > 1 are suppressed.

According to some embodiments of the present invention the input optical element and the output optical element are diffraction gratings having a periodic profile
shaped such that at least one portion of the light is dominantly coupled into a diffraction order \( m \) satisfying \(|m| > 1\).

According to some embodiments of the present invention the input optical element and the output optical element are diffraction gratings having a periodic profile shaped such that different portions of the light, respectively corresponding to different sub-spectra of the polychromatic light, are dominantly coupled into different diffraction orders.

According to some embodiments of the present invention the input optical element and the output optical element are diffraction gratings characterized by a periodic profile having a period which is larger than a largest wavelength of the polychromatic light.

According to some embodiments of the present invention the input optical element and the output optical element are diffraction gratings characterized by a periodic profile having at least two grooves per period.

Unless otherwise defined, all technical and/or scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the invention pertains. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of embodiments of the invention, exemplary methods and/or materials are described below. In case of conflict, the patent specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and are not intended to be necessarily limiting.

Implementation of the method and/or system of embodiments of the invention can involve performing or completing selected tasks manually, automatically, or a combination thereof. Moreover, according to actual instrumentation and equipment of embodiments of the method and/or system of the invention, several selected tasks could be implemented by hardware, by software or by firmware or by a combination thereof using an operating system.

For example, hardware for performing selected tasks according to embodiments of the invention could be implemented as a chip or a circuit. As software, selected tasks according to embodiments of the invention could be implemented as a plurality of software instructions being executed by a computer using any suitable operating system. In an exemplary embodiment of the invention, one or more tasks according to exemplary
embodiments of method and/or system as described herein are performed by a data processor, such as a computing platform for executing a plurality of instructions. Optionally, the data processor includes a volatile memory for storing instructions and/or data and/or a non-volatile storage, for example, a magnetic hard-disk and/or removable media, for storing instructions and/or data. Optionally, a network connection is provided as well. A display and/or a user input device such as a keyboard or mouse are optionally provided as well.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the invention are herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of embodiments of the invention. In this regard, the description taken with the drawings makes apparent to those skilled in the art how embodiments of the invention may be practiced.

In the drawings:

FIG. 1 is a schematic illustration of light diffraction by a linear diffraction grating;

FIG. 2 is a schematic illustration of an optical relay device, for relaying polychromatic light, according to various exemplary embodiments of the present invention;

FIG. 3 is a schematic illustration of a reflector assembly, according to various exemplary embodiments of the present invention;

FIGs. 4A-C show simulation results for reflectance of a reflector assembly as for various wavelengths;

FIG. 4D is a graph showing thicknesses layers in a reflector assembly, according to various exemplary embodiments of the present invention;

FIGs. 5A-B are schematic illustrations of a profile of grating, according to various exemplary embodiments of the present invention;

FIG. 6 is a graph showing the diffraction efficiency as a function of the incidence angle for three representative wavelengths;
FIG. 7 is a graph showing the overall optical power inputted into the device illustrated in Figure 2 in which the input and output elements are diffraction gratings having a profile shape as illustrated in Figures 5a-b;

FIG. 8 is a schematic illustration of a system for generating and transmitting an image, according to various exemplary embodiments of the present invention; and

FIGs. 9A-C are schematic illustrations of a wearable device, according to various exemplary embodiments of the present invention.

DESCRIPTION OF SPECIFIC EMBODIMENTS OF THE INVENTION

The present invention, in some embodiments thereof, relates to optics and, more particularly, but not exclusively, to an optical relay device for relaying polychromatic light and to wearable/portable display.

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not necessarily limited in its application to the details of construction and the arrangement of the components and/or methods set forth in the following description and/or illustrated in the drawings and/or the Examples. The invention is capable of other embodiments or of being practiced or carried out in various ways.

When a ray of light propagating within a light-transmissive substrate and striking one of its internal surfaces at an angle $\phi_i$ as measured from a normal to the surface, it can be either reflected from the surface or refracted out of the surface into the open air in contact with the substrate. The condition according to which the light is reflected or refracted is determined by Snell's law, which is mathematically realized through the following equation:

$$n_A \sin \phi_2 = n_s \sin \phi_{1s} \quad \text{(EQ. 1)}$$

where $n_s$ is the index of refraction of the light-transmissive substrate, $n_A$ is the index of refraction of the medium outside the light transmissive substrate ($n_s > n_A$), and $\phi_2$ is the angle in which the ray is refracted out, in case of refraction. Similarly to $\phi_1$, $\phi_2$ is measured from a normal to the surface. A typical medium outside the light transmissive substrate is air having an index of refraction of about unity.

As a general rule, the index of refraction of any substrate depends on the specific wavelength $\lambda$ of the light which strikes its surface. Given the impact angle, $\phi_1$, and the
refraction indices, $n_s$ and $n_λ$. Equation 1 has a solution for $φ_2$ only for $φ_i$ which is smaller than arcsine of $n_λ/n_s$ often called the critical angle and denoted $α_c$. Hence, for sufficiently large $φ_1$ (above the critical angle), no refraction angle $φ_2$ satisfies Equation 1 and light energy is trapped within the light-transmissive substrate. In other words, the light is reflected from the internal surface as if it had stroked a mirror. Under these conditions, total internal reflection is said to take place. Since different wavelengths of light (i.e., light of different colors) correspond to different indices of refraction, the condition for total internal reflection depends not only on the angle at which the light strikes the substrate, but also on the wavelength of the light. In other words, an angle which satisfies the total internal reflection condition for one wavelength may not satisfy this condition for a different wavelength.

In planar optics one of the methods to couple light in and out of the substrate is with the aid of diffraction gratings. Such diffraction elements are typically manufactured by holographic or lithographic means. Diffraction gratings can operate in transmission mode, in which case the light experiences diffraction by passing through the gratings, or in reflection mode in which case the light experiences diffraction while being reflected off the gratings.

Figure 1 schematically illustrates diffraction of light by a linear diffraction grating operating in transmission mode. One of ordinary skills in the art, provided with the details described herein would know how to adjust the description for the case of reflection mode.

A wavefront $l$ of the light propagates along a vector $l$ and impinges upon a grating $g$ engaging the $x$-$y$ plane. The normal to the grating is therefore along the $z$ direction and the angle of incidence of the light $φ_i$ is conveniently measured between the vector $z^*$ and the $z$ axis. In the description below, $φ$ is decomposed into two angles, $φ_x$ and $φ_y$, where $φ_x$ is the incidence angle in the $z$-$x$ plane, and $φ_y$ is the incidence angle in the $z$-$y$ plane. For clarity of presentation, only $φ_y$ is illustrated in Figure 1.

The grating has a periodic linear structure along a vector $g$, forming an angle $Θ_k$ with the $y$ axis. The period of the grating (also known as the grating pitch) is denoted by $D$. The grating is formed on a light transmissive substrate having an index of refraction denoted by $n_s$. 
Following diffraction by grating 2, wavefront 1 changes its direction of propagation. The principal diffraction direction which corresponds to the first order of diffraction is denoted by $\mathbf{d}$ and illustrated as a dashed vector in Figure 1. Similarly to the angle of incidence, the angle of diffraction $\phi_{d}$ is measured between the vector $\mathbf{d}$ and the $z$ axis, and is decomposed into two angles, $\phi_{dx}$ and $\phi_{dy}$, where $\phi_{dx}$ is the diffraction angle in the $x$-$z$ plane, and $\phi_{dy}$ is the diffraction angle in the $y$-$z$ plane.

