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(54) Title: OPTICAL PHASED ARRAY USING GUIDED RESONANCE WITH BACKSIDE REFLECTORS

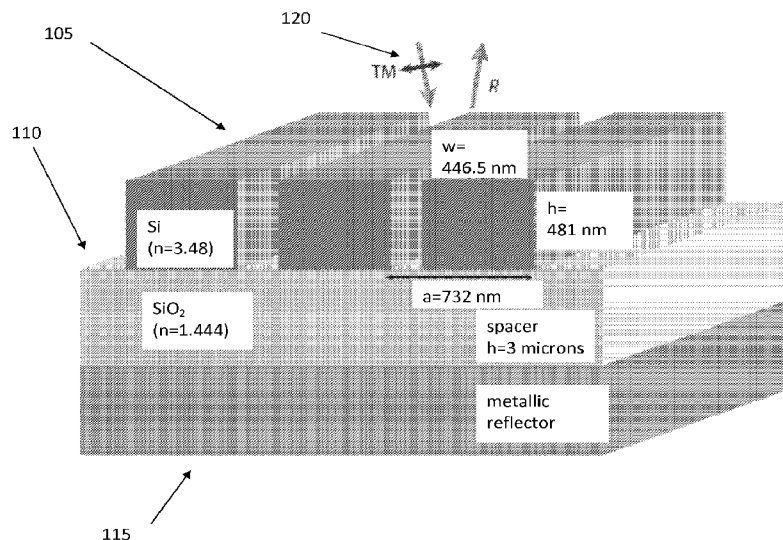


FIG. 1

(57) Abstract: Methods and systems for controlling the phase of electromagnetic waves are disclosed. A device can consist of a guided resonance grating layer, a spacer, and a reflector. A plurality of devices, arranged in a grid pattern, can control the phase of reflected electromagnetic phase, through refractive index control. Carrier injection, temperature control, and optical beams can be applied to control the refractive index.



OPTICAL PHASED ARRAY USING GUIDED RESONANCE WITH BACKSIDE REFLECTORS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to US Provisional Patent Application No. 62/032,327, 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-107198 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 phased arrays. More particularly, it relates to optical phased array using guided resonance with backside reflectors.

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 devices of the present disclosure.

[0006] Fig. 2 illustrates reflectance data of one embodiment of the devices of the present disclosure.

[0007] Fig. 3 illustrates reflectance phase data of one embodiment of the devices of the present disclosure.

[0008] Fig. 4 illustrates a suspended beam grating

[0009] Fig. 5 illustrates charge carrier control with transparent electrodes.

[0010] Fig. 6 illustrates an array of devices.

SUMMARY

[0011] In a first aspect of the disclosure, a device to control phase of electromagnetic waves is described, the device comprising: a resonance layer capable of sustaining a guided resonance of electromagnetic waves; a reflector layer; and a spacer layer between the reflector layer and the resonance layer.

[0012] In a second aspect of the disclosure, a method to control phase of electromagnetic waves is described, the method comprising: providing an array of devices arranged in a grid pattern, each device comprising: a resonance layer capable of sustaining a guided resonance of electromagnetic waves; a reflector layer; and a spacer layer between the reflector layer and the resonance layer; calculating a desired phase pattern for electromagnetic waves reflected by the array; controlling the refractive index of each device according to the desired phase pattern.

DETAILED DESCRIPTION

[0013] Phased array optics (PAO) are directed at controlling the phase of electromagnetic (or light) waves transmitting or reflecting from a two-dimensional surface. This control is achieved through adjustable surface elements. By dynamically controlling the optical properties of a surface on a microscopic scale, it is possible to steer the direction of light beams, or the view direction of sensors. Phased array beam steering can be used, for example, for optical switching and multiplexing in optoelectronic devices, and for aiming laser beams on a macroscopic scale.

[0014] For example, if a beam of light is transmitted across a specific area, phased array optics can comprise a way to control the phase of the light waves in different regions of that specific

area. In some applications, each region of that specific area can be termed as a pixel. Through this control, the output light beam can be adjusted to different conditions. For example, a light beam, such as a laser beam, could be transmitted through atmospheric disturbances that can negatively impact the beam characteristics. By controlling the phase of the light waves, the beam can be adjusted so that the negative influence of atmospheric disturbances can be reduced or negated.

[0015] Optical phased arrays (OPAs) are a versatile platform for many applications including, for example, beam steering, adaptive optics, Fourier optics, and holography. In an optical phased array, each pixel element individually controls the phase of the electromagnetic waves propagating in free space or in a medium. Commercially available OPAs rely on phase modulators based on liquid crystals (LC), however the slow response of LCs bounds the operational speed of such phase modulators to less than kHz frequencies. Standard micro-electro-mechanical systems (MEMS) enable a slightly higher operation speed, typically less than MHz frequency (see Ref. [1]), but can involve a complex device design, which can make such systems less suitable for mass production of the OPA devices.

