Title: STEREOSCOPIC EXIT PUPIL EXPANDER DISPLAY

Abstract: The specification and drawings present a new apparatus and method for providing a stereoscopic display in electronic devices with a diffractive exit pupil expander using sequentially switching between right and left images of one display (e.g., microdisplay). An optical delivery system can provide a sequential left and right image of the display and the illumination is then switched for left and right accordingly using exit pupil expander (EPE) with asymmetric, e.g., highly slanted, in-coupling gratings, sending light practically to only one direction (e.g., one area of the EPE substrate).
STEREOSCOPIC EXIT PUPIL EXPANDER DISPLAY

Cross-reference to related application.

This application discloses subject matter which is also disclosed and which may be claimed in co-pending, co-owned application (Att. Doc. No 944-003.185) filed on even date herewith.

Technical Field

The present invention relates generally to a display device and, more specifically, to a stereoscopic display which uses a plurality of diffractive elements for expanding the exit pupil of a display for viewing.

Background Art

While it is a common practice to use a low-resolution liquid-crystal display (LCD) panel to display network information and text messages in a mobile device, it is preferred to use a high-resolution display to browse rich information content of text and images. A microdisplay-based system can provide full color pixels at 50-100 lines per mm. Such high-resolution is generally suitable for a virtual display. A virtual display typically consists of a microdisplay to provide an image and an optical arrangement for manipulating light emerging from the image in such a way that it is perceived as large as a direct view display panel. A virtual display can be monocular or binocular.

The size of the beam of light emerging from imaging optics toward the eye is called exit pupil. In a Near-to-Eye Display (NED), the exit pupil is typically of less than 10mm in diameter. Further enlarging the exit pupil makes using the virtual display significantly easier, because the device can be put at a distance from the eye.

Normally, in order to provide a stereoscopic viewing using exit pupil beam expanders with plurality of diffractive elements, images of two microdisplays can be utilized.
Disclosure of the Invention

According to a first aspect of the invention, an apparatus, comprises: a substrate of optical material having a first surface and a second surface, the substrate comprising a first area and a second area substantially adjacent to each other along a line; two diffractive elements disposed on the first or the second surface and configured to receive sequentially two input optical beams comprising an optical image of a display such that one of the two input optical beams is received by one of the two diffractive elements and another of the two input optical beams is received by another of the two diffractive elements, wherein one of the two diffractive elements is disposed on the first area and another of the two diffractive elements is disposed on the second area, respectively; two further diffractive elements disposed on the first or the second surface, wherein one of the two further diffractive elements is disposed on the first area and another of the two further diffractive elements is disposed on the second area, respectively; and an optical delivery system, configured to sequentially switch the two input optical beams comprising the optical image of the display between the two diffractive elements, wherein at least part of each of the two sequentially switched input optical beams at any time is diffracted only in one of the two diffractive elements to provide a diffracted optical beam in the same area with the one of the two diffractive elements substantially within the first and second surfaces, and at least part of the diffracted optical beam in the first or the second area is further coupled out of the substrate by diffraction in one of the two further diffractive elements for providing two sequentially switched and substantially identical output optical beams, each comprising the optical image of the display with an expanded exit pupil in one or two dimensions.

According further to the first aspect of the invention, the two sequentially switched and substantially identical output optical beams may be for providing a stereoscopic image of the display.

According further to the first aspect of the invention, the two diffractive elements may be substantially next to each other and adjacent to the line.

Still further according to the first aspect of the invention, the optical delivery system may comprise two optical sources configured to provide two optical beams in substantially different directions for sequentially switching the two input optical beams. Further, the two optical sources may be configured to turn on and off in a
sequential manner with a predetermined period. Further still, the optical delivery
system may comprise a wire grid polarizer configured as a beam-splitter to re-direct
the two optical beams for the sequentially switching the two input optical beams
between the two diffractive elements and the display is a liquid crystal on silicon
display.

According further to the first aspect of the invention, the optical delivery
system may comprise a shutter configured to sequentially switch the two input optical
beams between the two diffractive elements with a predetermined period.

According still further to the first aspect of the invention, the substrate may be
a one-piece substrate.

According further still to the first aspect of the invention, the substrate may be
configured to have in a vicinity of the line an absorbing material on a surface of the
substrate opposite to a substrate surface with the disposed two diffractive elements.

According yet further still to the first aspect of the invention, the substrate
may be a split substrate such that the first area and second areas are physically
separated. Further, an absorbing material may be deposited on an end of at least one
of the first and the second parts in an area of their physical separation along the line.

Yet still further according to the first aspect of the invention, locations of the
two diffractive elements or the two further diffractive elements may be symmetrical
relative to the line.

Still yet further according to the first aspect of the invention, the two
diffractive elements may have an asymmetric groove shape such that the input optical
beam diffracted by each of the two diffractive elements is substantially coupled only
to an area, out of the first and the second areas, in which the each of the two
diffractive elements is disposed.

Still further still according to the first aspect of the invention, the two
diffractive elements may have an asymmetric groove shape and may be slanted
 gratings with a slanting angle of more than 20 degrees.

According further still to the first aspect of the invention, the two diffractive
elements may be asymmetric such that their groove shapes are mirror images of each
other with respect to the line which separates the first and the second areas.
According yet further still to the first aspect of the invention, the two
diffractive elements and the two further diffractive elements may be disposed on one
surface of the substrate.