The relation between the grating vector $g$, the diffraction vector $d$ and the incident vector $i$ can therefore be expressed in terms of five angles $(\Theta, \phi_{ix}, \phi_{iy}, \phi_{dx}$ and $\phi_{dy})$ and it generally depends on the wavelength $\lambda$ of the light and the grating period $D$ through the following pair of equations:

\[
\begin{align*}
\sin(\phi_{ix}) - n_s \sin(\phi_{dx}) &= QJD \sin(\Theta_R) \quad \text{(EQ. 2)} \\
\sin(\phi_{iy}) + n_s \sin(\phi_{dy}) &= QJD \cos(\Theta_R). \quad \text{(EQ. 3)}
\end{align*}
\]

Without the loss of generality, the Cartesian coordinate system can be selected such that the vector $i$ lies in the $y$-$z$ plane, hence $\sin(\phi_{ix}) = 0$. In the special case in which the vector $g$ lies along the $y$ axis, $\Theta = 0^\circ$ or $180^\circ$, and Equations 2-3 reduce to the following one-dimensional grating equation:

\[
\sin \phi_{ix} + n_s \sin \phi_{dy} = \pm \lambda/D. \quad \text{(EQ. 4)}
\]

According the known conventions, the sign of $\phi_{ix}$, $\phi_{iy}$, $\phi_{dx}$ and $\phi_{dy}$ is positive, if the angles are measured clockwise from the normal to the grating, and negative otherwise. The dual sign on the RHS of the one-dimensional grating equation relates to two possible orders of diffraction, $+1$ and $-1$, corresponding to diffractions in opposite directions, say, "diffraction to the right" and "diffraction to the left," respectively. Generally, there can also other orders of diffractions (namely other than $\pm 1$) and a more general form of Equation 4 reads:

\[
\sin \phi_{iy} + n_s \sin \phi_{dy} = m \lambda/D, \quad \text{(EQ. 5)}
\]

where $m$ is an integer $(m = 0, \pm 1, \pm 2, \ldots)$ denoting the diffraction order. The special case for which $m = 0$, is known in the literature as the zero diffraction order, and is sometimes referred to as the non-diffraction case. A light ray, entering a substrate through a grating, impinge on the internal surface of the substrate opposite to the grating at an angle which depends on the two diffraction components $\sin(\phi_{dy})$ and $\sin(\phi_{dy})$ according to the following equation:
When $\phi_d$ is larger than the critical angle $\phi_c$, the wavefront undergoes total internal reflection and begin to propagate within the substrate.

Generally, polychromatic light is coupled into a light transmissive substrate with the aid of input and output optical elements which can be of a refractive, reflective or diffractive type. In traditional configurations the input optical element incouple the light into the substrate at an angle which is above the critical angle thus ensuring propagation via total internal reflection in the substrate. When diffractive input elements are employed, the diffractive element is adjusted such that the first diffraction order ($m = \pm 1$) corresponds to an angle which is above the critical angle. Usually, in order to maximize the system efficiency the diffraction function in known planar configurations is adjusted to couple most of the incoming light into the first diffraction order.

When polychromatic light interacts with an input element, the response of one wavelength differs from the response of another wavelength. The different responses may lead to color non-uniformity over the field-of-view, since some wavelengths can enter the substrate while fulfilling the total internal reflection condition while other wavelengths may escape the substrate without propagation therein. Traditional techniques take the above limitation under consideration and design the input and output elements so as to ensure total internal reflection for the entire spectrum of the polychromatic light (to this end see, e.g., U.S. Patent No. 6,757,105 supra). Yet, such design, results in a rather narrow field-of-view. For example, for a substrate with refractive index of about 1.5, only light rays which impinge on the input element at an angle which is less than $3^\circ$ in absolute value, can propagate in the substrate by means of total internal reflection.

Attempts have been made to use an optical apparatus with several substrates in which each substrates is formed with an input and an output elements which are optimized to a specific range of wavelengths (to this end see, e.g., U.S. Published Application No. 20060221448 and U.S. Patent No. 7,206,107 supra). The present Inventors discovered a different solution to this problem.

Reference is now made to Figure 2 which is a schematic illustration of an optical relay device 10, for relaying polychromatic light, according to various exemplary embodiments of the present invention. The light is illustrated as a block arrow 12 in
Figure 2, and is to be understood as representing a light beam. A light beam is typically described as a plurality of light rays or a plurality of photons.

The light can be generated by, transmitted through or reflected from an object 34, such as, but not limited to, a display panel or the like. Thus, in some embodiments of the present invention light beam 12 constitutes an image of object 34. Hereinunder, a reference to "image 34" should be understood as a reference to the imagery information of object 34 carried by the light.

Device 10 is typically planar. Figure 2 illustrates a cross sectional view of device 10 in the y-z plane. Device 10 comprises a planar substrate 14 made of a light transmissive material and having a front side major surface 24 and a back side major surface 23. Substrate 14 is formed with an input optical element 13 for receiving and redirecting light 12 for propagation of the light in a lateral direction within substrate 14. The lateral direction is in the y-z plane and is generally along the y and/or -y direction, although locally some confined light propagation is allowed at an angle to the y direction since the propagation is via reflections as further detailed hereinunder.

A light ray is mathematically described as a one-dimensional mathematical object. As such, a light ray intersects any surface which is not parallel to the light ray at a point. A light beam therefore intersects a surface which is not parallel to the beam at a plurality of points, one point for each light ray of the beam. In the schematic illustration of Figure 2, light beam 12 intersects surface 23 at a plurality of points.

The angle by which input element 13 redirects a light ray depends on the angle of incidence, the wavelengths of the incoming light ray or photon, and the characteristics of the input element. In the case in which input element 13 is a linear diffraction grating, its grating period D, as discussed above, is a factor in determining the angle of redirection. Illustrated in Figure 2 are several exemplary ray orbits within substrate 14. Specifically, six orbits are shown, three representing rightward propagation (generally along the y direction) and three representing leftward propagation (generally along the -y direction). Yet, it is not intended to limit the scope of the preset invention to any number of ray orbits. Further, although Figure 2 shows both rightward and leftward propagation, this need not necessarily be the case since in some embodiments element 13 is constituted such that only rightward or only leftward propagation is allowed. For
example, when element 13 is located near the left end of substrate 14 leftward propagation is suppressed.

For clarity of presentation, the illustrated ray orbits corresponding to incoming light rays which are perpendicular to input element 13 (zero angle of incidence). One of ordinary skill in the art will know how to draw ray orbits corresponding to other angles of incidence. Thus, the illustrated ray orbits may be viewed as describing propagation of light rays having different wavelengths. For example, the orbits shown as solid lines may correspond to blue light rays, the orbits shown as dotted lines may correspond to red light rays and orbits shown as dashed lines may correspond to green light rays.

Device 10 further comprises one or more output optical elements 15, 19 formed in substrate 14 for receiving the propagated light and coupling the light out of substrate 14. Preferably, the output optical element(s) outcouple the propagated light in an angle preserving manner, namely, each light ray is redirected by the output optical elements to exit the substrate at an exit angle which is substantially the same as the angle of incidence (e.g., with an angular deviation of less than 0.1°, more preferably 0.03°)

Thus, an output element of device 10 provides an outgoing light beam 18. The outgoing light beam provided by element 15 is shown at 18a and the outgoing light beam provided by element 19 is shown at 18b.

In various exemplary embodiments of the invention all lateral light propagation in device 10 occurs within a single substrate. It is to be understood that although the schematic illustration of Figure 2 shows one input optical element and two output optical elements, other configurations, such as, but not limited to, a configuration in which device 10 includes one input element and one output element, are not excluded. When device 10 includes one input element and one output element, say output element 15, only one outgoing light beam (beam 18a in the present example) is provided.

The advantage of having two output optical elements is that such configuration can be used as a binocular device whereby light beam 18a is provided to a left eye 25 and light beam 18b is provided to a right eye 30.

Each of the input and output optical elements can be a refractive element, a reflective element or a diffractive element. In embodiments in which a refractive element is employed, the optical element can comprise a plurality of linearly stretched array of mini- or micro-prisms, and the redirection of light is generally by the refraction
phenomenon described by Snell's law. Thus, in these embodiments, the input element can refract the light into the substrate for propagation within the substrate and the output element(s) can refract one or more of the propagating light rays out of the substrate. Refractive elements in the form of mini- or micro-prisms are known in the art and are found, e.g., in U.S. Patent Nos. 5,396,350, 5,671,994, 6,425,675 and 6,081,331, the contents of which are hereby incorporated by reference.

