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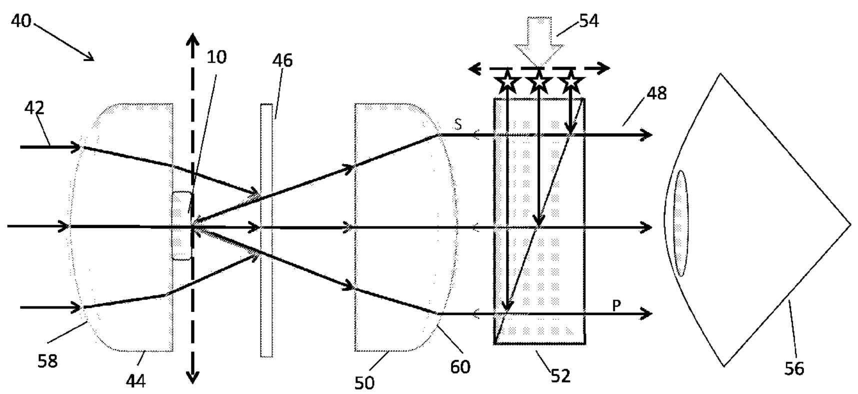

Fig. 2

(57) Abstract: The invention is an optical system for up-conversion of SWIR images into visible images. The optical system of the invention comprises a liquid crystal optically addressed spatial light modulator (LC-OASLM), which acts as an optical valve, and two optionally GRADIUM lenses to reduce the size and complexity of the optical setup. In embodiments of the invention, the photosensitive layer is replaced by a photodiode or array of photodiodes and the liquid crystal layer is replaced by an array (film) of organic light emitting diodes which emit light at the VIS by collecting SWIR light or by a fluorescence layer with sensitivity in the SWIR range.

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SWIR TO VISIBLE UP-CONVERSION OPTICAL SYSTEM

Field of the Invention

The invention is from the field of photon up-conversion devices. Specifically the invention is from the field of up-conversion devices for converting images detected in short wavelength infrared light into images in the visible wavelength range.

Background of the Invention

There is great interest in photon up-conversion devices in many fields. In particular in the field of devices capable of allowing humans to see images of scenes that are in nearly total darkness. Particularly important in this respect are devices that are capable of converting short wavelength infrared (SWIR) images into visible ones.

The importance of the SWIR range of wavelengths is that the spectral irradiance of natural light sources such as nightglow known also as airglow is several times stronger in the SWIR range than in the near infrared (NIR) range. Also the transparency through fog and dust is much higher in the SWIR range than in the visible or NIR. Thus scenes and objects that cannot be seen in visible light even in daylight can be viewed using SWIR natural light. In addition in this wavelength range the device doesn't need cooling.

In general, present day advanced SWIR to visible up-conversion devices have several deficiencies including high cost, relatively large size and weight, and in some cases require cooling using liquid nitrogen. In addition, other proposed up-conversion devices suffer from low quantum efficiency due to low SWIR photon absorption and Low efficiency of the conversion process.

Liquid crystals spatial light modulators are well established technology [1]. By using spatial light modulators (SLM), the phase and/or amplitude of a beam of light can be modulated. There are two standard types of light modulation using liquid crystals (LC) devices. The first type is the so called electrically addressed SLM (EASLM) wherein an electrical signal drives the orientation of the LC molecules which in turn causes a phase and/or amplitude modulation of the beam transmitted/reflected trough the device. The second type is the so called optically addressed SLM (OASLM), wherein an optical signal with wavelength λ_1 drives the LC molecules orientation which in turn causes a phase and/or amplitude modulation of a second beam with wavelength λ_2. The driving signal is usually called the writing beam, whereas the transmitted/reflected beam is usually called the reading beam; this writing beam usually absorbed by a photo conductive layer and the liquid crystals act as a modulator [2] on the reading beam.

It is a purpose of the present invention to provide a small low-cost up-conversion device for converting SWIR images into visible images.

Further purposes and advantages of this invention will appear as the description proceeds.

Summary of the Invention

Publications and other reference materials referred to herein are numerically referenced in the following text and respectively grouped in the appended Bibliography which immediately precedes the claims.