According still yet further to the first aspect of the invention, each area, the
first and the second area of the substrate, may comprise an intermediate diffractive
element such that the at least part of the optical beam diffracted in the first or the
second diffractive element is first coupled to the intermediate diffractive element,
which then couples, using a further diffraction in the intermediate diffractive element,
the at least part of the diffracted optical beam to one of the two further diffractive
elements disposed on the each area, to provide a two-dimensional exit pupil
expansion of one of the two input optical beams in the each area.

According to a second aspect of the invention, a method, comprises:
receiving two sequentially switched input optical beams by two diffractive elements
such that one of the two input optical beams is received by one of the two diffractive
elements and another of the two input optical beams is received by another of the two
diffractive elements, the two diffractive elements being disposed on a first or a second
surface of a substrate made of optical material, the substrate comprising a first area
and a second area substantially adjacent to each other along a line, and wherein the
one of the two diffractive elements is disposed on the first part and the other of the
two diffractive elements is disposed on the second part, respectively, wherein the two
sequentially switched input optical beams comprise an optical image of a display and
are provided by an optical delivery system; diffracting at least part of each of the two
sequentially switched input optical beams at any time only in one of the two
diffractive elements to provide a diffracted optical beam in the same area with the one
of the two diffractive elements substantially within the first and second surfaces; and
coupling at least part of the diffracted optical beam in the first or the second area out
of the substrate by diffraction in one of the two further diffractive elements for
providing two sequentially switched and substantially identical output optical beams,
each comprising the optical image of the display with an expanded exit pupil in one
or two dimensions, wherein the two further diffractive elements are disposed on the
first or the second surface, wherein one of the two further diffractive elements is
disposed on the first area and another of the two further diffractive elements is
disposed on the second area, respectively.
According further to the second aspect of the invention, the two sequentially
switched and substantially identical output optical beams may be for providing a
stereoscopic image of the display.

Further according to the second aspect of the invention, the two diffractive
elements may be substantially next to each other and adjacent to the line.

Still further according to the second aspect of the invention, the optical
delivery system may comprise two optical sources configured to provide two optical
beams in substantially different directions for sequentially switching the two input
optical beams.

According further to the second aspect of the invention, the optical delivery
system may comprise a shutter configured to sequentially switch the two input optical
beams between the two diffractive elements with a predetermined period.

According still further to the second aspect of the invention, the substrate may
be a one-piece substrate.

According further still to the second aspect of the invention, the substrate may
be a split substrate such that the first area and second areas are physically separated.

According yet further still to the second aspect of the invention, the two
diffractive elements may have an asymmetric groove shape such that the input optical
beam diffracted by each of the two diffractive elements is substantially coupled only
to an area, out of the first and the second areas, in which the each of the two
diffractive elements is disposed.

Yet still further according to the second aspect of the invention, the two
diffractive elements may be asymmetric such that their groove shapes are mirror
images of each other with respect to the line which separates the first and the second
areas.

According to a third aspect of the invention, an electronic device, comprises:
- a data processing unit;
- an optical engine operatively connected to the data processing unit for
  receiving image data from the data processing unit;
- a display device operatively connected to the optical engine for
  forming an image based on the image data; and
- an exit pupil expander device, comprising:
a substrate of optical material having a first surface and a second surface, the
substrate comprising a first area and a second area substantially adjacent to each other
along a line;

two diffractive elements disposed on the first or the second surface and
configured to receive sequentially two input optical beams comprising an optical
image of a display such that one of the two input optical beams is received by one of
the two diffractive elements and another of the two input optical beams is received by
another of the two diffractive elements, wherein one of the two diffractive elements is
disposed on the first area and another of the two diffractive elements is disposed on
the second area, respectively;

two further diffractive elements disposed on the first or the second surface,
wherein one of the two further diffractive elements is disposed on the first area and
another of the two further diffractive elements is disposed on the second area,
respectively; and

an optical delivery system, configured to sequentially switch the two input
optical beams comprising the optical image of the display between the two diffractive
elements, wherein

at least part of each of the two sequentially switched input optical beams at
any time is diffracted only in one of the two diffractive elements to provide a
diffracted optical beam in the same area with the one of the two diffractive elements
substantially within the first and second surfaces, and

at least part of the diffracted optical beam in the first or the second area is
further coupled out of the substrate by diffraction in one of the two further diffractive
elements for providing two sequentially switched and substantially identical output
optical beams, each comprising the optical image of the display with an expanded exit
pupil in one or two dimensions.

Further according to the third aspect of the invention, the two sequentially
switched and substantially identical output optical beams may be for providing a
stereoscopic image of the display.

Still further according to the third aspect of the invention, the two diffractive
elements may be substantially next to each other and adjacent to the line.

According further to the third aspect of the invention, the optical delivery
system may comprise two optical sources configured to provide two optical beams in
substantially different directions for sequentially switching the two input optical beams.

According still further to the third aspect of the invention, the substrate may be a one-piece substrate.

According yet further still to the third aspect of the invention, the substrate may be a split substrate such that the first area and second areas are physically separated.