In embodiments in which a reflective element is employed, any of the input and/or output optical elements can comprise a plurality of dielectric mirrors, and the redirection of light is generally by the reflection phenomenon, described by the basic law of reflection. Thus, in these embodiments, the input element can reflect the light into the substrate for propagation within the substrate and the output element(s) can reflect one or more of the propagating light rays out of the substrate. Reflective elements in the form of dielectric mirrors are known in the art and are found, e.g., in U.S. Patent No. 6,829,095 and U.S. Published Application No. 20030165017.

The input and/or output elements can also combine reflection with refraction. For example, the input and/or output optical elements can comprise a plurality of partially reflecting surfaces located in the substrate. In this embodiment, the partially reflecting surfaces are preferably parallel to each other. Optical elements of this type are known in the art and found, e.g., in U.S. Patent No. 6,829,095, the contents of which are hereby incorporated by reference.

In embodiments in which diffractive element is employed, the input and/or output elements can comprise a grating and the redirection of light is generally by the diffraction phenomenon. Thus, in these embodiments the input element can diffract the light into the substrate for propagation of the light within the substrate and the output element can diffract one or more of the propagating light rays out of the substrate.

The term "diffracting" as used herein, refers to a change in the propagation direction of a wavefront, in either a transmission mode or a reflection mode. In a transmission mode, "diffracting" refers to change in the propagation direction of a wavefront while passing through the diffractive element; in a reflection mode, "diffracting" refers to change in the propagation direction of a wavefront while reflecting off the diffractive element at an angle different from the basic reflection angle (which is identical to the angle of incidence).
The input and output optical elements of the present embodiments can be linear diffraction gratings having identical periods and being in a parallel orientation. This embodiment is advantageous because it is angle-preserving. Specifically, the identical periods and parallelism of the linear gratings ensure that for each light ray entering the device via the input grating and exiting the device via the output grating(s), the direction of entry is substantially the same as the direction of exit.

The identical periods and parallelism of the linear gratings can also ensure that the relative orientation between light rays exiting the substrate is similar to their relative orientation before the impingement on the input optical element. Thus, when the light constitutes a virtual image focused to infinity, whereby light rays emanating from a particular point of the object being viewed are parallel to each other while impinging on the input grating, exit the output grating(s) also parallel to each other and substantially at the same direction as the direction of entry. When the device includes two output gratings, such outgoing light rays are viewed by both eyes as arriving from the same angle in space. It will be appreciated that with such configuration viewing convergence is easily obtained without eye-strain or any other inconvenience to the viewer, unlike the other binocular devices in which relative positioning and/or relative alignment of the optical elements is necessary.

Although in Figure 2 input element 13 engages surface 24 and output optical elements 15 and 19 engage surface 23, this need not necessarily be the case, since the input and output optical elements can engage any of the surfaces 23 and 24 of substrate 14, in any combination. One ordinarily skilled in the art would appreciate that this corresponds to any combination of transmissive and reflective optical elements. Thus, for example, suppose that the input optical element is formed on surface 23 of substrate 14 and the output optical elements) are formed on surface 24. Suppose further that the light impinges on surface 23 and it is desired to outcouple the light out of surface 24. In this case, the input optical element and the output optical elements are all transmissive, so as to ensure that the entrance of the light through the input optical element, and the exit of the light through the output optical elements. Alternatively, if the input and output optical elements are all formed on surface 23, then the input optical element remain transmissive, so as to ensure the entrance of the light therethrough, while the output optical elements are reflective, so as to reflect the propagating light at an angle
which is sufficiently small to couple the light out. In such configuration, light can enter the substrate through the side opposite the input optical element, be reflected by the input optical element, propagate within the substrate and be outcoupled by the output optical element(s) operating in a transmission mode.

When one of the optical elements operates in reflection mode, it can be coated by a reflective coat 46, having high reflectivity of, for example, 80% or more. Reflective coat 46 can be, for example, aluminum, chromium or a gold foil.

In some embodiments of the present invention, the input optical element and output optical element are diffraction gratings having a periodic profile selected such that all diffraction orders $m$ satisfying $|m| > 1$ are suppressed.

As used herein a diffraction order $m$ (m being other than -1, 0 or 1) is said to be "suppressed" if the relative intensity of light rays that are coupled into diffraction order $m$ is substantially lower than the relative intensity of light rays that are coupled into the first diffraction order. In various exemplary embodiments of the invention the term refers to a diffraction condition in which the relative intensity of light rays coupled into diffraction order $m$ is below 30%, more preferably below 20%, more preferably below 10%, more preferably below 5%, more preferably below 3%, e.g., 2% or less.

The angles of each of the diffractive orders of a grating are determined by the period of the grating which can be defined as the distance between adjacent repetitive features of the grating. The diffraction efficiency of the various diffraction orders are determined by the wavelength and incidence angle on the one hand, and the shape of the grating's profile (period, repetitive pattern, modulation depth, etc). For a given grating's profile, the diffraction efficiency can be calculated, e.g., using an algorithm known as "coupled wave theory." Thus, for example, by an iterative process, the grating's profile can be selected such as to suppress all diffraction orders other than -1, 0 or 1.

The light impinging at the input optical element of device 10 is preferably collimated. In case the light is not collimated, a collimating system 44 can be positioned on the light path between image 34 and the input element.

Collimating system 44 can be, for example, a converging lens (spherical or non-spherical), an arrangement of lenses and the like. Collimating system 44 can also be a diffractive optical element, which may be spaced apart, carried by or formed in substrate 14. A diffractive collimating system may be positioned either on the entry surface of
substrate 14, as a transmissive diffractive element or on the opposite surface as a reflective diffractive element.

In various exemplary embodiments of the invention the light impinging at the input optical element of device 10 is polarized. This is typically the case when object 34 is, e.g., an LCD or LCoS (liquid crystal on silicon) which produces polarized light.

In various exemplary embodiments of the invention device 10 comprises a reflector assembly 20. Reflector assembly 20 serves for ensuring propagation of the light rays within substrate 14 towards output elements 15, 19. Reflector assembly 20 coats, at least partially, each of the two surfaces 23 and 24 of substrate 14. The part of reflector assembly that coats or partially coats surface 23 is denoted 20a and the part of reflector assembly that coats or partially coats surface 24 is denoted 20b. Reflector assembly 20 can be in the form of a dielectric coat. In various exemplary embodiments of the invention reflector assembly 20 is parallel to the major surfaces 23 and 24 of substrate 14.

In operation, reflector assembly 20 reflects at least a few light rays which emanate through surface 23 or 24 and impinge on part 20a or part 20b of assembly 20 back into substrate 14. Specifically, light rays which are redirected by the input element to impinge on the surfaces of the substrate at an angle which is above the critical angle experience total internal reflection, and light rays which are redirected by the input element to impinge on the surfaces of the substrate at an angle which is below the critical angle temporarily emanate from the substrate but are immediately recycled back into the substrate. In other words, light propagation in substrate 14 is established either via internal reflections off the internal surface of substrate 14, whereby the propagation angle is larger that the critical angle, or via reflections off assembly 20, whereby the propagation angle is larger that the critical angle.

The available range of incident angles at which the incoming light beam 12 can impinge on the input element and successfully propagate in the substrate and exit through the output element(s) is often referred to in the literature as a "field-of-view." A field-of-view can be expressed either inclusively, in which case its value corresponds to the difference between the minimal and maximal incident angles, or explicitly in which case the field-of-view has a form of a mathematical range or set. Thus, for example, a field-of-view, Ω, spanning from a minimal incident angle, α, to a maximal incident
angle, $\beta$, is expressed inclusively as $\Omega = \beta - \alpha$, and exclusively as $\Omega = [\alpha, \beta]$. The minimal and maximal incident angles are also referred to as leftmost and rightmost incident angles or clockwise and counterclockwise field-of-view angles, in any combination. The inclusive and exclusive representations of the field-of-view are used herein interchangeably.