The invention is a short wavelength infrared (SWIR) to visible wavelength (VIS) up conversion optical system. The system comprises:

a. a first GRADIUM lens **44**, which projects SWIR images into the optical system;

b. a LC-OASLM unit **10**, which accepts a SWIR image from the first GRADIUM lens **44**;
c. a VIS light source **54**;
d. a second GRADIUM lens **50**, which focus VIS light from the VIS source **54** onto the LC-OASLM unit **10** and projects VIS images from the LC-OASLM unit **10** towards infinity;
e. a short pass filter **46** which reflects SWIR light onto the LC-OASLM unit **10** and transmit VIS light from the VIS source to LC-OASLM unit **10** and back from LC-OASLM unit **10** to the second GRADIUM lens **50**; and
f. a polarization beam splitter (PBS) **52**;

wherein the LC-OASLM Unit **10** comprises:

A. a first optical substrate **12** comprising:
   i. a SWIR high reflecting coating film **14**;
   ii. a first glass substrate **16**; ;
   iii. an ITO layer **18**;
   iv. a SWIR photo sensitive layer **20**; and
   v. a first LC alignment layer **22**;
B. a LC layer **24**;
C. a second optical substrate **26** comprising:
   i. a second LC alignment layer **28**;
   ii. an ITO layer **30**;
   iii. a second glass substrate **32**; and
   iv. a SWIR anti reflection layer **34**.

In embodiments of the optical system of the invention the short pass filter **46** can have a concave shape.

In embodiments of the optical system of the invention the short pass filter **46** can have a convex shape.

In embodiments of the optical system of the invention the photosensitive layer **20** is replaced with a photodiode or array of photodiodes so that the first optical substrate **12** is comprised of:

i. a SWIR high reflecting coating film;
ii. an ITO layer
iii. a photodiode or array of photodiodes; and
iv. a first LC alignment layer.

In embodiments of the optical system of the invention the LC layer **24** is replaced with an array (film) of organic light emitting diodes (OLED) which emit light at the VIS by collecting SWIR light. In these embodiments the reading unit comprising green LED **54** and polarized beam splitter **52** and the alignment layers **22**, **28** on the optical substrates **12**, **26** are removed from the system.

In embodiments of the optical system of the invention the LC layer **24** is replaced with a fluorescence layer with sensitivity in the SWIR range. In these embodiments the reading unit comprising green LED **54** and polarized beam splitter **52** and the alignment layers **22**, **28** on the optical substrates **12**, **26** are removed from the system.

All the above and other characteristics and advantages of the invention will be further understood through the following illustrative and non-limitative description of embodiments thereof, with reference to the appended drawings.

Brief Description of the Drawings

— Fig. 1 schematically shows a liquid crystal optically addressed spatial light modulator, and

— Fig. 2 schematically shows the SWIR to visible up-conversion system of the invention.

Detailed Description of Embodiments of the Invention

The invention is an optical system for up-conversion of SWIR images into visible images. The optical system of the invention comprises a liquid crystal optically addressed spatial light modulator (LC-OASLM), which acts as an optical valve, and two optionally GRADIUM lenses to reduce the size and complexity of the optical setup. In embodiments of the invention, the liquid crystal layer is replaced by an array (film) of organic light emitting diodes which emit light at the VIS by collecting SWIR light or by a fluorescence layer with sensitivity in the SWIR range.

In Fig. 1 a liquid crystal optically addressed spatial light modulator (LC-OASLM) is depicted. This LC-OASLM **10** acts as an optical valve, which is comprised of: a first optical substrate **12**, a second optical substrate **26**, and a liquid crystal (LC) layer **24**. The first optical substrate is comprised of a first optical glass substrate **16** which is coated with a SWIR high reflection (HR) coating film **14** deposited on its left facet and with an indium tin oxide (ITO) layer **18** and a thin film photo sensing material **20** (photosensor) deposited on its right facet. This composite glass is used as one of the substrates for the construction of the LC-OASLM; The LC material is stacked between a first alignment layer **22** on the first optical substrate **12** and a second alignment layer **28** on the second optical substrate **26**. A comprehensive review of the preparation and construction procedures of LC devices can be found in [3]. The second optical substrate **26** is comprised of a second glass substrate **32** coated on its left facet with an ITO film **30**, which is used as a transparent electrode that, together with the photo sensing film **20**, provides an electrical field distribution, across the LC cell **10**. On the right facet of the ITO coated glass an anti-reflection coating layer **34** is deposited in order to improve the transitivity of the SWIR light from the LC-OASLM.