[0016] The phase modulation scheme described in the present disclosure utilizes phase delay accompanied by a resonance. The cross-sectional schematic of one embodiment of the device described in the present disclosure is depicted in Fig.1. In Fig. 1, a sub-wavelength grating (105), which possesses a guided resonance, sits on a metal reflector (115) separated by a silicon dioxide layer (110), for example a 3-micron silicon dioxide layer. In the embodiment of Fig. 1, the grating (105) comprises sections of Si with a height of 481 nm, a width of 446.5 nm and a spacing of 732 nm. In other embodiments, the dimensions of the grating may be adjusted according to the desired electromagnetic resonance.

[0017] In some embodiments, different materials may be used compared to the example of Fig. 1. For example, the reflector may be a metal, or a non-metallic material. The main property of the reflector is its ability to reflect electromagnetic waves, therefore any structure that possesses this property may be used. For example, instead of a continuous metallic layer, a reflector may consist in a grating, for example a Si grating tuned to reflect the electromagnetic waves. For

example, a sub-wavelength grating made of high refractive index materials may be used in some embodiments. Broadband ultra-high reflectivity gratings may be used.

[0018] In some embodiments, the spacer layer (110) may comprise different materials instead of silicon dioxide. The spacer layer may even consist of air, with the beams of the grating (105) suspended at each end. 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, with a reflector (410) at the bottom.

[0019] In the embodiment of Fig. 1, the sub-wavelength grating supports even symmetric guided modes (see Ref. [2]), therefore a 0.5° tilted off-axis plane wave with a transverse-magnetic (TM) polarization can be used as an incident wave (120) with a wavelength of around 1.55 μm . In this example the magnetic field is orthogonal to the direction of propagation of the electromagnetic wave.

[0020] By placing an external metal reflector (115) underneath the grating, with an appropriate separation length, typically longer than a wavelength of light, it is expected that the reflected amplitude is constant regardless of the guided resonance, while the reflected phase change becomes dispersive about 2π because of the coupling with the guided resonance inside the sub-wavelength grating. The modulation of the phase can be done by tuning the frequency of the guided resonance, by means of refractive index tuning of grating materials, see Ref. [3]. For instance, in the case of silicon as a material choice for grating bars, the carrier injection method (see Ref. [4]) or thermo-optic effect will be able to efficiently tune the resonance.

[0021] For the refractive index tuning of the grating material, different methods may be employed. For example, a current may be injected in the grating to change its refractive index. The current may be injected in the longitudinal direction of the beams of the grating, or it may be injected perpendicularly to the longitudinal direction of the beams of the grating. Therefore, the current may be in plane or perpendicularly to the plane of the grating layer. In some embodiments, the current may be injected using transparent conductive materials, for example indium tin oxide (ITO).

[0022] For example, referring to Fig. 5, a current may be injected in the grating (505) through a top and bottom transparent ITO electrode layers (510). The structure may also comprise a spacer (515), such as, for example, silicon dioxide or air, and a reflector (520), such as, for example, a metal layer or a reflecting Si grating layer. Many different materials may be used for the grating, as long as they enable use of a guided resonance. For example Si or SiN may be used.

[0023] The resonance of the grating may be controlled through a voltage (current injection). Other methods comprise temperature control, and optical control. Either through the control of temperature, or the application of, for example, a laser beam to the grating, the resonance may be controlled through the control of the refractive index. The refractive index can be controlled through the regulation of the charge carrier density.

[0024] Using rigorous coupled-wave analysis (RCWA) simulations, reflectivity spectra as well as the reflection phase as a function of wavelength can be calculated for the two cases, with and without the backside reflector, as shown in Figs. 2 and 3. Rigorous coupled-wave analysis (RCWA) is a semi-analytical method in computational electromagnetics that can be applied to solve scattering from periodic dielectric structures. It is a Fourier-space method so devices and fields are represented as a sum of spatial harmonics. For the case with backside reflector, while the reflectivity is kept constant around the guided resonance frequency, the reflected phase acquires a 2π differential, as expected. The phase modulation can be reasonably realized via index modulation of high index materials, thus enabling high-speed modulation with very high bandwidth in the hundreds MHz. By placing such a phase modulator in a two dimensional fashion, OPAs working at a very high speeds can be realized.

[0025] Fig. 6 illustrates an array of devices (605), each device as described above in the present disclosure. Each of the devices (610) can control the phase of electromagnetic waves incident at the area of the specific device. Each of the devices can be controlled as described in the present disclosure above, for example by controlling the refractive index of the grating of that specific device by charge injection. In other words, an array of devices allows control of phase that can be individually tuned in each area. Each of the devices may be termed as controlling a pixel of the overall area controlled by the array. Each of the devices can be controlled individually, for

example through individual application of voltage and currents. In this way, a varying phase control can be applied to an incident electromagnetic wave, according to the specific application. In some embodiments, the separation between each device in the array can be minimized, in order to have a fine grain control of the phase of the incident electromagnetic waves.