According to a fourth aspect of the invention, an apparatus, comprises:

means for optical delivery, for providing two sequentially switched input optical beams comprising an optical image of a display;

two means for diffraction,

for receiving two sequentially switched input optical beams by two means for diffraction such that one of the two input optical beams is received by one of the two means for diffraction and another of the two input optical beams is received by another of the two means for diffraction, the two means for diffraction being disposed on a first or a second surface of a substrate made of optical material, the substrate comprising a first area and a second area substantially adjacent to each other along a line, and wherein the one of the two means for diffraction is disposed on the first part and the another of the two diffractive elements is disposed on the second part, respectively, wherein the two sequentially switched input optical beams comprise an optical image of a display and are provided by the means for optical delivery, and

for diffracting at least part of each of the two sequentially switched input optical beams at any time only in one of the two means for diffraction to provide a diffracted optical beam in the same area with the one of the two means for diffraction substantially within the first and second surfaces; and

two further means for diffraction, for coupling at least part of the diffracted optical beam in the first or the second area out of the substrate by diffraction in one of the two further means for diffraction for providing two sequentially switched and
substantially identical output optical beams, left and right, each comprising the
optical image of the display with an expanded exit pupil in one or two dimensions,
wherein the two further means for diffraction are disposed on the first or the
second surface, wherein one of the two further means for diffraction is disposed on
the first area and another of the two further means for diffraction is disposed on the
second area, respectively.

According further to the fourth aspect of the invention, the apparatus may be a
stereoscopic optical device and the two sequentially switched and substantially
identical output optical beams may be for providing a stereoscopic image of the
display.

**Brief Description of the Drawings**

For a better understanding of the nature and objects of the present
invention, reference is made to the following detailed description taken in
conjunction with the following drawings, in which:

Figures 1a through 1d are schematic representations of a one-
dimensional diffractive exit pupil expander (EPE) as a part of a virtual display
(a cross sectional view is shown in Figure 1a and a top view of the EPE which
corresponds to a front of display is shown in Figure 1b), and schematic
representations (cross-sectional views) of an in-coupling grating (e.g., using
slanted asymmetric grating) shown in Figure 1c and an out-coupling grating,
shown in Figure 1d.

Figures 2a and 2b are schematic representations (cross sectional views) of a
stereoscopic optical device (display) with a flat diffractive exit pupil expander using
sequential switching between a right image (Figure 2a) and a left image (Figure 2b)
of a microdisplay, according to an embodiment of the present invention;

Figures 3a and 3b are schematic representations (cross sectional views) of a
stereoscopic optical device (display) with a split diffractive exit pupil expander using
sequential switching between a right eye image (Figure 3a) and a left eye image
(Figure 3b) of a microdisplay, according to an embodiment of the present invention;

Figures 4a and 4b are schematic representations (cross sectional views) of flat
slanted asymmetric gratings (Figure 4a) and a split in-coupling grating (Figure 4b)
which can be used in an exit pupil expander, according to an embodiment of the present invention;

Figures 5a and 5b are schematic representations (top views) of one area (out of two) of a two-dimensional diffractive exit pupil expander, wherein an intermediate diffractive element (grating) has an odd number of first order diffractions (shown in Figure 5a) or an even number of further first order reflections (shown in Figure 5b), according to an embodiment of the present invention; and

Figure 6 is a schematic representation of an electronic device, having a stereoscopic display with an exit pupil expander, according to an embodiment of the present invention.

Modes for Carrying Out the Invention

A new method and apparatus are presented for providing a stereoscopic display in electronic devices with a diffractive exit pupil expander using sequentially switching between right and left images of one display (e.g., microdisplay).

According to an embodiment of the present invention, an optical delivery system can provide a sequential left and right image of the display and the illumination is then switched for left and right accordingly using exit pupil expander (EPE) with asymmetric, e.g., highly slanted, in-coupling gratings, sending light practically to only one direction (e.g., one area of the EPE substrate). The embodiments of the present invention can be applied to a broad optical spectral range of optical beams but most importantly to a visible part of the optical spectrum where the optical beams are called light beams.

According to embodiments of the present invention, the stereoscopic optical device (e.g., the device can be a part of a virtual reality display) can comprise a substrate made of optical material having a first surface and an opposing second surface, wherein the substrate comprising a first area and a second area substantially adjacent to each other along a line.

Moreover, two diffractive elements (or in-coupling diffraction gratings) can be disposed on the first or the second surface and each of the diffractive elements can be configured to receive one of two input optical beams comprising an optical image of a display, wherein one of the two diffractive elements is disposed on the first area and another of the two diffractive elements is disposed on the second area,
respectively, and said two diffractive elements can be substantially next to each other and adjacent to said line.

Thus, at least part of each of the two sequentially switched input optical beams at any time is diffracted only in one of the two diffractive elements to provide a diffracted optical beam in the same area comprising said one of the two diffractive elements substantially within the first and second surfaces due to a total internal reflection.

According to an embodiment of the present invention, the optical delivery system can be configured to sequentially switch the two input optical beams comprising the optical image of the display between the two diffractive elements. Then the two areas can expand the exit pupil of the input optical beams independently in one or two dimensions to provide substantially identical two output optical beams, left and right, each comprising the optical image of the display with an expanded exit pupil in one or two dimensions, thus providing a stereoscopic image of the display to a user observing the left and right output optical beams, wherein the switching speed between left and right images is fast enough to "fuse" a stereoscopic image of the display in a human brain as known in the art.

