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(54) Title: OPTICAL SHUTTER BASED ON SUB-WAVELENGTH GRATINGS ACTUATED BY MICROELECTROMECHANICAL SYSTEMS

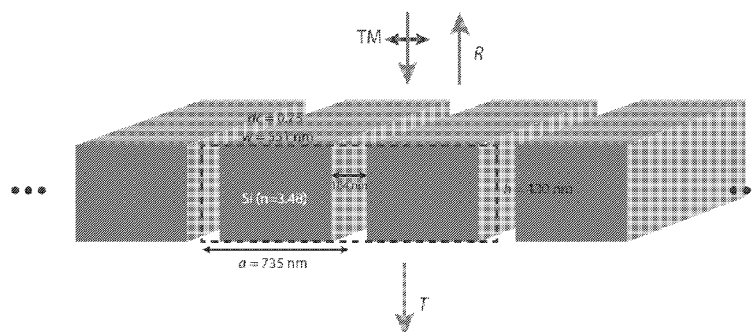


FIG. 1

(57) Abstract: Methods and systems for control of electromagnetic waves are disclosed. An optical shutter includes a sub-wavelength grating. Each beam of the grating can be controlled by electrostatic or mechanical forces in order to increase or decrease the gap between each beam. Electrostatic or acoustic control of the grating allows an optical shutter to switch on and off.



OPTICAL SHUTTER BASED ON SUB-WAVELENGTH GRATINGS ACTUATED BY MICROELECTROMECHANICAL SYSTEMS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to US Provisional Patent Application No. 62/032,334, filed on August 1, 2014, the disclosure of which is incorporated herein by reference in its entirety.

STATEMENT OF INTEREST

[0002] This invention was made with government support under DE-SC0001293 / T-107196 awarded by the Department of Energy. The government has certain rights in the invention. The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

TECHNICAL FIELD

[0003] The present disclosure relates to optical shutters. More particularly, it relates to optical shutter based on sub-wavelength gratings actuated by microelectromechanical systems.

BRIEF DESCRIPTION OF DRAWINGS

[0004] The accompanying drawings, which are incorporated into and constitute a part of this specification, illustrate one or more embodiments of the present disclosure and, together with the description of example embodiments, serve to explain the principles and implementations of the disclosure.

[0005] Fig. 1 illustrates a cross-sectional schematic of one embodiment of the device of the present disclosure.

[0006] Fig. 2 illustrates reflection spectrum changes caused by the actuation of the grating.

[0007] Fig. 3 illustrates an exemplary electrical control arrangement with each pair of grating bars.

[0008] Fig. 4 illustrates suspended beams for a grating.

[0009] Fig. 5 illustrates transparent beams on a grating.

[0010] Fig. 6 illustrates an exemplary embodiment of electrodes on a grating.

SUMMARY

[0011] In a first aspect of the disclosure, an optical shutter is described, the optical shutter comprising: a sub-wavelength grating comprising a plurality of parallel beams suspended, at each end, on a side structure; and electrodes connected to each beam of the plurality of parallel beams, wherein each beam is electrically connected to an opposite voltage relative to an immediately adjacent beam.

[0012] In a second aspect of the disclosure, a method to control transmission of electromagnetic waves is described, the method comprising: providing a shutter comprising: a sub-wavelength grating comprising a plurality of parallel beams suspended, at each end, on a side structure, and electrodes connected to each beam of the plurality of beams, wherein a first beam and every other beam from the first beam is electrically connected to a first voltage, and all remaining beams are electrically connected to a second voltage; and applying the first and second voltage, wherein the first voltage is higher than the second voltage, based on a desired closed or open position of the shutter.

[0013] In a third aspect of the disclosure, a method to control transmission of electromagnetic waves is described, the method comprising: providing a shutter comprising: a sub-wavelength grating comprising a plurality of parallel beams suspended, at each end, on a side structure, and means to apply acoustic waves to each beam of the plurality of beams; and applying acoustic waves to each beam of the plurality of beams based on a desired closed or open position of the shutter.

DETAILED DESCRIPTION

[0014] An optical shutter is a device that controls a light beam intensity for a given period of time, and is typically used for gating laser beams, precise exposure time control, or simply blocking unwanted light. Mechanical iris shutters are very common but may not be suitable for fast and precise timing control. More sophisticated shutters are based on ferroelectric liquid crystals sandwiched by two identical polarizers, see Ref. [1]. In this type of shutters, the shuttering speed is limited by the rotational speed of the liquid crystal molecules, typically less than a kHz. Recently, the use of phase transition materials such as vanadium dioxide (VO₂), see Ref. [2], was proposed to realize an ultrafast optical shutter.