[0026] In the examples above in the present disclosure, a grating of longitudinal beams has been described as an example. However, it is intended that any structure capable of sustaining a guided resonance may also be used. For example, gratings different from longitudinal beams may be used.

[0027] In some embodiments, a desired phase pattern for electromagnetic waves reflected by an array of the devices can be realized by controlling the refractive index of each device of the array. In some embodiments, the incident phase can also be measured prior to applying the phase control through the array. In other embodiments, the phase may be already known or estimated, therefore no measurement may be necessary. In some embodiments, the gratings can be made of materials other than silicon, such as for example germanium, gallium arsenide, gallium phosphide and silicon nitride

[0028] 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.

[0029] 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.

[0030] 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.

[0031] 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.

[0032] The references in the present application, shown in the reference list below, are incorporated herein by reference in their entirety.

References

- [1] W. Yang, T. Sun, Y. Rao, M. Megens, T. Chan, B.-W. Yoo, D. A. Horsley, M. C. Wu, and C. J. Chang-Hasnain, "High-speed optical phased array using high-contrast grating all-pass filters," in *Indium Phosphide and Related Materials IPRM, International Conference on (IEEE, 2012)* pp. 22–24.
- [2] J. M. Foley, S. M. Young, and J. D. Phillips, "Symmetry-protected mode coupling near normal incidence for narrow-band transmission filtering in a dielectric grating," *Phys. Rev. B* 89, 165111 (2014).
- [3] Y. Horie, A. Arbabi, and A. Faraon, "Reflective Optical Phase Modulator Based on High-Contrast Grating Mirrors," *CLEO: Science and Innovations* (2014).
- [4] C. Qiu, J. Chen, Y. Xia, and Q. Xu, "Active dielectric antenna on chip for spatial light modulation," *Sci. Rep.* 2, 855 (2012).

CLAIMS

What is claimed is:

1. A device to control phase of electromagnetic waves comprising:
 - a resonance layer capable of sustaining a guided resonance of electromagnetic waves;
 - a reflector layer; and
 - a spacer layer between the reflector layer and the resonance layer.
2. The device of claim 1, wherein the resonance layer is a grating comprising parallel beams.
3. The device of any one of claims 1-2, wherein the grating is made of silicon.
4. The device of any one of claims 1-3, wherein the reflector layer is a metallic layer.
5. The device of any one of claims 1-3, wherein the reflector layer is a silicon grating.
6. The device of any one of claims 1-5, wherein the spacer layer is made of silicon dioxide.
7. The device of any one of claims 1-5, wherein the spacer layer is made of air and the parallel beams are suspended, at each end, on a side structure.
8. The device of any one of claims 1-7, further comprising a first transparent electrode layer between the resonance layer and the spacer layer, and a second transparent electrode layer on a surface of the resonance layer opposite to that of the first transparent electrode layer.
9. The device of claim 8, wherein the first and second transparent electrode layers are made of indium tin oxide.

10. An array to control phase of electromagnetic waves comprising:
 - a plurality of devices according to any one of claims 1-9, arranged in a grid pattern.

11. A method to control phase of electromagnetic waves comprising:
 - providing an array of devices arranged in a grid pattern, each device comprising:
 - a resonance layer capable of sustaining a guided resonance of electromagnetic waves;
 - a reflector layer; and
 - a spacer layer between the reflector layer and the resonance layer;
 - calculating a desired phase pattern for electromagnetic waves reflected by the array; and
 - controlling the refractive index of each device according to the desired phase pattern.

12. The method of claim 11, further comprising measuring a phase pattern of electromagnetic waves incident on the array.

13. The method of any one of claims 11-12, wherein the resonance layer is a grating comprising parallel beams.

14. The method of any one of claims 11-13, wherein the grating is made of silicon.

15. The method of any one of claims 11-14, wherein the reflector layer is a metallic layer.

16. The method of any one of claims 11-14, wherein the reflector layer is a silicon grating.

17. The method of any one of claims 11-16, wherein the spacer layer is made of silicon dioxide.

18. The method of any one of claims 11-16, wherein the spacer layer is made of air and the parallel beams are suspended, at each end, on a side structure.

19. The method of claim 18, further comprising a first transparent electrode layer between the resonance layer and the spacer layer, and a second transparent electrode layer on a surface of the resonance layer opposite to that of the first transparent electrode layer.
20. The method of claim 19, wherein the first and second transparent electrode layers are made of indium tin oxide.
21. The method of claim 20, wherein controlling the refractive index of each device comprises injecting a current through the first and second transparent electrode layers of each device, wherein the current injected in each device is according to the desired phase pattern.
22. The method of claim 21, wherein at least one current value injected in a device of the array is different from at least one other current value injected in a different device of the array.