In case of a simple one-dimensional exit pupil expansion, two further diffractive elements (or out-coupling diffraction gratings) can be disposed on the first or the second surface (e.g., two further diffractive elements may have parallel periodic lines and/or be symmetric relative to said line), wherein one of the two further diffractive elements is disposed on the first area and another of said two further diffractive elements is disposed on the second area, respectively, thus at least part of the diffracted optical beam in each of the first and the second areas of the substrate is further coupled out of the substrate by diffraction (as known in the art) in each of the two further diffractive elements, thus providing substantially identical two output optical beams alternating sequentially in time. It is noted that the two diffractive elements and the two further diffractive elements can be disposed on one surface or on different surfaces of said substrate.

In case of a two-dimensional exit pupil expansion, each of the first and the second areas of the substrate can comprise an intermediate diffractive element such that the at least part of the optical beam diffracted in the first or the second diffractive element is first coupled to the intermediate diffractive element, which then couples,
using a further diffraction in the intermediate diffractive element, the at least part of
the diffracted optical beam to one of the two further diffractive elements disposed in
each area, thus providing the two-dimensional exit pupil expansion of one of the two
input optical beams by the each of the first and the second areas. The intermediate
diffractive element can have an odd number of first order diffractions or an even
number of further first order reflections as known in the art and, e.g., described by T.
Levola in “Diffractive Optics for Virtual Reality Displays”, SID Eurodisplay 05,
Edinburg (2005), SID 02 Digest, Paper 22.1.

According to further embodiments of the present invention, the optical
delivery system can comprise two optical sources (e.g., light emitting diodes,
typically providing a polarized light) configured to provide two optical beams in
substantially different directions for sequentially switching the two input optical
beams, wherein the two optical sources are configured to turn on and off in a
sequential manner with a predetermined period. The optical delivery system can
further comprise a beamsplitter, e.g., using a wire grid polarizer configured as a
polarized beam-splitter to re-direct two optical beams for sequentially switching the
two input optical beams between said two diffractive elements (see Examples in
Figures 2a, 2b, 3a and 3b). Furthermore, the optical delivery system may comprise a
shutter configured to sequentially switch the two input optical beams between said
two diffractive elements with the predetermined period: a) in addition to turning on
and off the light sources for improving separation of the left and right input optical
beams or b) instead of the turning on and off the light sources thus prolonging the
lifetime of the light sources by avoiding a large signal modulation regime of the
optical sources. For example, a liquid crystal on silicon (LCOS) type microdisplay
can be switched, e.g., with 480 frames/second speed which implies 160
frames/second full color speed and 80 frame/second stereoscopic speed.

According to a further embodiment of the present invention, the substrate used
for the EPE can be implemented as one-piece substrate using, e.g., highly asymmetric
slanted diffraction grating with a high efficiency coupling to a desired area (first or
second) of the substrate by the corresponding input diffractive elements. The contrast
can be further improved by providing an absorbing material on the opposite surface
of the substrate (i.e., opposite to the surface with the disposed input diffractive
elements). The width of this absorbing material should be optimized (e.g., to be
approximately the same as the thickness of the substrate) in order to absorb only optical beams propagating in unwanted directions. In case of the one-piece flat substrate, the two diffractive elements adjacent to each other can be considered as one diffraction grating, e.g., with two highly asymmetric slanted areas of the grating.

According to another embodiment of the present invention, the substrate used for the EPE can be implemented as a split substrate, such that said first area and second areas are physically separated. In addition, this split substrate can be configured that the first and the second areas can rotate in a predetermined angle range relative to each other around said line which separates the first and the second areas to provide better viewing.

According to embodiments of the present invention, the two diffractive elements (or the in-coupling diffraction gratings) can be implemented using a variety of different types of diffraction gratings, e.g., planar diffraction gratings manufactured using lithographic methods or classically ruled (having different groove angles and profiles, such as binary, triangular, sinusoidal, etc.). The two diffractive elements (i.e., their grooves) can be symmetric or asymmetric relative to the line which divides (virtually or physically) the first and the second areas. The term “asymmetric” in regard to the grooves of the two in-coupling gratings can have two aspects: a) when periodic lines (or grooves) of the two gratings are not parallel, and b) when grooves of the two gratings have different slanted angles. Therefore, one possibility is to have non-parallel asymmetric periodic lines in the two in-coupling diffraction gratings, thus re-directing only wanted components in each part of the substrate to the corresponding out-coupling gratings. Another solution (which can be combined with periodic line asymmetry) is to use slanted gratings (e.g., using a slanting angle of at least more than 20 degrees and optimally between 35 and 50 degrees) for increasing the coupling efficiency and reducing an “optical crosstalk” between the first and the second parts (or left and right parts) of the split substrate. In other words, the asymmetric gratings (used as the two diffractive elements) can provide that the input optical beam diffracted by each of the two diffractive elements is substantially coupled only in a desired direction to the part in which said each of the two diffractive elements is disposed.