When a SWIR beam is projected onto the photosensitive layer **20**, a local electron-hole charge separation is produced which influences the local voltage level across the LC cell **10**. As a result, the LC molecules in this region change their orientation which causes a local modulation of the birefringence dispersion or the effective refractive index; this process is usually termed "writing" [4]. When a visible beam is incident on OASLM **10**, the reflected beam is modulated only at the region where the local voltage change occurred; this process is usually termed "reading" [5, 6].

Fig. 2 schematically shows the SWIR to visible up-conversion system **40** of the invention. The optical setup is comprised of a first GRADIUM lens **44** that functions in a similar manner to a Mirau objective lens. The LC-OASLM detailed in Fig. 1 is centered at the middle of the objective lens **44** and also serves as an annular aperture for the first GRADIUM lens **44**. To the right of the first GRADIUM lens 44 there is a short-pass filter **46** that reflects SWIR wavelengths **42** and transmits visible light **48**. Short-pass filter **46** is located at a position from which it will reflect the writing beam to the LC-OASLM **10** at the focal plane of the first GRADIUM lens **44** and transmit a reading beam to the back focal plane of a second GRADIUM lens **50**. The short pass filter **46** can be flat as drawn in figure 2 or it can be curved (concave or convex) so that an erect image is obtained on the photosensor with the minimum number of components. The second GRADIUM lens b and a polarized beam splitter (PBS) **52** are placed after short-pass filter b. On top of PBS **52** there is a green LED **54** that functions as a reading beam. The first GRADIUM lens **44** has a SWIR antireflection coating **58** deposited on all its surfaces to maximize transmission of SWIR light. The second GRADIUM lens **50** has a visible antireflection coating 60 deposited on all its surfaces to maximize transmission of visible light. The overall optical conversion system shown in Fig. 2 projects a visible image onto a human eye **56** that is identical to the SWIR image gathered by the first GRADIUM lens **44**.

The incoming SWIR light **42** from the left is diffracted by the first GRADIUM lens **44** onto the short-pass filter **46**, which reflects the SWIR light to the LC-OASLM layer **10** generating a writing process. Simultaneously, the visible reading light is projected from the green LED **54** onto the PBS **52** which separates the S and P polarization components by reflecting the S component at the dielectric beam splitter coating to the second GRADIUM lens, while allowing the P component to pass. The polarized reading light beam is focused on the LC-OASLM **10**, which acts as an optical LC valve working in reflection. The visible light reads the SWIR image and changes polarization due to birefringence modulation caused by the liquid crystals. The visible P polarized light is reflected from LC-OASLM **10** back to the PBS **52** through the second GRADIUM lens **50** and continues to the human eye **56**. With the optical arrangement shown in Fig. 2 the visible image seen by the observer is up-side-down relative to the SWIR image, but there are several different options that are well known in the art for inverting the final image.

In another embodiment of the invention the LC layer is replaced with an array (film) of organic light emitting diodes (OLED) which emit visible light upon receiving photocurrent from the photosensor generated by the SWIR light. In this case the reading unit comprising green LED **54** and polarized beam splitter **52** can be removed. Also when an OLED array is used there is no need for the alignment layers **22**, **28** on the optical substrates **12**, **26**.

In another embodiment of the invention the LC layer is replaced with a fluorescence layer with sensitivity in the SWIR range. In this case the reading unit comprising green LED **54** and polarized beam splitter **52** and the alignment layers **22**, **28** on the optical substrates **12**, **26** can be removed from the system.

In another embodiment of the invention the photosensor maybe made of a photodiode structure or an array of photodiodes sensitive to the SWIR light.

Although embodiments of the invention have been described by way of illustration, it will be understood that the invention may be carried out with many variations, modifications, and adaptations, without exceeding the scope of the claims.

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Claims

1. A short wavelength infrared (SWIR) to visible wavelength (VIS) up conversion optical system comprising:
   a. a first GRADIUM lens **44**, which projects SWIR images into the optical system;
   b. a LC-OASLM unit **10**, which accepts a SWIR image from the first GRADIUM lens **44**;
   c. a VIS light source **54**;
   d. a second GRADIUM lens **50**, which focus VIS light from the VIS source **54** onto the LC-OASLM unit **10** and projects VIS images from the LC-OASLM unit **10** towards infinity;
   e. a short pass filter **46** which reflects SWIR light onto the LC-OASLM unit **10** and transmit VIS light from the VIS source to LC-OASLM unit **10** and back from LC-OASLM unit **10** to the second GRADIUM lens **50**; and
   f. a polarization beam splitter (PBS) **52**;

   wherein the LC-OASLM Unit **10** comprises:

   A. a first optical substrate **12** comprising:
      i. a SWIR high reflecting coating film **14**;
      ii. a first glass substrate **16**; ;
      iii. an ITO layer **18**;
      iv. a SWIR photo sensitive layer **20**; and
      v. a first LC alignment layer **22**;

   B. a LC layer **24**;

   C. a second optical substrate **26** comprising:
      i. a second LC alignment layer **28**;
      ii. an ITO layer **30**;
      iii. a second glass substrate **32**; and
      iv. a SWIR anti reflection layer **34**.