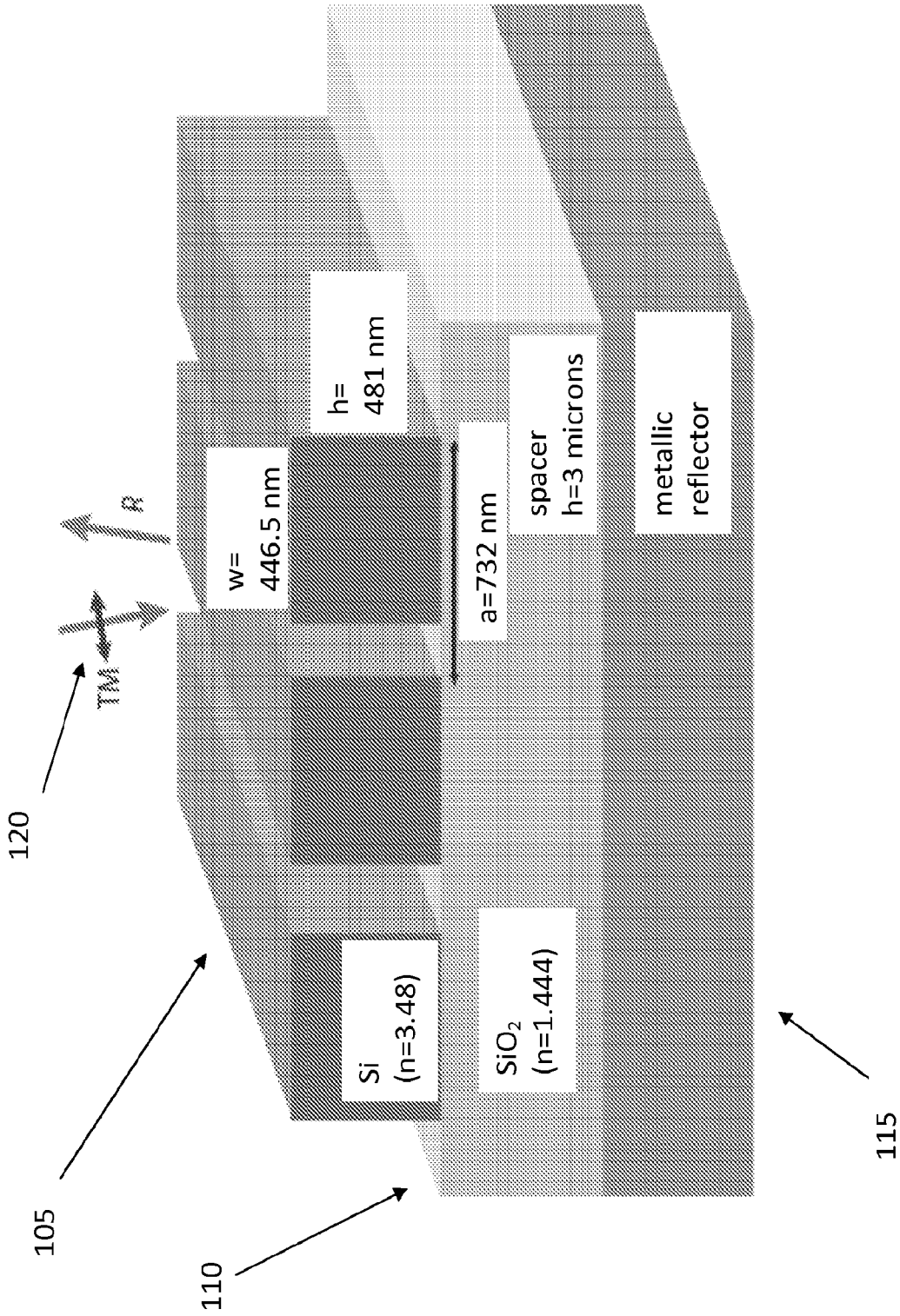


FIG. 1

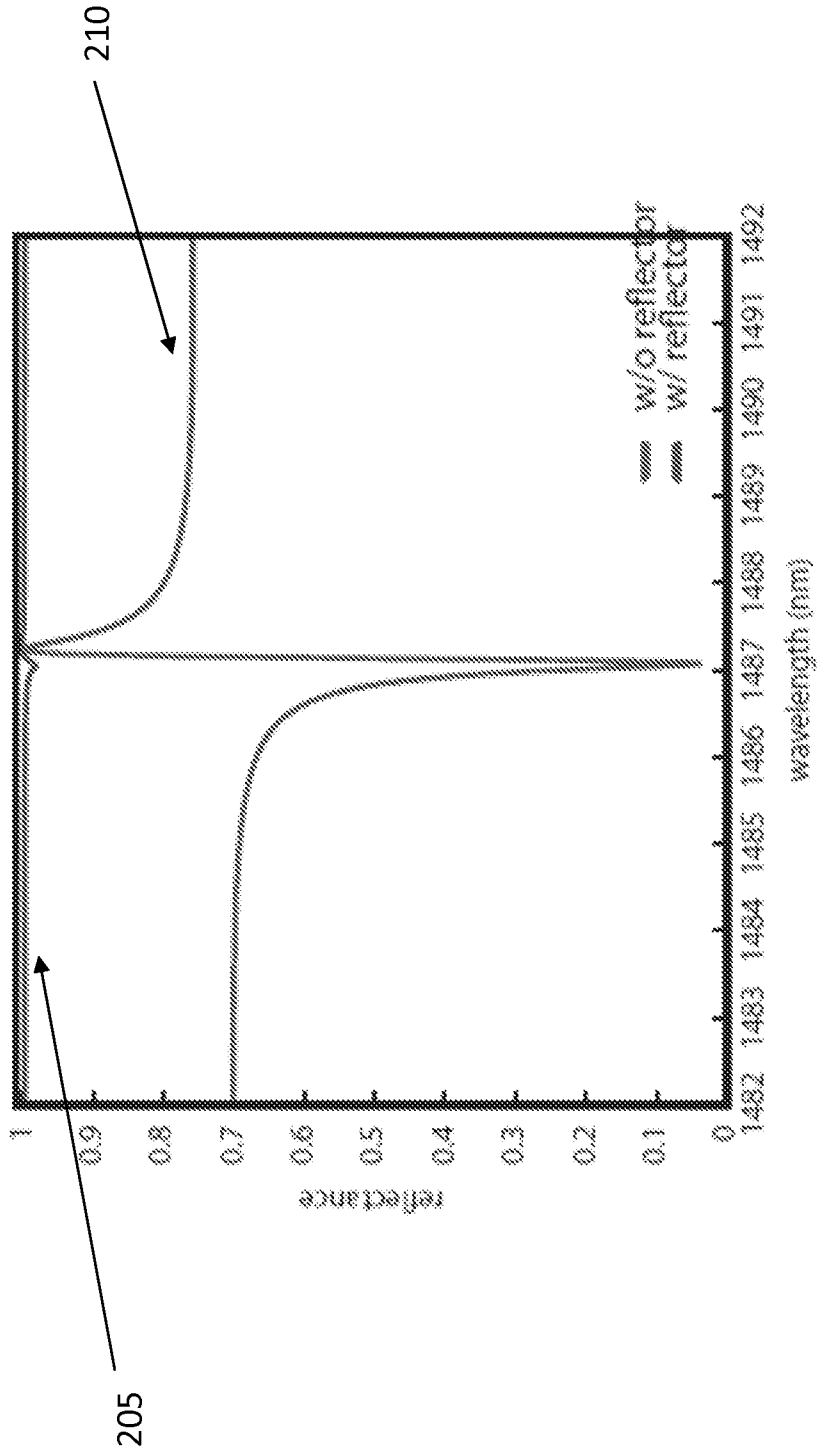


FIG. 2

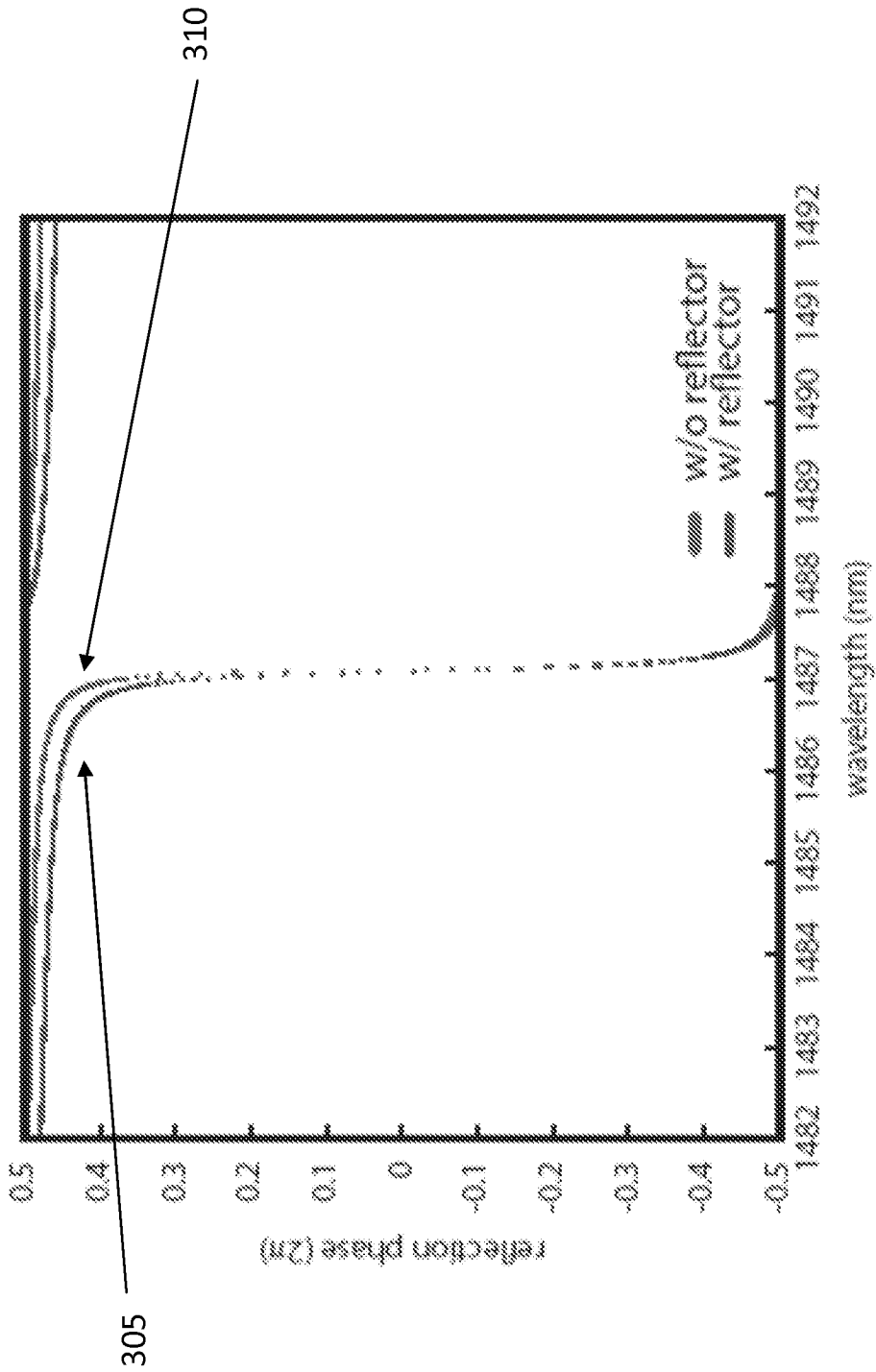


FIG. 3

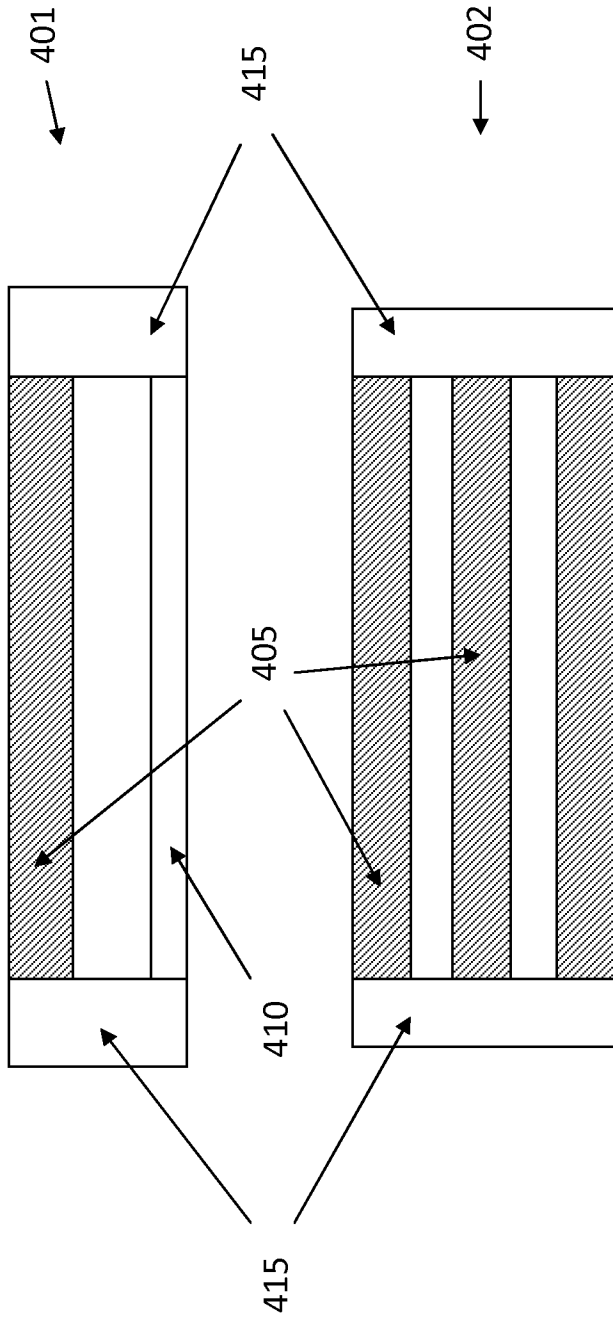


FIG. 4

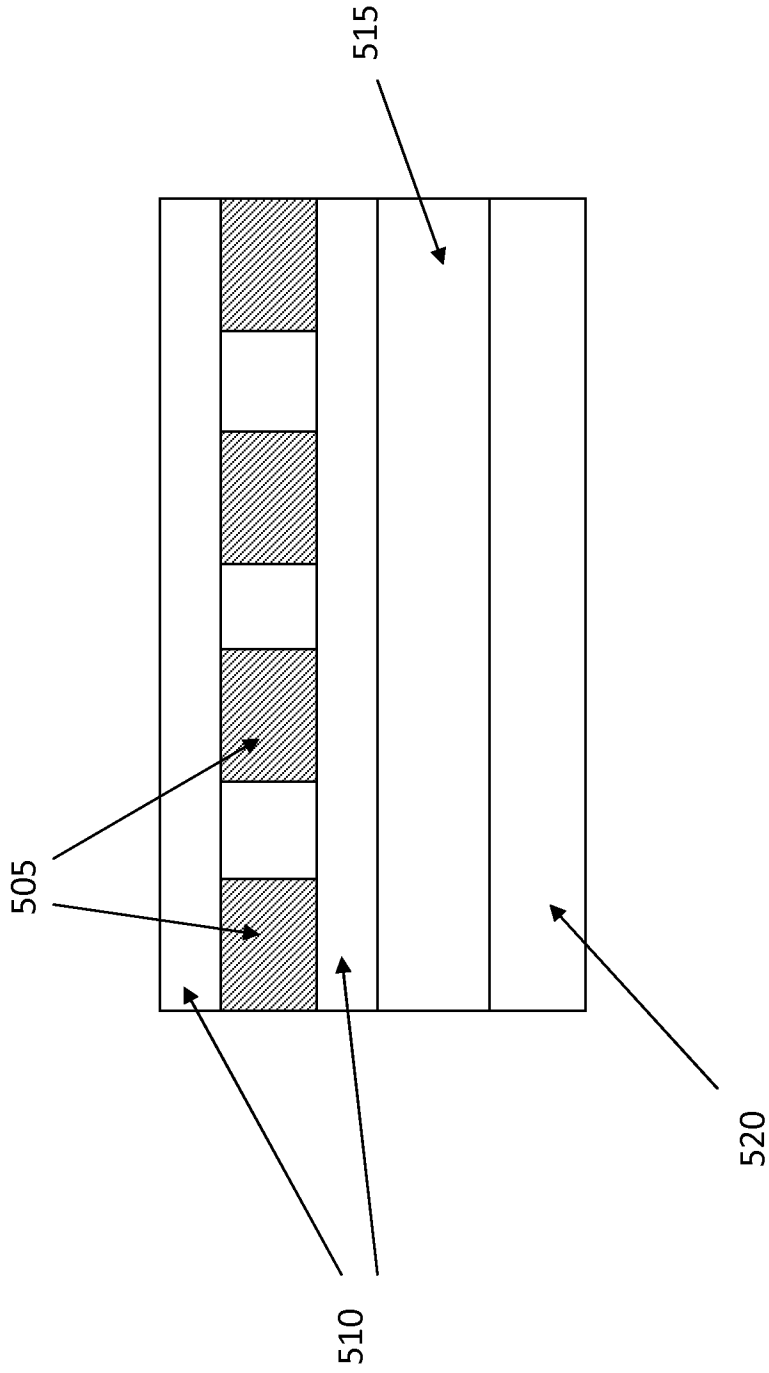


FIG. 5

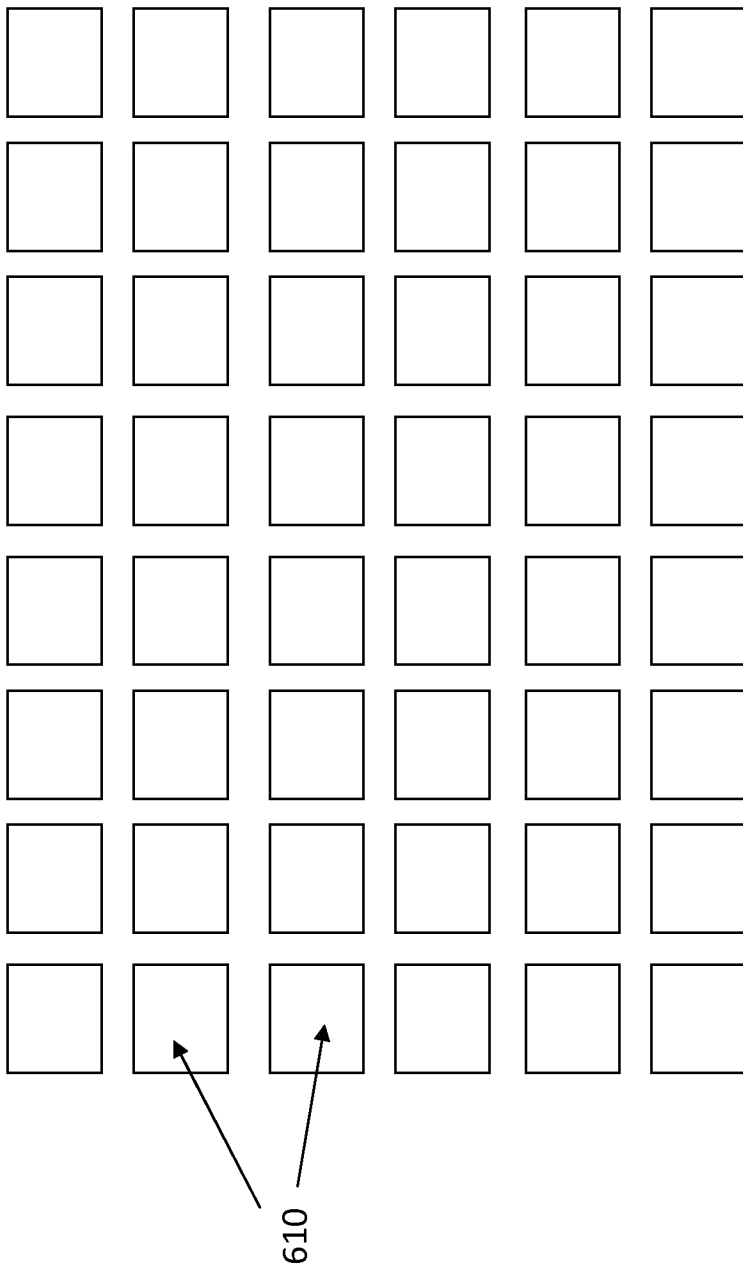


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/043018**A. CLASSIFICATION OF SUBJECT MATTER****G02B 26/06(2006.01)i, G02B 27/44(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 26/06; G02F 1/025; H01L 21/20; G01N 