Furthermore, according to an embodiment of the present invention, in order to provide the effective coupling and minimize the “optical crosstalk” between the two
parts of the split or one-piece substrate, the two slanted gratings can be asymmetric such that their slanting angles are equal but have opposite signs relative to the optical axis of the system creating the input optical beam, i.e., the groove shapes are mirror images of each other with respect to the line which separates the first and the second parts. Moreover, an absorbing material can be deposited on the first and/or the second part in an area of their physical separation along the line which separates the first and the second areas in the case of the split substrate.

Figures 1a through 1d show schematic representations of a one-dimensional diffractive exit pupil expander (EPE) with a cross sectional view shown in Figure 1a and a top view shown in Figure 1b, thus providing two substantially identical images for the right and left eyes, and schematic representations (a top view of an EPE which corresponds to a front of display is shown in Figure ) of an in-coupling grating (e.g., using a slanted asymmetric grating) shown in Figure 1c and an out-coupling grating, shown in Figure 1d. The light is coupled out from the out-coupling grating. The amount of out-coupling at each time the beam meets the grating depends on the grating properties. The system can be designed so that at least for one wavelength and incoming angle the output is uniform, i.e. \( r_1 = r_2 = \ldots \), as shown in Figure 1d, wherein \( r_1, r_2, \ldots \) and \( t_1, t_2, \ldots \) are reflected and transmitted optical beams out of the EPE, respectively, and \( I_1, I_2, \ldots \) are reflected optical beams inside the EPE by the total internal reflection. Figures 2-6 demonstrate different embodiments of the present invention for providing a stereoscopic image of the display (e.g., the microdisplay). The example of the EPE and its elements shown in Figures 1a-1d can be used for applying embodiments of the present invention. Figures 2-6 demonstrate different embodiments of the present invention.

Figures 2a and 2b show examples among others of schematic representations (cross sectional views) of a stereoscopic optical device (display) 10 (or an EPE device) with a flat diffractive exit pupil expander 12 (e.g., a one-piece substrate) using sequential switching between a right image 32-1d (Figure 2a) and a left image 32-2d (Figure 2b) of a microdisplay 24, according to an embodiment of the present invention. The microdisplay 24 in this example can utilize, e.g., a liquid crystal on silicon (LCOS).
The EPE 12 is a solid substrate comprising two adjacent areas 12a and 12b that are adjacent to each other along a line 18 (here line 18 is an imaginary line). The area 12a comprises the in-coupling grating 14a and an out-coupling grating 16a and the area 12b comprises the in-coupling grating 14b and an out-coupling grating 16b, respectively. The adjacent gratings 14a and 14b can be highly asymmetric as further shown in an example of Figure 4a.

According to an embodiment of the present invention, the optical delivery system can be configured to sequentially switch the two input optical beams comprising the optical image of the microdisplay 24 between the two diffractive elements 14a and 14b. The optical delivery system can comprise two optical sources (e.g., light emitting diodes) 20a and 20b which can be combined in a dual light source 20, configured to provide two optical beams 32-1 and 32-2 (typically polarized) in substantially different directions as shown in Figures 2a and 2b, respectively, for sequentially switching the two input optical beams 32-1b and 32-2b comprising images of the microdisplay 24 which are diffracted to the corresponding optical beams 32-1c and 32-2c by the in-coupling gratings 14a and 14b and further diffracted to the optical output beams (the right and the left images of the microdisplay 30) 32-1d and 32-2d, wherein the two optical sources 20a and 20b are configured to turn on and off in a sequential manner with the predetermined period as discussed above.

Thus, a stereoscopic image of the microdisplay 30 is provided to a user observing the left and right output optical beams 32-1d and 32-2d sequentially switched, wherein the switching speed between left and right images is fast enough to “fuse” a stereoscopic image of the microdisplay in a human brain as known in the art.

The optical delivery system, e.g., for an LCOS microdisplay 24 can further comprise a wire grid polarizer 26 configured as a polarization beam-splitter to redirect two optical beams reflected for sequentially switching the two input optical beams between said two diffractive elements (see Examples in Figures 2a, 2b, 3a and 3b). In principle a traditional 50% beam splitter can be also utilized which will result in more than 75% optical power loss, therefore using the wire grid polarizer which minimizes the optical power loss to a minimum (typically less than 20%) is advantageous. The wire grid polarizer is known in the art and described, e.g., by S. Arnold, E. Gardner, D. Hansen and R. Perkins in “An improved polarizing

Furthermore, the optical delivery system may comprise a shutter 30 configured to sequentially switch the two input optical beams 32-1b and 32-2b between the two diffractive elements 14a and 14b with the predetermined period: a) in addition to turning on and off the light sources 20a and 20b for improving the separation of the left and right input optical beams 32-1b and 32-2b or b) instead of turning on and off the light sources 20a and 20b thus simplifying the illumination optics.

Figures 3a and 3b show examples among others of schematic representations (cross sectional views) of a stereoscopic optical device (display) 10a with a split diffractive exit pupil expander (EPE) 12-1 using sequential switching between the right image 32-1d (Figure 3a) and the left image 32-2d (Figure 3b) of the LCOS microdisplay 24, according to an embodiment of the present invention. The only difference in Figures 3a and 3b, compared to Figures 2a and 2b, is using the split EPE comprising physically separated areas 12a and 12b and physically separated input diffraction gratings 14a and 14b, respectively. Using split input diffraction gratings 14a and 14b can provide better optical isolation between the areas 12a and 12b and better separation of the images 32-1d and 32-2d. In addition, this split substrate 12-1 can be configured that the first and the second areas 12a and 12b can rotate relative to each around the line 18 in a predetermined angle range (in a direction 15 as shown in figures 3a and 3b) to provide better viewing if required.