[0015] The optical shutters described in the present disclosure utilize sub-wavelength gratings made of high refractive index materials, where the grating bars are dynamically actuated by microelectromechanical systems (MEMS), for example based on electrostatic forces. Owing to the lightweight design for the gratings described in the present disclosure, which can be combined with MEMS technology, faster shuttering speeds can be achieved. These shuttering speeds can then be limited only by the mechanical frequency of the grating bars. The sub-wavelength grating design of the present disclosure is based on a high contrast grating (HCG), see Ref. [3], where sub-wavelength gratings made of high refractive index silicon are air-suspended, as shown for example in Figs. 1 and 4.

[0016] In the embodiment of Fig. 1, the grating comprises sections of Si with a height of 430 nm, a width of 551 nm, a gap of 184 nm and a spacing of 735 nm.

[0017] High contrast gratings are single layer near-wavelength grating physical structures where the grating material has a large contrast in index of refraction compared to its surroundings. The term near-wavelength refers to the grating period.

[0018] High contrast gratings can have many distinct attributes that are not found in conventional gratings. These features include broadband ultra-high reflectivity, broadband ultra-high transmission, and very high quality factor resonance, for optical beam normal or in oblique incidence to the grating surface. High reflectivity gratings can be ultrathin, for example less than

0.15 of the optical wavelength. The reflection and transmission phase of the optical beam through the high contrast grating can be engineered to cover a full 2π range while maintaining a high reflection or transmission coefficient.

[0019] The grating bars of a high contrast grating can be considered as a periodic array of waveguides with an electromagnetic wave being guided along the grating thickness direction. Upon plane wave incidence, depending on wavelength and grating dimensions, only a few waveguide-array modes are excited. In standard high contrast gratings, due to the large index contrast and near-wavelength dimensions, there exists a wide wavelength range where only two waveguide-array modes have real propagation constants in the z direction and, hence, carry energy. The two waveguide-array modes depart from the grating input plane, propagate downward to the grating exiting plane, and then reflect back up. After propagating through the grating thickness, each propagating mode can accumulate a different phase. At the exiting plane, owing to a strong mismatch with the exiting plane wave, the waveguide modes not only reflect back to themselves but also couple into each other. As the modes propagate and return to the input plane, similar mode coupling occurs. Following the modes through one round trip, the reflectivity solution can be attained. The two modes can interfere at the input and exiting plane of the high contrast grating, leading to various distinct properties. Some of the properties of standard high contrast gratings can be applied to the gratings of the present disclosure.

[0020] The exemplary sub-wavelength grating design shown in Fig. 1 exhibits a broadband reflection for normally incident TM polarized light around a wavelength $\lambda = 1550$ nm. When two grating bars move towards each other the gap between the two grating bars becomes narrower, the reflection spectrum dramatically changes and becomes very transmissive, as plotted in Fig. 2.

[0021] For example, if the original 184 nm gap size (205) between every two pairs of grating bars is decreased to 55.2 nm (210, a 70% change), the reflectivity for the grating goes down (215) to less than 10% for the wavelength range of 50 nm around $\lambda = 1440$ nm. Since the gratings are still in the sub-wavelength regime, no higher-order diffraction exists. The sub-wavelength grating bars can be actuated, for example, by electrostatic forces by applying a voltage to the grating bars in pairs, so that attractive/repulsive electrostatic forces act on each

pair of grating bars, allowing control of the device. RCWA calculations for the reflectivity spectra are illustrated in Fig. 2.

[0022] Fig. 3 illustrates an exemplary arrangement where each pair of grating bars, for example pair (305) is connected to a voltage supply. The electrostatic force between each pair causes an attractive force and a decrease in the gap (310). By controlling the gap between the bars, the grating response to the electromagnetic waves can be controlled, thereby allowing operation of the shutter in the closed and open positions.

[0023] The bars of the grating can be coupled in pairs to the voltage supply, as illustrated in Fig. 3. In some embodiments, the electrical connections to the bars of the gratings comprise transparent electrodes, for example indium tin oxide (ITO) electrodes. Other materials may be used for the grating, instead of Si, for example SiN.

[0024] Regarding the operation speed of optical shutter, the mechanical resonance will impose a limit on the response time of the actuation, which can be expected to be driven at MHz frequencies, see Ref. [4].