11/00; G02F 1/07; G02F 1/035; H01L 29/93; G01N 15/02; H01S 5/125; H01S 5/183; G02B 27/44

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: resonance, reflector layer, spacer layer, grating

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2010-0316083 A1 (CHANG-HASNAIN et al.) 16 December 2010 See paragraphs [0018]-[0141], claim 15 and figure 1.	1-3, 11-13
Y	US 6288824 B1 (KASTALSKY) 11 September 2001 See column 3, line 47- column 4, line 16 and figure 1.	1-3, 11-13
A	US 2003-0173647 A1 (MONTELIUS et al.) 18 September 2003 See paragraphs [0019]-[0062], claim 1 and figures 6a-6f.	1-3, 11-13
A	JP 2011-075992 A (FUJITSU LTD.) 14 April 2011 See figure 20.	1-3, 11-13
A	JP 4947047 B2 (SHIMADZU CORP.) 06 June 2012 See figure 7.	1-3, 11-13

 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

18 November 2015 (18.11.2015)

Date of mailing of the international search report

19 November 2015 (19.11.2015)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2015/043018**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.: 9, 19-22
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:
The claims refer to a multiple dependent claim that refers to other multiple dependent claims.
Therefore, the meaning of the technical feature to which they refer is vague and unclear.

3. Claims Nos.: 4-8, 10, 14-18
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/US2015/043018

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010-0316083 A1	16/12/2010	US 2007-0115553 A1 US 2007-0153860 A1 US 2010-0316079 A1 US 7304781 B2 US 8059690 B2 US 8189643 B2 WO 2005-089098 A2 WO 2005-089098 A3	24/05/2007 05/07/2007 16/12/2010 04/12/2007 15/11/2011 29/05/2012 29/09/2005 02/03/2006
US 6288824 B1	11/09/2001	None	
US 2003-0173647 A1	18/09/2003	US 6818959 B2	16/11/2004
JP 2011-075992 A	14/04/2011	JP 5282712 B2 US 2011-0103734 A1 US 8718413 B2	04/09/2013 05/05/2011 06/05/2014
JP 4947047 B2	06/06/2012	EP 1990627 A1 EP 1990627 A4 EP 1990627 B1 US 2009-0128809 A1 US 7626698 B2 WO 2007-099615 A1	12/11/2008 12/03/2014 15/04/2015 21/05/2009 01/12/2009 07/09/2007