In various exemplary embodiments of the invention reflector assembly 20 is constituted so as to selectively allow transmission of light therethrough. This embodiments is particularly useful for allowing the incoming light to enter substrate 14 through assembly 20 and/or allowing the outgoing light to exit substrate 14 through assembly 20, as shown in Figure 2. In these embodiments, at least part of assembly 20 is disposed in the optical path of the incoming light before the input element.

In some embodiments of the present invention assembly 20 substantially reflects light rays impinging on assembly 20 at an angle within a first predetermined angular range, and substantially transmits light rays of the polychromatic light impinging on assembly 20 at an angle within a second predetermined angular range, which is preferably different from the first angular range. The first predetermined angular range is referred to hereinunder as the "reflection angular range" and is represented mathematically by the set $A = \{ \theta : \theta \geq \theta_{\text{min}}^{R} \}$, where $\theta_{\text{min}}^{R}$ is the minimal (in absolute value) incidence angle for which assembly 20 substantially reflects light. The second predetermined angular range is referred to hereinunder as the "transmission angular range" and is represented mathematically by the set $B = \{ \theta : \theta \leq \theta_{\text{max}}^{T} \}$, where $\theta_{\text{max}}^{T}$ is the maximal (in absolute value) incidence angle for which assembly 20 allows substantial transmission. Thus, if an incidence angle of a light ray is less than $\theta_{\text{max}}^{T}$ degrees, then reflector assembly 20 allows transmission of the light ray therethrough, and if the incidence angle of a light ray is at least $\theta_{\text{min}}^{R}$, then reflector assembly 20 reflects the light ray.

The selective reflection and transmission capabilities of reflector assembly 20 can be characterized by the angular dependence of the relation (e.g., difference) between the effective reflection coefficient $R$ and the transmission coefficient $T$ of reflector assembly 20. Thus, for angles of incidence within the reflection range, the effective reflection coefficient $R$ of assembly 20 is greater than the effective transmission
coefficient $T$ thereof, and for angles of incidence within the transmission range, the
effective transmission coefficient is greater than the effective reflection coefficient

The term "substantial reflection" and any deflection thereof, describes a relation
in which $R - T \geq 0.4$, more preferably $R - T \geq 0.5$, more preferably $R - T \geq 0.6$, more
preferably $R - T \geq 0.7$, more preferably $R - T \geq 0.8$, more preferably $R - T \geq 0.9$. The
term "substantial transmission" and any deflection thereof, describes a relation in which
$T - R \geq 0.4$, more preferably $T - R \geq 0.5$, more preferably $T - R \geq 0.6$, more preferably $T - R \geq 0.7$, more preferably $T - R \geq 0.8$, more preferably $T - R \geq 0.9$.

According to some embodiments of the present invention, reflector assembly 20
substantially reflects all polychromatic light rays that impinge on assembly 20 at an
angle $\theta$ e A, and substantially transmits all polychromatic light rays that impinge on
assembly 20 at an angle $\theta$ e B. In various exemplary embodiments of the invention the
above selective transmission/reflection property of assembly 20 is for any light ray
having a wavelength ranging from about 440 nm to about 650 nm.

It is appreciated that the transmission range may be different upon entry of light
into device 10 than upon exit of light out of device 10. The transmission range on entry
is referred to hereinunder as external transmission range, and transmission range on exit
is referred to hereinunder as internal transmission range. Similarly, the reflection range
for light rays arriving at the reflector assembly from within the substrate differs from the
reflection range for light rays arriving at the reflector assembly from outside the
substrate (e.g., while propagating in free air). The reflection range for light rays arriving
at the reflector assembly from within the substrate is referred to hereinunder as internal
reflection range, and reflection range for light rays arriving at the reflector assembly
from outside the substrate is referred to hereinunder as external reflection. Unless
otherwise stated, a reference to a reflection range should be understood as a reference to
an internal reflection range, and a reference to a transmission range should be
understood as a reference to an external transmission range.

In various exemplary embodiments of the invention the (internal) reflection
angular range includes angles which are smaller that the critical angle for total internal
reflection within substrate 14. For example, the $\theta_{\text{R}}^{\text{R}}$ of the reflection angular range can
satisfy $\theta_{\text{R}}^{\text{R}} < \sin^{-1}(l/n)$, where $n$ is the refractive index of substrate 14.
Preferably, the (external) transmission angular range and the (internal) reflection angular range are mutually exclusive angular ranges, namely that there is no overlap between the two ranges. This embodiment corresponds to the relation $\theta_{R_{m}} > \theta_{T_{max}}$. Typical values for $\theta_{R_{m}}$ and $\theta_{T_{max}}$ are, without limitation, about $20^\circ$ for $\theta_{R_{m}}$ and about $15^\circ$ for $\theta_{T_{max}}$.

The optical characteristics of the input element can be selected so as to optimize the field-of-view of device 10 for given transmission and reflection angular ranges. For example, the input element can be constituted such that when the angle of incidence of a light ray is within the transmission range, the input element redirects the ray to enter the substrate at an angle which is within the reflection range. In such configuration, all light rays within the transmission range enter substrate 14 through assembly 20 to successfully propagate within substrate 14 via internal reflection off the inner surface of substrate 14 or via reflections off assembly 20, and the angular field-of-view of device 10 equals the transmission angular range of assembly 20. Yet, this need not necessarily be the case, since in some embodiments, it may be not necessary for all light rays within the transmission range to propagate within substrate 14. In such configuration, the transmission range of assembly 20 is wider than the angular field-of-view of device 10.

The input element, transmission range and reflection range can be selected such that the angular field-of-view of device 10 is at least $\pm10^\circ$ ($20^\circ$ in inclusive representation), more preferably at least $\pm15^\circ$ ($30^\circ$ in inclusive representation), more preferably at least $\pm20^\circ$ ($40^\circ$ in inclusive representation), more preferably at least $\pm25^\circ$ ($50^\circ$ in inclusive representation). When the polychromatic light constitutes an image which is spanned over a certain angular range within the field-of-view (preferably, but not obligatorily the entire field-of-view) device 10 can provide each eye with the image by its entirety.

As a numerical example, suppose that for angle of incidence $\theta$ satisfying $|\theta| < 15^\circ$ the transmission coefficient $T$ of assembly 20 dominates its reflection coefficient $R$ (e.g., $T > 0.7$ and $R < 0.3$ reflection, more preferably $T > 0.8$ and $R < 0.2$, more preferably $T > 0.9$ and $R < 0.1$, more preferably $T > 0.95$ and $R < 0.05$) and that for angle of incidence $\theta$ satisfying $|\theta| > 20^\circ$ the reflection coefficient of assembly 20 dominates its transmission coefficient (e.g., $R > 0.7$ and $T < 0.3$, more preferably $R > 0.8$
and $T < 0.2$, more preferably $R > 0.9$ and $T < 0.1$, more preferably $R > 0.95$ and $T < 0.05$). Thus, in this example, $\theta^1_{n_{\text{air}}}$ equals $15^\circ$ and $\theta^R_{m_{\text{th}}}$ equals $20^\circ$. The input element can then be a diffractive optical element which efficiently diffracts light rays such that for all incidence angles $\theta_j$ satisfying $Q_j \in B$ the corresponding diffraction angles $\theta_d$ satisfy $\theta_d \in A$. In such configuration, all light rays within the transmission range enter the substrate $14$ through assembly $20$ to successfully propagate within substrate $14$ via internal reflection (e.g., total internal reflection) off the inner surface of substrate $14$ or via reflection off assembly $20$ and the angular field-of-view characterizing device $10$ is $[-15^\circ, +15^\circ]$.

Generally, the transmission and reflection coefficients of the dielectric coating may depend on the spectrum and/or polarization state of the polychromatic light. In some embodiments of the present invention the polychromatic light beam is a transverse-electric (TE) wave.

Reflective assembly $20$ allows trapping of light rays inside the device such that they propagate at an angle which is smaller than the critical angle. Thus the effective field-of-view transmitted efficiently through the device of the present embodiments is larger than the effective field-of-view transmitted through a device which is based solely on total internal reflection.