Figure 4a shows one example among others of a schematic representation of slanted asymmetric gratings 14a and 14b (which can be considered as one diffraction grating 14) used in the exit pupil expander 12 (with one-piece substrate) of a stereoscopic optical display 10 shown in Figures 2a and 2b, according to an embodiment of the present invention. The optical contrast can be further improved by providing an absorbing material (e.g., an absorbing coating) 17 on a surface of the substrate 12 opposite to the substrate surface with the disposed input diffraction gratings 14a and 14b in a vicinity of the line 18 (as shown in Figure 4a). If the width of the absorbing area is optimized to be small enough compared to the total width of the gratings 14a and 14b as shown in Figure 4a, only the unwanted optical beams will be absorbed. These unwanted beams are the optical beams which are transmitted
by the gratings 14a and 14b without diffracting and those diffracted beams that propagate in unwanted directions.

Figure 4b shows one further example among others of a schematic representation of a split exit pupil expander 12-1 of a stereoscopic optical display 10a shown in Figures 3a and 3b using split slanted asymmetric in-coupling gratings 14a and 14b (diffractions grooves of gratings 14a and 14b face different directions relative to the optical axis of the system providing input optical beams), according to an embodiment of the present invention. According to a further embodiment, the ends of the diffraction gratings 14a and 14b can be coated with an absorbing material 20a and 20b along the line 18 to further optically isolate the areas 12a and 12b. Similarly to Figure 4a, the absorbing materials 17a and 17b can be used in addition or instead of absorbing material 20a and 20b to further improve the optical contrast.

Figures 5a and 5b show further examples among others of schematic representations (cross-sectional views) of one area out of two areas 12a or 12b of a two-dimensional diffractive exit pupil expander 12 or 12-1, according to an embodiment of the present invention. An intermediate diffractive element (diffraction grating) 24 or 26 has odd number of first order diffractions (shown in Figure 4a) or even number of further first order reflections (shown in Figure 4b) as described by T. Levola in “Diffractive Optics for Virtual Reality Displays”, SID Eurodisplay 05, Edinburg (2005), SID 02 Digest, Paper 22.1. The angle \( \rho \) is a rotation angle between the periodic lines of the intermediate diffraction grating 26 and the in-coupling grating 14a or 14b.

Figure 6 shows an example of a schematic representation of an electronic device, having a stereoscopic display 10 or 10a with the exit pupil expander (EPE) 12, according to an embodiment of the present invention.

The exit pupil expander (EPE) 12 or 12-1 can be used in an electronic (portable) device 100, such as a mobile phone, personal digital assistant (PDA), communicator, portable Internet appliance, hand-hand computer, digital video and still camera, wearable computer, computer game device, specialized bring-to-the-eye product for viewing and other portable electronic devices. As shown in Figure 6, the portable device 100 has a housing 210 to house a communication unit 212 for receiving and transmitting information from and to an external device (not shown). The portable device 100 also has a controlling and processing unit 214 for handling
the received and transmitted information, and a virtual display system 230 for viewing. The virtual display system 230 includes a micro-display or an image source 192 and an optical engine 190. The controlling and processing unit 214 is operatively connected to the optical engine 190 to provide image data to the image source 192 to display an image thereon. The EPE device 10 or 10a, according to embodiments of the present invention, can be optically linked to an optical engine 190.

Furthermore, the image source 192, as depicted in Figure 6, can be a sequential color LCOS (Liquid Crystal On Silicon) device, an OLED (Organic Light Emitting Diode) array, an MEMS (MicroElectro Mechanical System) device or any other suitable micro-display device operating in transmission, reflection or emission.

Moreover, the electronic device 100 can be a portable device, such as a mobile phone, personal digital assistant (PDA), communicator, portable Internet appliance, hand-held computer, digital video and still camera, wearable computer, computer game device, specialized bring-to-the-eye product for viewing and other portable electronic devices. However, the exit pupil expander, according to the present invention, can also be used in a non-portable device, such as a gaming device, vending machine, band-o-matic, and home appliances, such as an oven, microwave oven and other appliances and other non-portable devices.

It is to be understood that the above-described arrangements are only illustrative of the application of the principles of the present invention. Numerous modifications and alternative arrangements may be devised by those skilled in the art without departing from the scope of the present invention, and the appended claims are intended to cover such modifications and arrangements.
What is claimed is:

1. An apparatus, comprising:

   a substrate of optical material having a first surface and a second surface, said
   substrate comprising a first area and a second area substantially adjacent to each other
   along a line;

   two diffractive elements disposed on the first or the second surface and
   configured to receive sequentially two input optical beams comprising an optical
   image of a display such that one of the two input optical beams is received by one of
   the two diffractive elements and another of the two input optical beams is received by
   another of the two diffractive elements, wherein one of the two diffractive elements is
   disposed on the first area and another of the two diffractive elements is disposed on
   the second area, respectively;

   two further diffractive elements disposed on the first or the second surface,
   wherein one of the two further diffractive elements is disposed on the first area and
   another of said two further diffractive elements is disposed on the second area,
   respectively; and

   an optical delivery system, configured to sequentially switch said two input
   optical beams comprising the optical image of the display between said two
   diffractive elements, wherein

   at least part of each of the two sequentially switched input optical beams at
   any time is diffracted only in one of the two diffractive elements to provide a
   diffracted optical beam in the same area with said one of the two diffractive elements
   substantially within the first and second surfaces, and

   at least part of the diffracted optical beam in the first or the second area is
   further coupled out of the substrate by diffraction in one of said two further
   diffractive elements for providing two sequentially switched and substantially
   identical output optical beams, each comprising the optical image of the display with
   an expanded exit pupil in one or two dimensions.
2. The apparatus of claim 1, wherein said two sequentially switched and substantially identical output optical beams are for providing a stereoscopic image of the display.

3. The apparatus of claim 1, wherein said two diffractive elements are substantially next to each other and adjacent to said line.

4. The apparatus of claim 1, wherein said optical delivery system comprises two optical sources configured to provide two optical beams in substantially different directions for sequentially switching the two input optical beams.

5. The apparatus of claim 4, wherein said two optical sources are configured to turn on and off in a sequential manner with a predetermined period.

6. The apparatus of claim 4, wherein said optical delivery system comprises a wire grid polarizer configured as a beam-splitter to re-direct the two optical beams for said sequentially switching the two input optical beams between said two diffractive elements and said display is a liquid crystal on silicon display.

7. The apparatus of claim 1, wherein said optical delivery system comprises a shutter configured to sequentially switch the two input optical beams between said two diffractive elements with a predetermined period.

8. The apparatus of claim 1, wherein said substrate is a one-piece substrate.

9. The apparatus of claim 1, wherein said substrate is configured to have in a vicinity of said line an absorbing material on a surface of the substrate opposite to a substrate surface with the disposed two diffractive elements.

10. The apparatus of claim 1, wherein said substrate is a split substrate such that said first area and second areas are physically separated.
11. The apparatus of claim 8, wherein an absorbing material is deposited on an end of at least one of the first and the second parts in an area of their physical separation along said line.

12. The apparatus of claim 1, wherein locations of said two diffractive elements or said two further diffractive elements are symmetrical relative to said line.

13. The apparatus of claim 1, wherein said two diffractive elements have an asymmetric groove shape such that the input optical beam diffracted by each of the two diffractive elements is substantially coupled only to an area, out of the first and the second areas, in which said each of the two diffractive elements is disposed.

14. The apparatus of claim 1, wherein said two diffractive elements have an asymmetric groove shape and are slanted gratings with a slanting angle of more than 20 degrees.

15. The apparatus of claim 1, wherein said two diffractive elements are asymmetric such that their groove shapes are mirror images of each other with respect to the line which separates the first and the second areas.

16. The apparatus of claim 1, wherein said two diffractive elements and said two further diffractive elements are disposed on one surface of said substrate.

17. The apparatus of claim 1, wherein each area, the first and the second area of said substrate, comprises an intermediate diffractive element such that the at least part of the optical beam diffracted in the first or the second diffractive element is first coupled to said intermediate diffractive element, which then couples, using a further diffraction in said intermediate diffractive element, said at least part of said diffracted optical beam to one of said two further diffractive elements disposed on said each area to provide a two-dimensional exit pupil expansion of one of said two input optical beams in said each area.
18. A method, comprising:

receiving two sequentially switched input optical beams by two diffractive elements such that one of the two input optical beams is received by one of the two diffractive elements and another of the two input optical beams is received by another of the two diffractive elements, said two diffractive elements being disposed on a first or a second surface of a substrate made of optical material, said substrate comprising a first area and a second area substantially adjacent to each other along a line, and wherein said one of the two diffractive elements is disposed on the first part and said another of the two diffractive elements is disposed on the second part, respectively,

wherein said two sequentially switched input optical beams comprise an optical image of a display and are provided by an optical delivery system;

diffracting at least part of each of the two sequentially switched input optical beams at any time only in one of the two diffractive elements to provide a diffracted optical beam in the same area with said one of the two diffractive elements substantially within the first and second surfaces; and

coupling at least part of the diffracted optical beam in the first or the second area out of the substrate by diffraction in one of said two further diffractive elements for providing two sequentially switched and substantially identical output optical beams, each comprising the optical image of the display with an expanded exit pupil in one or two dimensions,

wherein the two further diffractive elements are disposed on the first or the second surface, wherein one of the two further diffractive elements is disposed on the first area and another of said two further diffractive elements is disposed on the second area, respectively.

19. The method of claim 18, wherein said two sequentially switched and substantially identical output optical beams are for providing a stereoscopic image of the display.

20. The method of claim 18, wherein said two diffractive elements are substantially next to each other and adjacent to said line.
21. The method of claim 18, wherein said optical delivery system comprises two optical sources configured to provide two optical beams in substantially different directions for sequentially switching the two input optical beams.

22. The method of claim 18, wherein said optical delivery system comprises a shutter configured to sequentially switch the two input optical beams between said two diffractive elements with a predetermined period.