2. The optical system of claim 1 where the short pass filter **46** has a concave shape.

3. The optical system of claim 1 where the short pass filter **46** has a convex shape.

4. The optical system of claim 1 where the photosensitive layer 20 is replaced with a photodiode or array of photodiodes so that the first optical substrate **12** is comprised of:
   i. a SWIR high reflecting coating film;
   ii. an ITO layer
   iii. a photodiode or array of photodiodes; and
   iv. a first LC alignment layer.

5. The optical system of claim 1 where the LC layer 24 is replaced with an array (film) of organic light emitting diodes (OLED) which emit light at the VIS by collecting SWIR light

6. The optical system of claim 5 wherein the reading unit comprising green LED 54 and polarized beam splitter 52 and the alignment layers 22, 28 on the optical substrates 12,26 are removed from the system.

7. The optical system of claim 1 where the LC layer 24 is replaced with a fluorescence layer with sensitivity in the SWIR range.

8. The optical system of claim 7 wherein the reading unit comprising green LED 54 and polarized beam splitter 52 and the alignment layers 22, 28 on the optical substrates 12,26 are removed from the system.

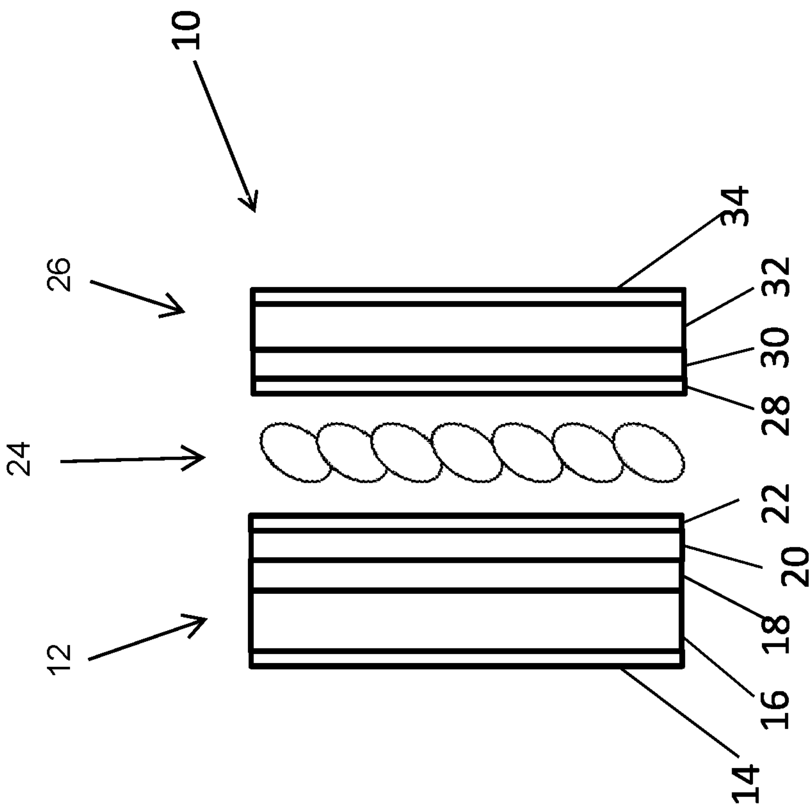

Fig. 1

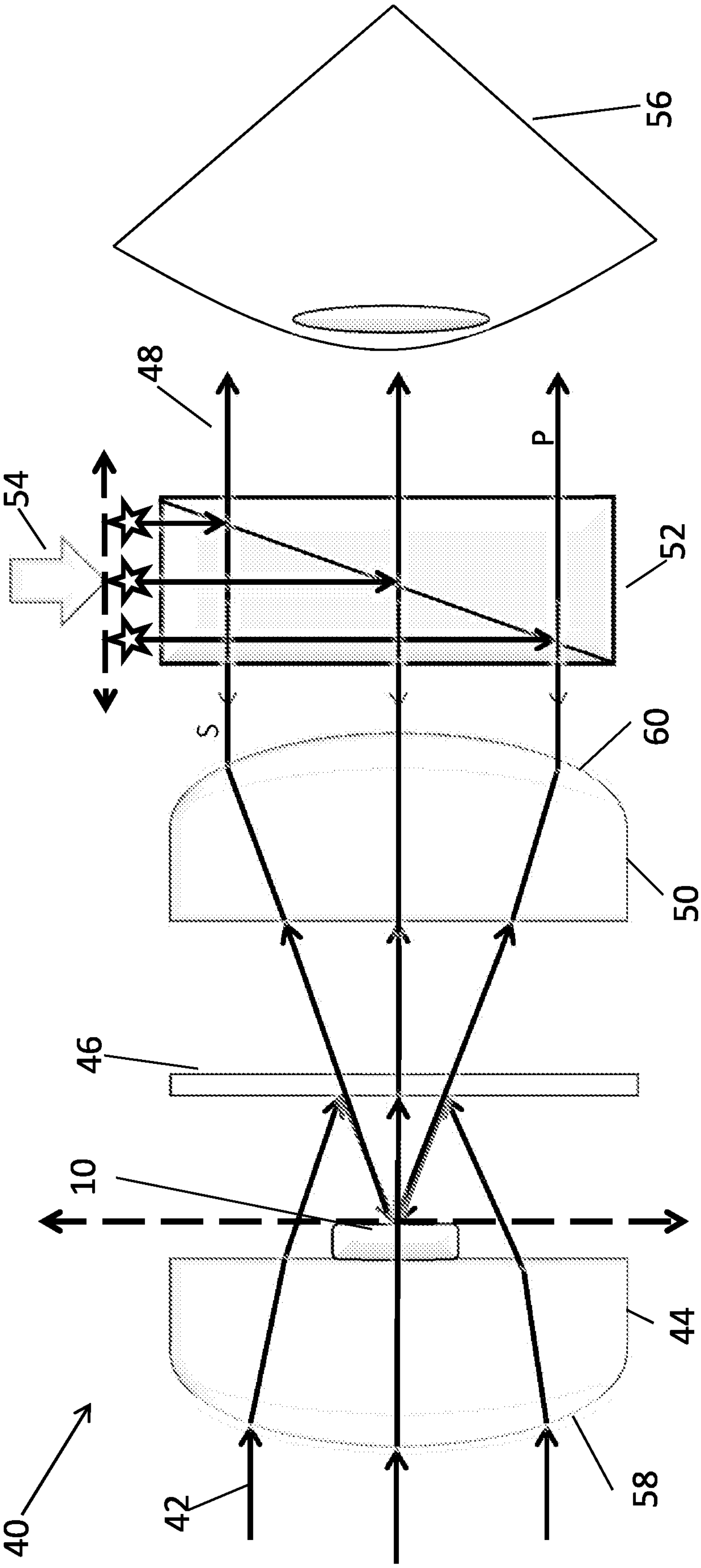

Fig. 2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2016/050617

A. CLASSIFICATION OF SUBJECT MATTER