The predetermined angular range for which the transmission coefficient of assembly $20$ dominates the reflection coefficient can be selected to be similar to the range of angles in which optical information is carried by the incoming light beam $12$. For example, when the incoming light beam or part thereof constitutes an image, which covers a range of angles specified, for example by the size of image $34$ and the optical magnification of collimating lens $44$, the predetermined angular range of transmission of assembly $20$ can be set to fit the range of angles covering the image.

In various exemplary embodiments of the invention reflector assembly $20$ comprises a plurality of layers, e.g., a stack of layers, arranged such that adjacent layers have different refractive indices. An embodiment of the present invention is schematically illustrated in Figure $3$ which is a fragmentary view of assembly $20$. Shown in Figure $3$ are several layers which form an alternating sequence $(/I_1, n-i, n_s, n-i)$ of refractive indices. Such arrangement results in a alternating change in the refractive index within assembly $20$ along the $z$ direction.
The number of different refractive indices in the sequence (two different refractive indices $n_i$ and $m$ are illustrated in Figure 3) is not limited and can be two, three or more. The number of layers in assembly 20 is also not limited. It was found by the present inventors that 32 layers are sufficient, but more than 32 layers can also be used. Thus, in some embodiments of the present invention, the number of layers is at least 32, more preferably at least 36, more preferably at least 40. For example, in simulations performed by the present Inventors, reflector assemblies with 48 layers and 64 layers were tested. In all cases the aforementioned process of light propagation was demonstrated. Also contemplated are embodiments in which assembly 20 has a plurality of layers which do not form an alternating sequence of refractive indices. In other words, the change in refractive index within assembly 20 along the $z$ direction is not necessarily periodic.

Figures 4a-c show simulation results for the reflectance of a reflector assembly for light rays impinging on the reflector assembly from within the substrate as a function of the internal incidence angle (between the light rays and the normal to the reflector assembly) for various wavelengths in the range $447 \leq \lambda \leq 643$ nm, which are typical to RGB LED based illumination source. In the simulations the reflector assembly was simulated as having 64 layers forming an alternating sequence of the following materials: $\text{SiO}_2$ with refractive index of 1.48 and $\text{TiO}_2$ with refractive index of 2.34. The thicknesses of the layers are depicted in Figure 4d which is a graph showing the thickness as a function of the layer's serial number (0 to 63, with layer No. 0 being the closest to the surface of substrate 14).

As shown in Figures 4a-c, the reflectance of the reflector assembly has a step-like behavior for an RGB LED based illumination system wavelengths with low values (5 % or less) for low angles and high values for high angles. Figures 4a-c demonstrate a reflector assembly for which the internal predetermined transmission angular range is from $-10^\circ$ to $+10^\circ$. This corresponds to an external transmission angular range which is from $-15^\circ$ to $+15^\circ$.

The present inventors found that the outgoing light beams provided by traditional planar optics techniques have inadequate image profile.

The profile of an image is the optical characteristic of a collection of light rays forming a light beam constituting the image. The optical characteristic can be a
wavelength (or equivalently a frequency or color), an intensity or an angle of propagation. Conveniently, an image profile is represented by a function \( I(\theta, \lambda) \), which returns the intensity / as a function of the angle \( \theta \) and the wavelength \( \lambda \). For fixed value of \( \lambda \) the image profile is referred to as an "intensity-angle profile" which describes the intensity / as a function of the angle \( \theta \), for fixed value of \( \theta \), the image profile is referred to as an "intensity-wavelength profile" which describes the intensity / as a function of the wavelength \( \lambda \).

The inadequate light profile of traditional planar optics techniques, can be explained as follows: (i) when the transmitted image is a monochromatic screen with one of the fundamental RGB colors R or G or B the user perceives a screen having a non-uniform intensity-angle profile, namely that the intensity \( I \) varies along y direction; and (ii) when the transmitted image is a monochromatic screen which is a specific combination of the RGB colors, the user perceives a non-uniform intensity-angle profile as well as a non-uniform intensity-wavelength, namely that both the intensity and the color vary along the y direction.

The inventors of the present invention found inadequacy in the color profile provided by traditional planar optics light relay techniques. The present inventors found that one of the reasons for such inadequacy is the relatively large difference in the optical paths for light rays of different colors and the associated large difference in number of hopes for different colors. As an example, the present inventors calculated that for a substrate having a refractive index of 1.51 which is formed with a grating having a period of 0.52 \( \mu \text{m} \), the maximal diffraction angles for red (wavelength of about 630 nm), green (wavelength of about 520 nm) and blue (wavelength of about 460 nm) light rays are 70.1°, 54.4° and 46.3°, respectively, and the minimal diffraction angles for red, green and blue light rays are 41.7°, 32.5° and 26.6°, respectively. This corresponds to rather large deviations between the diffraction angles of light rays having different colors. Comparing the diffraction angles for normal incident light rays (hereinafter "mid diffraction angles") of these colors (about 55.9° for the red, about 43.4° for the green and about 36.5° for the blue) it was realizes that, on the average, there can be a difference of about 20° between the diffraction angles of red and blue light rays.
Since the diffraction angle directly affects the hop length of a light ray (the lateral distance propagated by a light ray within the substrate between two successive points of reflections off the same surface of the substrate), light rays with shorter wavelengths propagate with shorter hops, compared to light rays with longer wavelengths. As a result, a light ray with shorter wavelength experiences more hops than a light ray with longer wavelength, and the optical path along which light rays with shorter wavelengths propagate is longer than the optical path along which light rays with longer wavelengths propagate. Thus, the shorter wavelengths impinge and interact with the input/output gratings more times than the longer one. Since part of the light is diffracted out by the gratings on every point of interaction the overall color uniformity across the field-of-view is deteriorated. For shorter wavelengths it is more difficult to achieve color uniformity than for the longer wavelengths.

The present inventors found that by imposing diffraction conditions whereby for at least some wavelengths the light is diffracted at higher diffraction order, the aforementioned optical path difference can be significantly reduced. Thus, in various exemplary embodiments of the invention the input and output optical elements are diffraction gratings having a periodic profile shaped such that at least one portion of the light is dominantly coupled into a diffraction order \( m \) satisfying \( \eta m > 1 \).

As used herein, the term "dominantly coupled into a diffraction order \( m \)" refers to a diffraction condition in which the relative intensity of light rays that are coupled into any non-zero diffraction order other than \( m \) is lower than the relative intensity of light rays that are coupled into diffraction order \( m \).

In various exemplary embodiments of the invention the term refers to a diffraction condition in which the relative intensity of light rays coupled into diffraction order \( m \) is above 10%, more preferably above 20%, more preferably above 30%. Light rays which are coupled into a diffraction order \( \eta m \leq 1 \) can have suppressed intensity and/or they escape the substrate substantially without lateral propagation therein.

The angles of each of the diffractive orders of a grating are determined by the period of the grating which can be defined as the distance between adjacent repetitive features of the grating. The diffraction efficiency of the various diffraction orders are
determined by the wavelength and incidence angle on the one hand, and the shape of the grating’s profile (period, repetitive pattern, modulation depth, etc).

For a given grating’s profile, the diffraction efficiency can be calculated, e.g., using an algorithm known as "coupled wave theory." Thus, for example, by an iterative process, the grating’s profile can be selected such as to obtain the desired relative diffraction efficiencies for the various non-zero diffraction orders. Specifically, a query profile can be inputted to the algorithm and the algorithm can calculate the relative diffraction efficiencies. The calculated relative diffraction efficiencies are then analyzed to determine whether or not they satisfy a predetermined criterion or set of criteria. If the relative diffraction efficiencies do not satisfy the set of criteria, the query profile is modified and the algorithm recalculates the relative diffraction efficiencies. The process can continues iteratively until the criterion or set of criteria are met, in which case the shape of the profiles of the input and output gratings can be set to the most recent query profile.