23. The method of claim 18, wherein said substrate is a one-piece substrate.

24. The method of claim 18, wherein said substrate is a split substrate such that said first area and second areas are physically separated.

25. The method of claim 18, wherein said two diffractive elements have an asymmetric groove shape such that the input optical beam diffracted by each of the two diffractive elements is substantially coupled only to an area, out of the first and the second areas, in which said each of the two diffractive elements is disposed.

26. The method of claim 18, wherein said two diffractive elements are asymmetric such that their groove shapes are mirror images of each other with respect to the line which separates the first and the second areas.

27. An electronic device, comprising:
   - a data processing unit;
   - an optical engine operatively connected to the data processing unit for receiving image data from the data processing unit;
   - a display device operatively connected to the optical engine for forming an image based on the image data; and
   - an exit pupil expander device, comprising:
     - a substrate of optical material having a first surface and a second surface, said substrate comprising a first area and a second area substantially adjacent to each other along a line;
two diffractive elements disposed on the first or the second surface and
configured to receive sequentially two input optical beams comprising an optical
image of a display such that one of the two input optical beams is received by one of
the two diffractive elements and another of the two input optical beams is received by
another of the two diffractive elements, wherein one of the two diffractive elements is
disposed on the first area and another of the two diffractive elements is disposed on
the second area, respectively;

two further diffractive elements disposed on the first or the second surface,
wherein one of the two further diffractive elements is disposed on the first area and
another of said two further diffractive elements is disposed on the second area,
respectively; and

an optical delivery system, configured to sequentially switch said two input
optical beams comprising the optical image of the display between said two
diffractive elements, wherein

at least part of each of the two sequentially switched input optical beams at
any time is diffracted only in one of the two diffractive elements to provide a
diffracted optical beam in the same area with said one of the two diffractive elements
substantially within the first and second surfaces, and

at least part of the diffracted optical beam in the first or the second area is
further coupled out of the substrate by diffraction in one of said two further
diffractive elements for providing two sequentially switched and substantially
identical output optical beams, each comprising the optical image of the display with
an expanded exit pupil in one or two dimensions.

28. The electronic device of claim 27, wherein said two sequentially switched and
substantially identical output optical beams are for providing a stereoscopic image of
the display.

29. The electronic device of claim 27, wherein said two diffractive elements are
substantially next to each other and adjacent to said line.

30. The electronic device of claim 27, wherein said optical delivery system
comprises two optical sources configured to provide two optical beams in
substantially different directions for sequentially switching the two input optical beams.

31. The electronic device of claim 27, wherein said substrate is a one-piece substrate.

32. The electronic device of claim 27, wherein said substrate is a split substrate such that said first area and second areas are physically separated.

33. An apparatus, comprising:
   means for optical delivery, for providing two sequentially switched input optical beams comprising an optical image of a display;
   two means for diffraction,
   for receiving two sequentially switched input optical beams by two means for diffraction such that one of the two input optical beams is received by one of the two means for diffraction and another of the two input optical beams is received by another of the two means for diffraction, said two means for diffraction being disposed on a first or a second surface of a substrate made of optical material, said substrate comprising a first area and a second area substantially adjacent to each other along a line, and wherein said one of the two means for diffraction is disposed on the first part and said another of the two diffractive elements is disposed on the second part, respectively, wherein said two sequentially switched input optical beams comprise an optical image of a display and are provided by said means for optical delivery, and
   for diffracting at least part of each of the two sequentially switched input optical beams at any time only in one of the two means for diffraction to provide a diffracted optical beam in the same area with said one of the two means for diffraction substantially within the first and second surfaces; and
   two further means for diffraction, for coupling at least part of the diffracted optical beam in the first or the second area out of the substrate by diffraction in one of
said two further means for diffraction for providing two sequentially switched and substantially identical output optical beams, left and right, each comprising the optical image of the display with an expanded exit pupil in one or two dimensions,

wherein the two further means for diffraction are disposed on the first or the second surface, wherein one of the two further means for diffraction is disposed on the first area and another of said two further means for diffraction is disposed on the second area, respectively.

34. The apparatus of claim 33, wherein said apparatus is a stereoscopic optical device and said two sequentially switched and substantially identical output optical beams are for providing a stereoscopic image of the display.
Figure 4a

Figure 4b
Figure 6
A. CLASSIFICATION OF SUBJECT MATTER

IPC: see extra sheet
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: G02B

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

SE, DK, FI, NO classes as above

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<tr>
<td>A</td>
<td>WO 2004109349 A2 (ELOP ELECTRO-OPTICS INDUSTRIES LTD.), 16 December 2004 (16.12.2004), page 21, line 11 - page 29, line 2; page 37, line 25 - page 46, line 18, figures 1-8</td>
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<td>WO 2004055556 A1 (NOKIA CORPORATION), 1 July 2004 (01.07.2004), page 4 - page 5, figures 1-5</td>
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Further documents are listed in the continuation of Box C. See patent family annex.

Date of the actual completion of the international search: 16 January 2007

Date of mailing of the international search report: 19-01-2007

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<td>WO 03032017 A2 (PLANOP PLANAR OPTICS LTD.), 17 April 2003 (17.04.2003), page 16, line 1 - page 24, line 8, figures 3-6</td>
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