[0025] The beams of the grating can be suspended at each end, in order to allow their free movement relative to each other, as caused by electrostatic forces. For example, as visible in Fig. 4 as side view (401) and top view (402), the beams of the grating (405) may be suspended at each end to a side structure (415), for example a Si structure.

[0026] Fig. 5 illustrates an exemplary implementation of the actuation method of Fig. 3. Each pair of beams in the grating is connected to an opposite voltage. For example, bars (505) are connected to one voltage (515) through transparent ITO electrodes (510) covering the majority (or entirety) of the bars, while the remaining bars are connected to the opposite voltage (520).

[0027] Fig. 6 illustrates an alternative embodiment of Fig. 5, where the electrodes (605) are only connected to a small part of the surface of the bars. For this embodiment, transparent electrodes may be used. In some embodiments, non transparent electrodes may also be used, if the electrodes do not interfere with the operation of the shutter. For example, the grating may extend

to a larger area than the area of the beam, therefore the electrodes would be outside the area of the beam while still being able to actuate the shutter in the ON and OFF positions.

[0028] In some embodiments, the gap between parallel beams can be between 200 nm and 1 μ m.

[0029] In some embodiments, the actuation of the beams of the grating is carried out through the application of acoustic waves. In some embodiments, the gratings can be made from materials different than silicon, such as, for example, germanium, gallium arsenide, gallium phosphide, silicon nitride or materials with similar properties.

[0030] A number of embodiments of the disclosure have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the present disclosure. Accordingly, other embodiments are within the scope of the following claims.

[0031] The examples set forth above are provided to those of ordinary skill in the art as a complete disclosure and description of how to make and use the embodiments of the disclosure, and are not intended to limit the scope of what the inventor/inventors regard as their disclosure.

[0032] Modifications of the above-described modes for carrying out the methods and systems herein disclosed that are obvious to persons of skill in the art are intended to be within the scope of the following claims. All patents and publications mentioned in the specification are indicative of the levels of skill of those skilled in the art to which the disclosure pertains. All references cited in this disclosure are incorporated by reference to the same extent as if each reference had been incorporated by reference in its entirety individually.

[0033] It is to be understood that the disclosure is not limited to particular methods or systems, which can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting. As used in this specification and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the content clearly dictates otherwise. The term "plurality" includes two or more referents unless the content clearly dictates otherwise. Unless defined otherwise, all technical and

scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the disclosure pertains.

[0034] The references in the present application, shown in the reference list below, are incorporated herein by reference in their entirety.

References

[1] “Optical shutter in newports webpage,” <http://assets.newport.com/pdfs/e5598.pdf>, accessed: 2014-07-30.

[2] M. Rini, A. Cavalleri, R. W. Schoenlein, R. L’opez, L. C. Feldman, J. Richard F Haglund, L. A. Boatner, and T. E. Haynes, “Photoinduced phase transition in VO₂ nanocrystals: ultrafast control of surface-plasmon resonance,” *Opt. Lett.* 30, 558 (2005).

[3] C. J. Chang-Hasnain and W. Yang, “High-contrast gratings for integrated optoelectronics,” *Adv. Opt. Photonics* 4, 379 (2012).

[4] J. Y. Ou, E. Plum, J. Zhang, and N. I. Zheludev, “An electromechanically reconfigurable plasmonic metamaterial operating in the near-infrared,” *Nature Nanotech.* 8, 252 (2013).

CLAIMS

What is claimed is:

1. An optical shutter comprising:
a sub-wavelength grating comprising a plurality of parallel beams suspended, at each end, on a side structure; and
electrodes connected to each beam of the plurality of parallel beams, wherein each beam is electrically connected to an opposite voltage relative to an immediately adjacent beam.
2. The optical shutter of claim 1, wherein the sub-wavelength grating is made of silicon.
3. The optical shutter of any one of claims 1-2, wherein the electrodes are made of indium tin oxide.
4. The optical shutter of any one of claims 1-3, wherein the electrodes cover a majority top surface of the parallel beams.
5. The optical shutter of any one of claims 1-3, wherein the electrodes cover a minority top surface of the parallel beams.
6. The optical shutter of any one of claims 1-5, wherein a gap between the parallel beams is between 200 nm and 1 nm.
7. A method to control transmission of electromagnetic waves, the method comprising:
providing a shutter comprising:
a sub-wavelength grating comprising a plurality of parallel beams suspended, at each end, on a side structure, and electrodes connected to each beam of the plurality of beams, wherein a first beam and every other beam from the first beam is electrically connected to a first voltage, and all remaining beams

are electrically connected to a second voltage; and
applying the first and second voltage, wherein the first voltage is higher than the second voltage, based on a desired closed or open position of the shutter.