Dominant coupling into a diffraction order \( n > 1 \) can reduce optical path difference between light rays of different colors. In various exemplary embodiments of the invention the shape of the grating's profile is selected such that different portions of the light, respectively corresponding to different sub-spectra of the polychromatic light, are dominantly coupled into different diffraction orders. Preferably, the spectrum of the polychromatic light is diffracted by the input and output gratings such that light rays belonging to a first sub-spectrum are efficiently and predominantly diffracted at a higher order than light rays belonging to a second sub-spectrum, where the first sub-spectrum corresponds to shorter wavelengths (e.g., blue or near blue light) and the second sub-spectrum corresponds to longer wavelengths (e.g., red or green light). Such construction reduces the difference in diffraction angles between the first and second sub-spectra hence also reduces the differences in optical paths.

For example, suppose that the shape of the gratings' profile is selected such that the red and green light is dominantly coupled into the second diffraction order and the blue light is dominantly coupled into the third diffraction order. In this embodiment, the optical difference between red light rays and blue light rays is reduced since the difference in second order diffraction angle for red light and third order diffraction angle for blue light is significantly smaller than 20°.
In traditional devices which employ diffraction gratings in which the first diffraction order dominates all other orders, the typical grating period is comparable or slightly smaller than the shortest wavelength of the visible spectrum. Unlike traditional devices, some embodiments of the present invention employ diffraction gratings having a period which is larger than the largest wavelength of the visible spectrum.

An illustrative and non-limiting example is provided in Table 1 below which compares diffraction angles of several orders as calculated for a field-of-view of ±12°, grating period of 1.25 µm and substrate refractive index of 1.51. Calculations are shown for three wavelengths 630 nm (generally red light), 530 nm (generally green light) and 460 nm (generally blue light). In Table 1, "mid diffraction angle" refers to a diffraction angle corresponding to an incidence angle of 0°.

<table>
<thead>
<tr>
<th></th>
<th>630 nm</th>
<th>530 nm</th>
<th>460 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>first diffraction order</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>max diffraction angle</td>
<td>28.1</td>
<td>24.7</td>
<td>22.4</td>
</tr>
<tr>
<td>min diffraction angle</td>
<td>11.3</td>
<td>8.2</td>
<td>6.1</td>
</tr>
<tr>
<td>mid diffraction angle</td>
<td>19.7</td>
<td>16.5</td>
<td>14.3</td>
</tr>
<tr>
<td><strong>second diffraction order</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>max diffraction angle</td>
<td>53.6</td>
<td>44.4</td>
<td>38.7</td>
</tr>
<tr>
<td>min diffraction angle</td>
<td>32.0</td>
<td>25.1</td>
<td>20.5</td>
</tr>
<tr>
<td>mid angle</td>
<td>42.8</td>
<td>34.7</td>
<td>29.6</td>
</tr>
<tr>
<td><strong>third diffraction order</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>max diffraction angle</td>
<td></td>
<td></td>
<td>60.3</td>
</tr>
<tr>
<td>min diffraction angle</td>
<td></td>
<td></td>
<td>36.4</td>
</tr>
<tr>
<td>mid angle</td>
<td></td>
<td></td>
<td>48.4</td>
</tr>
</tbody>
</table>

Table 1 demonstrates that a 1.25 µm grating period can results in higher diffraction orders. Suppose, for example, that propagation with the substrate is generally at angles which are about 20° or more. As shown in Table 1, for all wavelengths tested, the diffraction angles for the first diffraction order are too small for allowing efficient propagation within the substrate (see, e.g., since the mid diffraction angles all of which being less than 20°). On the other hand, the second order diffraction angles for 630 nm and 530 nm and the third order diffraction angles for 460 nm are well above 20°. Thus, construction of the grating’s profile such that for wavelengths of, say, 450-470 nm the dominant diffraction order is the third order, and for wavelengths of, say, 520-640 nm
the dominant diffraction order is the second, results in a maximal difference between the mid diffraction angles which is about 48.4 - 34.7 = 13.7. This difference is significantly smaller that the maximal difference of 20° which is attainable when only first diffraction order is allowed.

Dominant high order diffraction, particularly such that different sub-spectra are dominantly coupled into different diffraction orders can be achieved, for example, using a diffraction grating characterized by a periodic profile having at least two grooves per period. Figures 5a-b are schematic illustrations of a profile of grating 70, according to various exemplary embodiments of the present invention. Figure 5a illustrates a single grating period of grating 70 and Figure 5b illustrates the periodicity of grating 70 showing four periods 76a, 76b, 76c and 76d. In this illustrative and non-limiting example, grating 70 has a periodic square wave profile with a period of 1300 nm. Each period of the grating has three grooves 72a, 72b and 72c, and three ridges 74a, 74b and 74c. The two or more of grooves 72a-c or and ridges 74a-c can have different widths, as illustrated in Figure 5a.

The profile shape of grating 70 as illustrated in the periodic profile depicted in Figure 5a-b can ensure that different sub-spectra of the incoming polychromatic light are dominantly coupled into different diffraction orders. Specifically, in computer simulations performed by the present Inventors it was found that a grating having such profile shape ensures that for the sub-spectrum which includes the blue light (approximately defined by the wavelength range 460 nm ±10 nm) the dominant diffraction order is 3, and for the sub-spectrum which include the red light 630 nm ±10 nm and the green light 530 nm ±10 nm the dominant diffraction order is 2.

Figure 6 is a graph showing the diffraction efficiency as a function of the incidence angle for three reprehensive wavelengths: 630 nm (generally red light, designated R in Figure 6), 530 nm (generally green light, designated G in Figure 6) and 460 nm (generally blue light, designated B in Figure 6). The graph was obtained by computer simulations in which the diffraction off diffraction gratings having a profile shape as illustrated in Figures 5a-b was simulated. The simulations revealed that the dominant diffraction order for the blue light was 3 and the dominant diffraction orders for the red and green lights were 2. The efficiency of all other non-zero diffraction orders were below 2%, and these orders are not shown in Figure 6. The zero diffraction
order (efficiency of 20% - 50%) is also not shown. Note that in practice the overall light efficiency is twice the values shown in Figure 6, since the light is diffracted symmetrically into positive and negative diffraction orders. The curves in Figure 6 indicate that most of the intensity that is coupled to non-zero diffraction order is diffracted by the grating at a diffraction order which is ±2 for the red and green light and +3 for the blue light.

Figure 7 is a graph showing the overall optical intensity inputted into the device illustrated in Figure 2 in which the input and output elements are diffraction gratings having a profile shape as illustrated in Figures 5a-b. The calculations were via computer simulations whereby the blue light was dominantly coupled into the third diffraction order and the red and green lights were dominantly coupled into the second diffraction order, as further detailed hereinabove. During simulations, several impingements of incoupled light rays onto the gratings were taken into account, by considering both the hop length and the length of the gratings along the lateral direction. Since a light ray may experience several diffraction events at a single grating the energy loss in consecutive hops hitting the input grating was calculated. Shown in Figure 7 is the overall optical intensity (expressed as percentage from the optical intensity of the source) which is relayed by the device to one eye. Figure 7 demonstrate that the diffraction grating of the present embodiments provides substantially uniform color output across a wide angular field-of-view.

Figure 8 is a schematic illustration of a system 100 for generating and transmitting an image, according to various exemplary embodiments of the present invention. System 100 comprises an optical relay device (e.g., device 10) for transmitting image 34 into left eye 25 and right eye 30 of the user, and an image generating system 121 for providing optical relay device 10 with collimated polychromatic light constituting the image.

In various exemplary embodiments of the invention light beam is spanned over an angular range of at least 25 degrees (e.g., from -12.5° to +12.5°), more preferably at least 30° (e.g., from -15° to +15°). The optical relay device preferably relays the polychromatic light beam via internal reflections and/or reflections off the reflector assembly; as described above. The light beam is preferably relayed to provide each of the left eye and the right eye of the user with a view of the angular range by its entirety.
Ideally, a multicolor image is a spectrum as a function of wavelength, measured at a plurality of image elements. This ideal input, however, is rarely attainable in practical systems. Therefore, the present embodiment also addresses other forms of imagery information. A large percentage of the visible spectrum (color gamut) can be represented by mixing red, green, and blue colored light in various proportions, while different intensities provide different saturation levels. Sometimes, other colors are used in addition to red, green and blue, in order to increase the color gamut. In other cases, different spectral ranges within the human visible spectrum.