IPC (2016.01) G02F 1/133500, H04N 5/33, G02B 3/02

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 (2016.01) G02F, H04N

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 6573953 B1 Igasaki et.al. 03 Jun 2003 (2003/06/03) Column 5, line 9-column 6, line 44, figs. 1, 2.	1-8
A	US 2004/0258353 A1 Gluckstad et.al. 23 Dec 2004 (2004/12/23) Abstract, paragraphs [0032]-[0034], [0061]-[0069], figs. 3, 4	1-8
A	US 4831452 A Takanashi et.al. 16 May 1989 (1989/05/16) The entire document.	1-8
A	US 6894846 B1 He et.al. 17 May 2005 (2005/05/17) The entire document.	1-8

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

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Date of the actual completion of the international search	Date of mailing of the international search report
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INTERNATIONAL SEARCH REPORT
Information on patent family members

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B. FIELDS SEARCHED:

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Databases consulted: THOMSON INNOVATION, Google Patents, Google Scholar, PatBase
Search terms used: Up convert, wavelength convert, GRADIUM lens, GRIN lens, graded-index lens, SWIR/short wavelength infrared, infrared, visible, optically addressed spatial light modulator/OASLM, liquid crystal, spatial light modulator/SLM, reflect, filter, beamsplitter, polarization, ITO.