8. The method of claim 7, wherein the sub-wavelength grating is made of silicon.
9. The method of any one of claims 7-8, wherein the electrodes are made of indium tin oxide.
10. The method of any one of claims 7-9, wherein the electrodes cover a majority top surface of the parallel beams.
11. The method of any one of claims 7-9, wherein the electrodes cover a minority top surface of the parallel beams.
12. The optical shutter of any one of claims 7-11, wherein a gap between the parallel beams is between 200 nm and 1 nm.
13. The method of any one of claims 7-12, wherein applying the first and second voltage comprises at least:
 - for a first, second, third and fourth beam being successive beams in the sub-wavelength grating, applying the first voltage to the first and third beam and the second voltage to the second and fourth beam; and
 - through the applying the first voltage and second voltage, reducing a gap between the first and second beam, and reducing a gap between the third and fourth beam while increasing a gap between the second and third beam.
14. A method to control transmission of electromagnetic waves, the method comprising:
 - providing a shutter comprising:

a sub-wavelength grating comprising a plurality of parallel beams suspended, at each end, on a side structure, and means to apply acoustic waves to each beam of the plurality of beams; and

applying acoustic waves to each beam of the plurality of beams based on a desired closed or open position of the shutter.

15. The method of claim 14, wherein applying acoustic waves comprises at least:

applying acoustic waves to a first, second and third beam, the first, second and third beam being successive beams in the sub-wavelength grating; and

through the acoustic waves, reducing a gap between the first and second beam while increasing a gap between the second and third beam.

16. The optical shutter of any one of claims 14-15, wherein a gap between the parallel beams is between 200 nm and 1 nm.

17. The optical shutter of any one of claims 14-16, wherein the sub-wavelength grating is made of silicon.

18. The method of claim 7, wherein the sub-wavelength grating is made of a material selected from the group comprising: germanium, gallium arsenide, gallium phosphide and silicon nitride.

19. The optical shutter of claim 16, wherein the sub-wavelength grating is made of a material selected from the group comprising: germanium, gallium arsenide, gallium phosphide and silicon nitride.