In a different form of color imagery, a wide-spectrum light source is used, with the imagery information provided by the use of color filters. The most common such system is using white light source with cyan, magenta and yellow filters, including a complimentary black filter. The use of these filters could provide representation of spectral range or color gamut similar to the one that uses red, green and blue light sources, while saturation levels are attained through the use of different optical absorptive thickness for these filters, providing the well known "grey levels."

Thus, the multicolored image can be displayed by three or more channels, such as, but not limited to, Red-Green-Blue (RGB) or Cyan-Magenta-Yellow-Black (CMYK) channels. RGB channels are typically used with light emitting display (e.g., CRT or OLED) or spatial light modulator systems (e.g., Digital Light Processing™ (DLPTM) or LCD or LCos illuminated with RGB light sources such as LEDs). CMYK images are typically used for passive display systems (e.g., print). Other forms are also contemplated within the scope of the present invention.

When the multicolor image is formed from a discrete number of colors (e.g., an RGB display), system 121 provides a plurality of discrete values of wavelength. For example, a multicolor image can be provided by an OLED array having red, green and blue organic diodes (or white diodes used with red, green and blue filters) which are viewed by the eye as continues spectrum of colors due to many different combinations of relative proportions of intensities between the wavelengths of light emitted thereby.

Image generating system 121 can be either analog or digital. An analog image generating system typically comprises a light source 127, at least one image carrier 29 and a collimating system 44. Collimating system 44 serves for focusing the image to
infinity, if it is not already focused to infinity prior to impinging on substrate 14. In the schematic illustration of Figure 8, collimating system 44 is illustrated as integrated within system 121, however, this need not necessarily be the case since, for some applications, it may be desired to have collimating system 44 as a separate element. Thus, system 121 can be formed of two or more separate units. For example, one unit can comprise the light source and the image carrier, and the other unit can comprise the collimating system. Collimating system 44 is positioned on the light path between the image carrier and the input element of device 10.

Any collimating element known in the art may be used as collimating system 44, for example a converging lens (spherical or non-spherical), an arrangement of lenses, a diffractive optical element and the like.

In case of a converging lens, a light ray going through a typical converging lens that is normal to the lens and passes through its center, defines the optical axis. The bundle of rays passing through the lens cluster about this axis and may be well imaged by the lens, for example, if the source of the light is located as the focal plane of the lens, the image constituted by the light is projected to infinity.

Representative examples for light source 127 include, without limitation, a lamp (incandescent or fluorescent), one or more LEDs or OLEDs, and the like. Representative examples for image carrier 29 include, without limitation, a miniature slide, a reflective or transparent microfilm and a hologram. The light source can be positioned either in front of the image carrier (to allow reflection of light therefrom) or behind the image carrier (to allow transmission of light therethrough). Optionally and preferably, system 121 comprises a miniature CRT. Miniature CRTs are known in the art and are commercially available, for example, from Kaiser Electronics, a Rockwell Collins business, of San Jose, California.

A digital image generating system typically comprises at least one display and a collimating system. The use of certain displays may require, in addition, the use of a light source. In the embodiments in which system 121 is formed of two or more separate units, one unit can comprise the display and light source, and the other unit can comprise the collimating system.

Light sources suitable for a digital image generating system include, without limitation, a lamp (incandescent or fluorescent), one or more LEDs (e.g., red, green and
blue LEDs) or OLEDs, and the like. Suitable displays include, without limitation, rear-illumination transmissive or front-illuminated reflective LCD/LCoS, OLED arrays, Digital Light Processing™ (DLP™) units, miniature plasma display, and the like. A light emitting display, such as OLED or miniature plasma display, may not require the use of additional light source for illumination. Transparent miniature LCDs are commercially available, for example, from Kopin Corporation, Hopewell Junction, New York. Reflective LCDs are are commercially available, for example, from DisplayTech, Aurora. Miniature OLED arrays are commercially available, for example, from eMagin Corporation, Hopewell Junction, New York. DLP™ units are commercially available, for example, from Texas Instruments DLP™ Products, Piano, Texas. The pixel resolution of the digital miniature displays varies from QVGA (320 x 240 pixels) or smaller, to WQUXGA (3840 x 2400 pixels).

System 100 is particularly useful for enlarging a field-of-view of devices having relatively small screens. For example, cellular phones and personal digital assistants (PDAs) are known to have rather small on-board displays. PDAs are also known as Pocket PC, such as the trade name iPAQ™ manufactured by Hewlett-Packard Company, Palo Alto, California. The above devices, although capable of storing and downloading a substantial amount of information in a form of single frames or moving images, fail to provide the user with sufficient field-of-view due to their small size displays.

Thus, according to a preferred embodiment of the present invention system 100 comprises a data source 125 which can communicate with system 121 via a data source interface 123. Any type of communication can be established between interface 123 and data source 125, including, without limitation, wired communication, wireless communication, optical communication or any combination thereof. Interface 123 is preferably configured to receive a stream of imagery data (e.g., video, graphics, etc.) from data source 125 and to input the data into system 121. Many types or data sources are contemplated. According to a preferred embodiment of the present invention data source 125 is a communication device, such as, but not limited to, a cellular telephone, a personal digital assistant and a portable computer (laptop). Additional examples for data source 125 include, without limitation, television apparatus, portable television device, satellite receiver, video cassette recorder, digital versatile disc (DVD) player, digital moving picture player (e.g., MP4 player), digital camera, video graphic array (VGA)
card, and many medical imaging apparatus, e.g., ultrasound imaging apparatus, digital X-ray apparatus (e.g., for computed tomography) and magnetic resonance imaging apparatus.

In addition to the imagery information, data source 125 may generates also audio information. The audio information can be received by interface 123 and provided to the user, using an audio unit 31 (speaker, one or more earphones, etc.).

According to various exemplary embodiments of the present invention, data source 125 provides the stream of data in an encoded and/or compressed form. In these embodiments, system 100 further comprises a decoder 33 and/or a decompression unit 35 for decoding and/or decompressing the stream of data to a format which can be recognized by system 121. Decoder 33 and decompression unit 35 can be supplied as two separate units or an integrated unit as desired.

System 100 preferably comprises a controller 37 for controlling the functionality of system 121 and, optionally and preferably, the information transfer between data source 125 and system 121. Controller 37 can control any of the display characteristics of system 121, such as, but not limited to, brightness, hue, contrast, pixel resolution and the like. Additionally, controller 37 can transmit signals to data source 125 for controlling its operation. More specifically, controller 37 can activate, deactivate and select the operation mode of data source 125. For example, when data source 125 is a television apparatus or being in communication with a broadcasting station, controller 37 can select the displayed channel; when data source 125 is a DVD or MP4 player, controller 37 can select the track from which the stream of data is read; when audio information is transmitted, controller 37 can control the volume of audio unit 31 and/or data source 125.

System 100 or a portion thereof (e.g., device 10) can be integrated with a wearable device, such as, but not limited to, a helmet or spectacles, to allow the user to view the image, preferably without having to hold optical relay device 10 by hand.

Device 10 can also be used in combination with a vision correction device 130 (not shown, see Figure 9), for example, one or more corrective lenses for correcting, e.g., short-sightedness (myopia). In this embodiment, the vision correction device is preferably positioned between the eyes and device 20. According to a preferred
embodiment of the present invention system 100 further comprises correction device 130, integrated with or mounted on device 10.

Alternatively system 100 or a portion thereof can be adapted to be mounted on an existing wearable device. For example, in one embodiment device 10 is manufactured as a spectacles clip which can be mounted on the user's spectacles, in another embodiment, device 10 is manufactured as a helmet accessory which can be mounted on a helmet's screen.