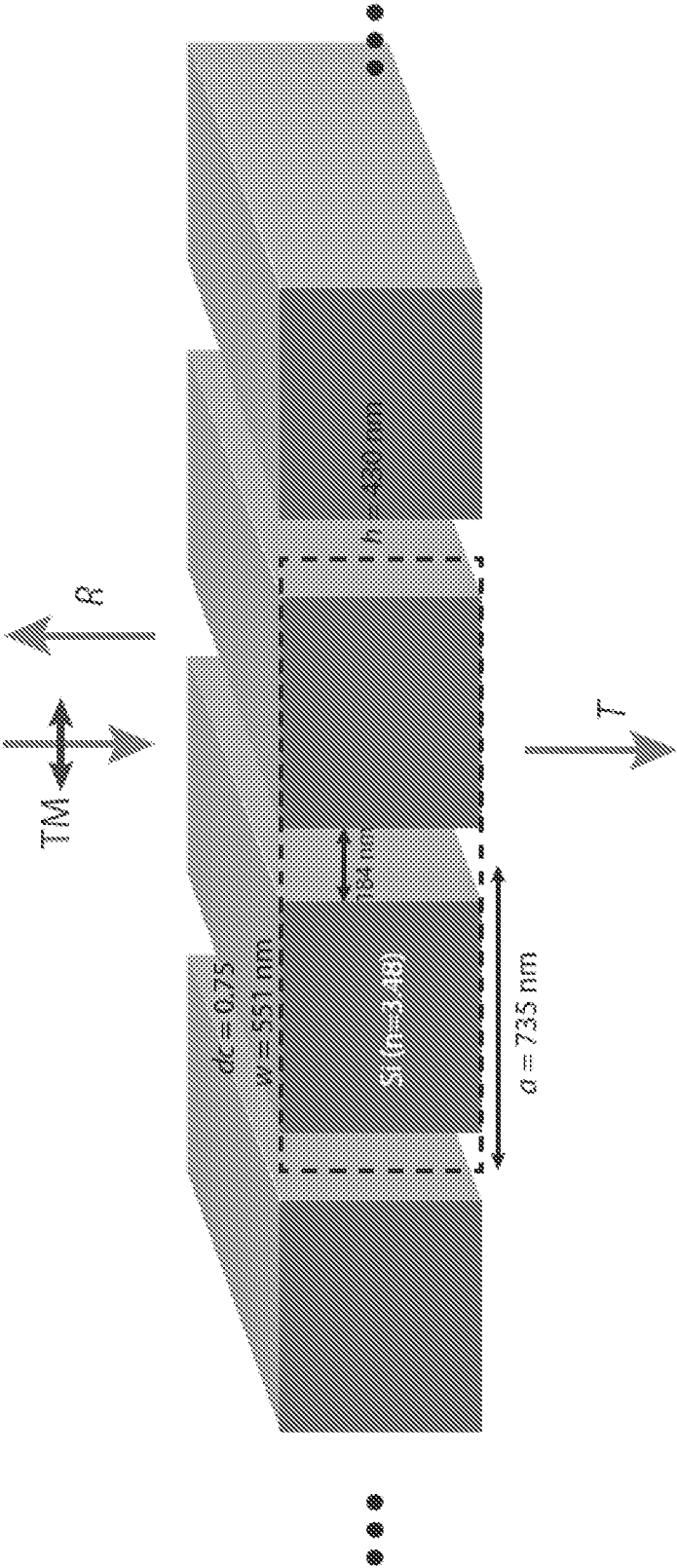


FIG. 1

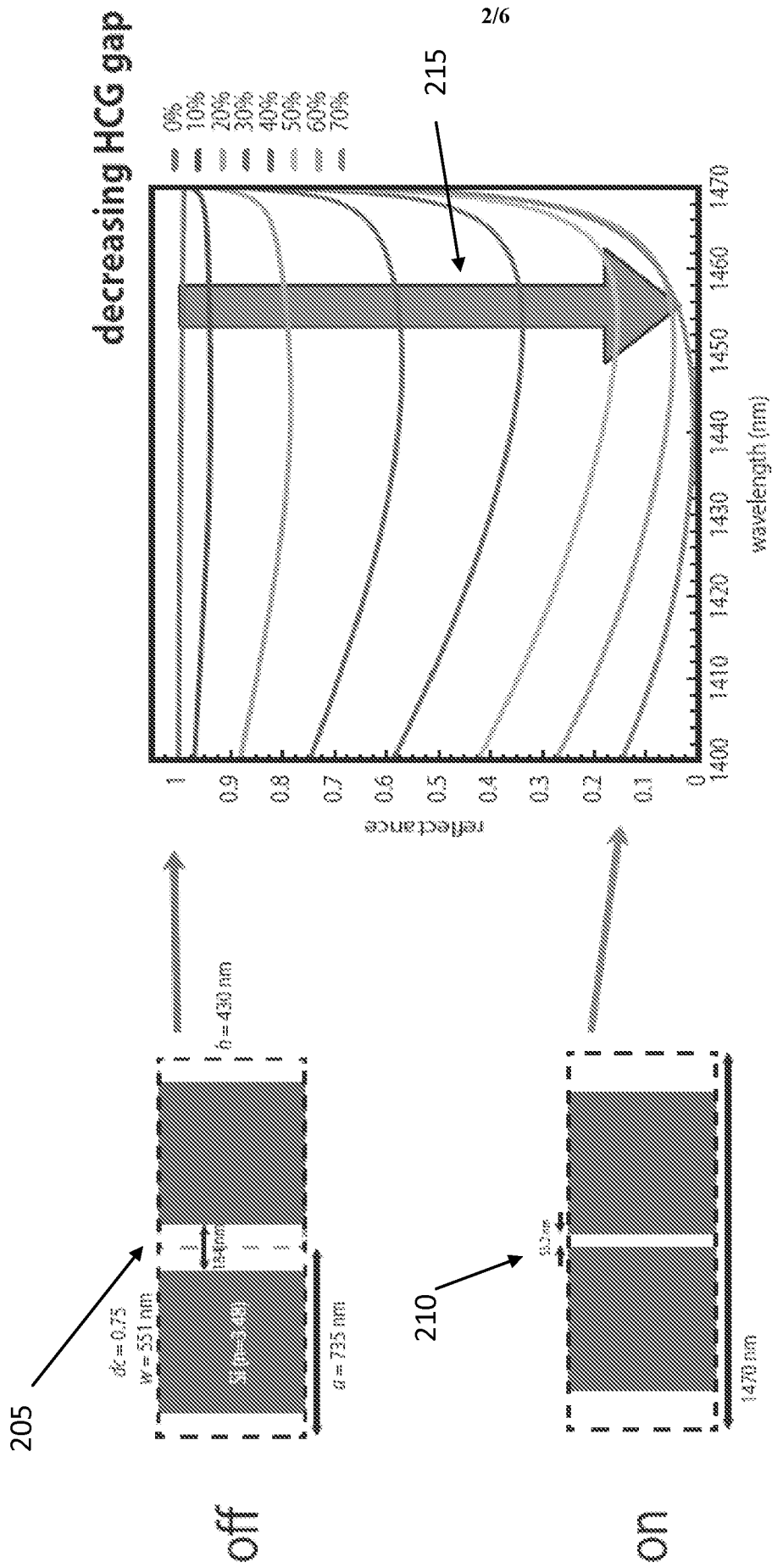


FIG. 2

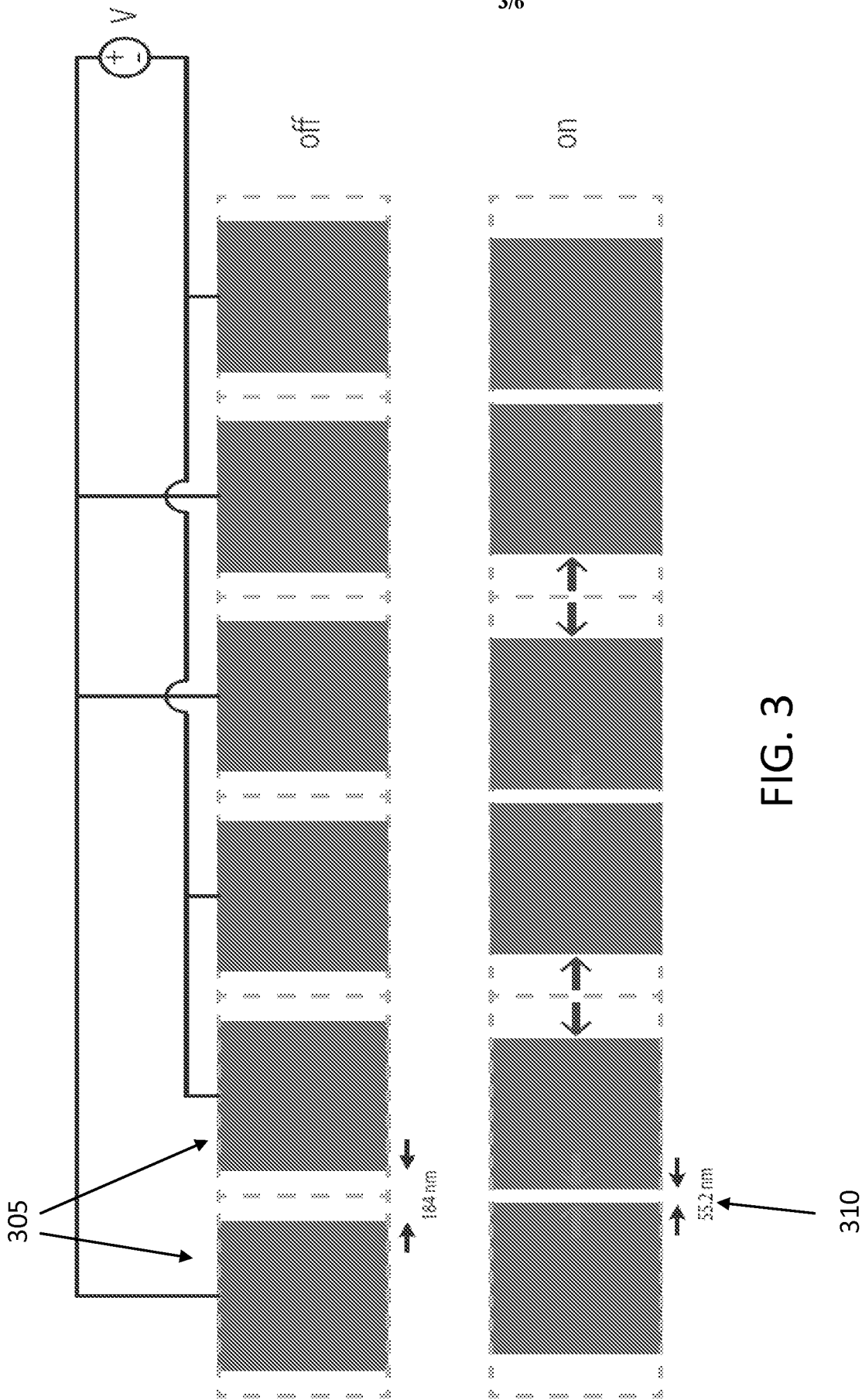


FIG. 3

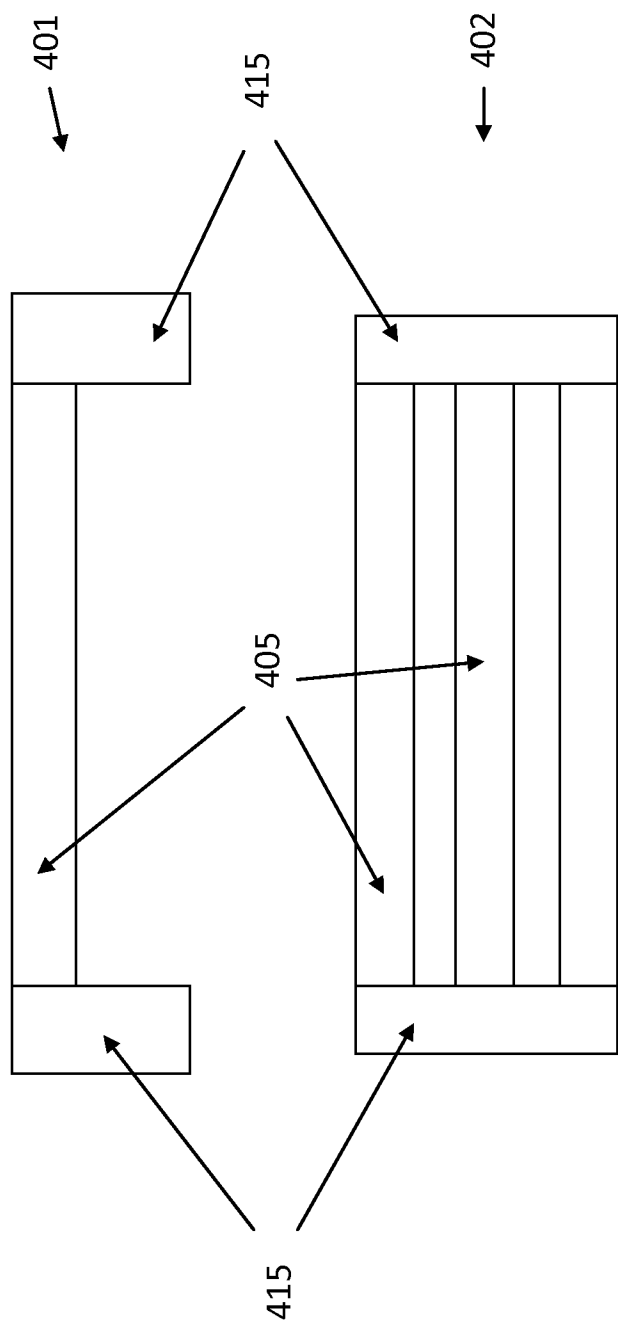


FIG. 4

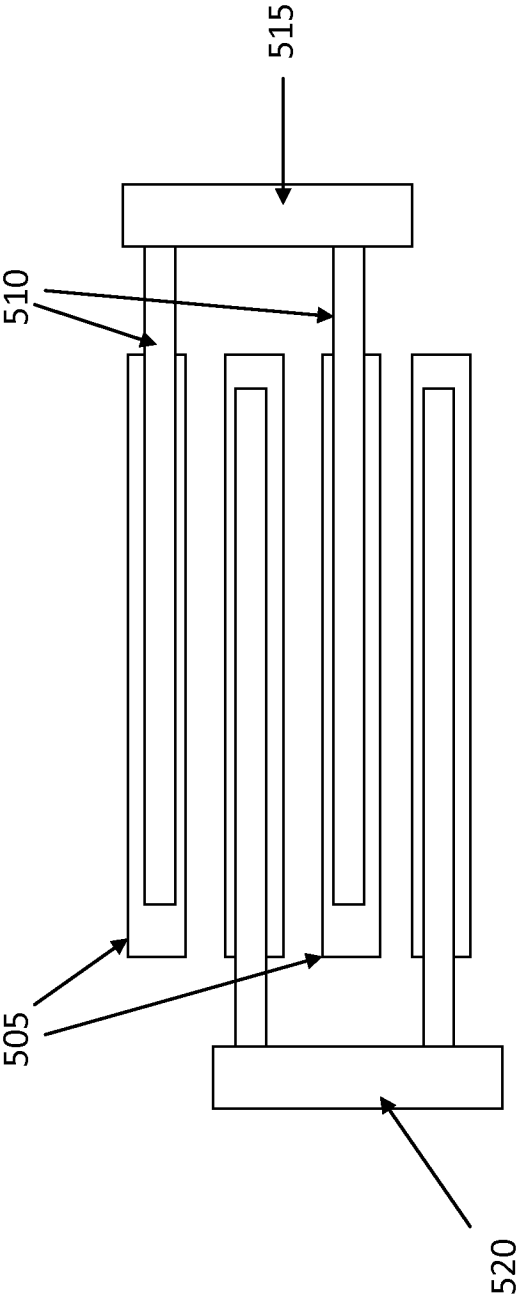


FIG. 5

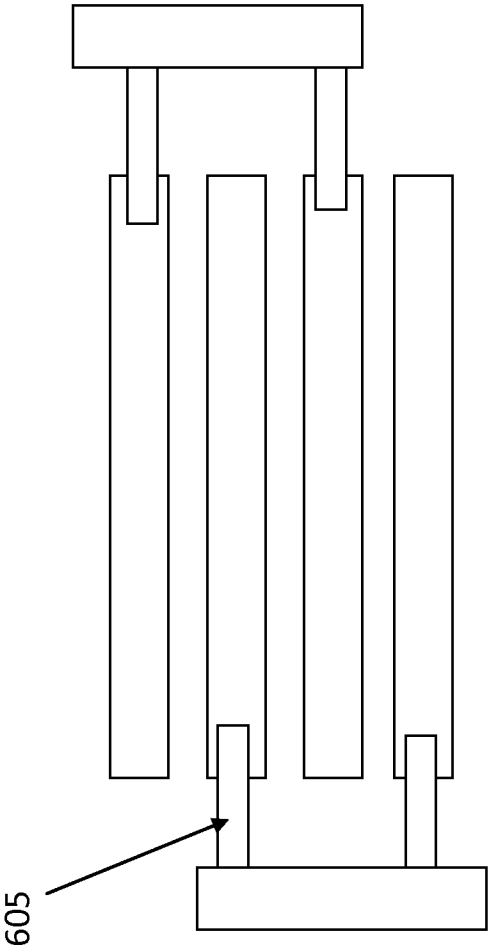


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/043014**A. CLASSIFICATION OF SUBJECT MATTER****G02B 27/00(2006.01)i, G03B 9/08(2006.01)i, G03B 9/58(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02B 27/00; G02F 1/025; H01L 21/20; G01N 11/00; G02F 1/295; G02F 1/035; H01L 29/93; G01N 15/02; G03B 9/08; G03B 9/58

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & Keywords: optical, shutter, a sub-wavelength grating, electrode

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2003-0173647 A1 (MONTELIUS et al.) 18 September 2003 See paragraphs [0019]-[0062], claim 1 and figures 6a-6f.	1-3, 7-9, 14-16 , 18-19
Y	TAKAHASHI et al. `A Study on Optical Diffraction Characteristics of Skewed MEMS Pitch Tunable Gratings`, Optical MEMS and Nanophotonics, 2007 IEEE/LEOS International Conference on, Hualien : IEEE, 12 Aug 2007- 16 July 2007 <retrieve:http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=437389> See page 175, right column, line 20 - page 176, right column, line 22 and figures 2, 5.	1-3, 7-9, 14-16 , 18-19
A	US 2006-0274987 A1 (MONY et al.) 07 December 2006 See paragraphs [0032]-[0040].	1-3, 7-9, 14-16 , 18-19
A	JP 2011-075992 A (FUJITSU LTD.) 14 April 2011 See figure 20.	1-3, 7-9, 14-16 , 18-19
A	JP 4947047 B2 (SHIMADZU CORP.) 06 June 2012 See figure 7.	1-3, 7-9, 14-16 , 18-19



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

20 November 2015 (20.11.2015)

Date of mailing of the international search report

23 November 2015 (23.11.2015)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORTInternational application No.
PCT/US2015/043014**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☒ Claims Nos.: 4-6, 10-13, 17
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/043014

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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