Reference is now made to Figures 9a-c which illustrate a wearable device 110 in a preferred embodiment in which spectacles are used. According to the presently preferred embodiment of the invention device 110 comprises a spectacles body 112, having a housing 114, for holding image generating system 21 (not shown, see Figure 8); a bridge 122 having a pair of nose clips 118, adapted to engage the user's nose; and rearward extending arms 116 adapted to engage the user's ears. Optical relay device 10 is preferably mounted between housing 114 and bridge 122, such that when the user wears device 110, element 17 is placed in front of left eye 25, and element 15 is placed in front of right eye 30. According to a preferred embodiment of the present invention device 110 comprises a one or more earphones 119 which can be supplied as separate units or be integrated with arms 116.

Interface 123 (not explicitly shown in Figures 9a-c) can be located in housing 114 or any other part of body 112. In embodiments in which decoder 33 is employed, decoder 33 can be mounted on body 112 or supplied as a separate unit as desired. Communication between data source 25 and interface 123 can be, as stated, wireless, in which case no physical connection is required between wearable device 110 and data source 25. In embodiments in which the communication is not wireless, suitable communication wires and/or optical fibers 120 are used to connect interface 123 with data source 25 and the other components of system 100.

The present embodiments can also be provided as add-ons to the data source or any other device capable of transmitting imagery data. Additionally, the present embodiments can also be used as a kit which includes the data source, the image generating system, the binocular device and optionally the wearable device. For example, when the data source is a communication device, the present embodiments can be used as a communication kit.
As used herein, the term "about" refers to ±10%.

The terms "comprises", "comprising", "includes", "including", "having" and their conjugates mean "including but not limited to".

The term "consisting of means "including and limited to".

The term "consisting essentially of means that the composition, method or structure may include additional ingredients, steps and/or parts, but only if the additional ingredients, steps and/or parts do not materially alter the basic and novel characteristics of the claimed composition, method or structure.

As used herein, the singular form "a", "an" and "the" include plural references unless the context clearly dictates otherwise. For example, the term "a compound" or "at least one compound" may include a plurality of compounds, including mixtures thereof.

Throughout this application, various embodiments of this invention may be presented in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the invention. Accordingly, the description of a range should be considered to have specifically disclosed all the possible subranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed subranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

Whenever a numerical range is indicated herein, it is meant to include any cited numeral (fractional or integral) within the indicated range. The phrases "ranging/ranges between" a first indicate number and a second indicate number and "ranging/ranges from" a first indicate number "to" a second indicate number are used herein interchangeably and are meant to include the first and second indicated numbers and all the fractional and integral numerals therebetween.

It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable subcombination or as suitable in any other described
embodiment of the invention. Certain features described in the context of various embodiments are not to be considered essential features of those embodiments, unless the embodiment is inoperative without those elements.

Although the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims.

All publications, patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present invention. To the extent that section headings are used, they should not be construed as necessarily limiting.
WHAT IS CLAIMED IS:

1. An optical relay device, for relaying polychromatic light, comprising:
   - an input optical element formed in a planar substrate for receiving and redirecting the light for propagation of the light in a lateral direction within said substrate;
   - an output optical element formed in said substrate for receiving light propagating within said substrate and coupling said light out of said substrate; and
   - a reflector assembly at least partially coating opposite surfaces of said substrate for substantially reflecting light rays impinging on said reflector assembly at an angle within a first angular range, and substantially transmitting light rays of the polychromatic light impinging on said reflector assembly at an angle within a second angular range;
   wherein said first angular range is different from said second angular range.

2. A system for generating and transmitting an image, comprising the optical relay device of claim 1, and an image generating system for providing the optical relay device with collimated light constituting the image.

3. A method of viewing an image using the device of claim 1, comprising transmitting a light beam constituting the image to said input optical element and viewing the image through said output optical element.

4. An optical relay device for relaying polychromatic light, comprising:
   - an input optical element formed in a substrate for receiving and redirecting the light for propagation of the light in a lateral direction within said substrate; and
   - an output optical element formed in said substrate for receiving light propagating within said substrate and coupling said light out of said substrate;
   wherein said input optical element and said output optical element are diffraction gratings having a periodic profile shaped such that at least one portion of the light is dominantly coupled into a diffraction order $m$ satisfying $|m| > 1$. 

5. A system for generating and transmitting an image, comprising the optical relay device of claim 4, and an image generating system for providing the optical relay device with collimated light constituting the image.

6. A method of viewing an image using the device or claim 4, comprising transmitting a light beam constituting the image to said input optical element and viewing the image through said output optical element.

7. The device, system or method according to any of claims 1-6, wherein said output optical element is a left eye output optical element for receiving light propagating leftward within said substrate and outcoupling said light in a direction of a left eye of a viewer, and the device further comprises a right eye output optical element for receiving light propagating rightward within said substrate and outcoupling said light in a direction of a right eye of said viewer.

8. The device, system or method according to any of claims 1-7, wherein at least one of said input and said output optical elements is a reflective optical element coated by a reflective coat.

9. A system for generating and transmitting an image, comprising:
   an image generating system for generating a collimated polychromatic light beam constituting an image spanned over an angular range of at least 25 degrees; and
   an optical relay device, having a single substrate at least partially coated with a reflector assembly, for relaying said polychromatic light beam within said single substrate via internal reflections and/or reflections off said reflector assembly;
   said polychromatic light beam being relayed to provide each of a left eye and a right eye of a user with a view of said angular range by its entirety.

10. The system of claim 9, wherein said optical relay device comprises:
    an input optical element for redirecting the light for propagation of the light in a lateral direction within said substrate;
a left eye output optical element for receiving light propagating leftward within said substrate and outcoupling said light in a direction of said left eye; and

a right eye output optical element for receiving light propagating rightward within said substrate and outcoupling said light in a direction of said right eye;

wherein at least one of said input and said output optical elements is a reflective optical element coated by a reflective coat.

11. The device, system or method of any of claims 1-9, wherein at least a few light rays of said polychromatic light propagate within said substrate at a propagation angle which is smaller than a critical angle.

12. The device, system or method according to any of claims 1-3, 9 and 10, wherein said reflector assembly comprises a plurality of layers arranged such that adjacent layers of said plurality of layers have different refractive indices.

13. The device, system or method of claim 12, wherein said plurality of layers form an alternating sequence of refractive indices.

14. The device, system or method of claim 13, wherein said plurality of layers comprises at least 32 layers.

15. The device, system or method according to any of claims 1-3, 9 and 10, wherein said reflector assembly is constituted for selectively transmitting or reflecting of any light ray having a wavelength ranging from about 440 nm to about 650 nm in a manner such that:

if an incidence angle of said light ray is less than 15 degrees, then said reflector assembly allows transmission of said light ray therethrough; and

if said incidence angle of said light ray is at least 20 degrees, then said reflector assembly reflects said light ray.

16. The device, system or method according to any of claims 1-3 and 10, wherein said input optical element and said output optical element are diffraction
gratings having a periodic profile shaped such that all diffraction orders $m$ satisfying $m > 1$ are suppressed.

17. The device, system or method according to any of claims 1-3 and 10, wherein said input optical element and said output optical element are diffraction gratings having a periodic profile shaped such that at least one portion of the light is dominantly coupled into a diffraction order $m$ satisfying $m > 1$.

18. The device, system or method according to any of claims 1-3 and 10, wherein said input optical element and said output optical element are diffraction gratings having a periodic profile shaped such that different portions of the light, respectively corresponding to different sub-spectra of the polychromatic light, are dominantly coupled into different diffraction orders.

19. The device, system or method according to any of claims 1-3 and 10, wherein said input optical element and said output optical element are diffraction gratings characterized by a periodic profile having a period which is larger than a largest wavelength of said polychromatic light.

20. The device, system or method according to any of claims 1-3 and 10, wherein said input optical element and said output optical element are diffraction gratings characterized by a periodic profile having at least two grooves per period.
FIG. 5A

FIG. 5B