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OPTICAL MODULATOR

The present invention relates to an optical modulator and a method of controlling the same. The invention relates specifically, but not exclusively, to a micro opto-electro-

5   mechanical systems (MOEMS) spatial optical modulator for use in an imaging system.

Spatial optical modulators are of interest for a variety of imaging applications including scientific instruments and commercial products.

10   By way of background to the present invention, MOEMS optical modulators are known which utilise optical interference effects to control the intensity and / or phase of a beam of light. For example, Lewis et al., SPIE-5614 (1994), pp. 24 – 30 describes an optical modulator structure based on a MOEMS device with a tuneable gap that acts as a resonant optical cavity (silicon-air-silicon Fabry-Perot etalon). The device described

15   in Lewis et al. does however differ from most MOEMS optical modulator structures in that it may act in transmission as well as reflection.

Goossen et al, IEEE Phot. Tech. Lett. 6 (1994), pp. 1119 – 1121 describes an optical modulator, operated in reflective mode, based on a resonant Fabry-Perot cavity

20   incorporating a tuneable cavity below a moveable membrane. In the device referred to in Goossen et al., the membrane is supported by arms above an air gap and is moveable by means of electrostatic force resulting from a bias voltage applied between an electrode placed around the circumference of the membrane and an underlying substrate. When the membrane is brought into close proximity with the underlying

25   substrate, an anti-reflection condition exists and so the reflected signal is diminished. In transmission the contrast between the open and closed states is very low and the design would not be suitable as a spatial light modulator for use in the infra-red spectral region. Whilst the modulator described in Goossen may be usefully employed in fibre-optic communications applications, such a structure is difficult to scale up into a two-

30   dimensional arrays having fine pitch geometries (10μm – 50μm) because its fill factor would be unacceptably low. In addition, the stresses in the materials used within the modulator are such that a more compact support structure could not be realised without significantly distorting the moveable membrane. Further, the device referred to in Goossen et al. is susceptible to distortion due to differential thermal coefficients of

35   expansion of the materials used therein (metal over nitride structure). Such distortion

would compromise the optical performance of the device since the resonant cavity would be ill-defined.

The electrode being limited to the periphery of the membrane to maximise fill factor
5   means only a small proportion of the area is used to drive the device electrostatically. Thus high voltages are required to modulate the device. Similarly, the metal being above the membrane, increases the inter-electrode gap and reduces the resulting force unless a higher drive voltage is applied. The finite size of the upper electrode required on the device and associated drive voltages makes this device unsuitable for scaling to
10   small pixel sizes (15-50μm) required for large area (two dimensional) arrays with high pixel counts.

US patent 5,636,052 describes a reflective display comprising a two-dimensional spatial optical modulator having an array of MOEMS optical modulators. Each
15   modulator within the array comprising a moveable membrane suspended over a substrate. Each optical modulator employs optical interference effects between the moveable membrane and the underlying substrate which causes the modulator to either substantially reflect or absorb an optical signal. The display operates exclusively in reflection. The optical modulators within the array are individually addressable via
20   associated drive electronics using a row-column addressing scheme. An active row-column addressing matrix is employed with each modulator having at least one address transistor associated therewith. The drive electronics may be fabricated on the same substrate as the spatial optical modulator contiguous to each individual modulator. As will be appreciated by the skilled reader, this arrangement facilitates
25   interfacing of data signals with the spatial optical modulator but may reduce the fill-factor of the array. Additionally, the high temperature micro-electro-mechanical (MEMS) processing steps used to fabricate the modulator membrane can degrade the characteristics of the transistors within the drive electronics. Furthermore, fabricating the drive electronics in the substrate interferes with the optical properties of the
30   substrate, thereby restricting the spatial optical modulator to reflective operation only.

The majority of MEMS array addressing schemes are based on buried (in-pixel) addressing electronics. Whilst the hysteretic characteristic of electrostatic devices is widely known, addressing schemes for MEMS devices based on this phenomenon are
35   not. One exception may be found in EP 1 341 025, however, such addressing schemes

have not hitherto been employed for MOEMS spatial optical modulators of the present invention. EP 1 341 025 describes a reflective MEMS optical display system which uses activation electrodes to operate a plurality of MEMS reflectors and separate storage electrodes to latch the MEMS reflectors into preferred positions. In contrast to the present invention, the device described EP 1 341 025 only operates in reflection since the electrodes therein are not optically transmissive. Accordingly, the drive electrodes in EP 1 341 025 do not form part of the optical structure of the device. Finally, the addressing scheme discussed in EP 1 341 025 is unable to reset individual reflectors within the display system.

It is an object of the invention to provide an alternative MOEMS spatial optical modulator, which mitigates at least some of the disadvantages of the devices described above. It is a further object of the invention to provide a passive method of controlling a MOEMS spatial optical modulator that does not require in-pixel electronics. Another objective of the present invention is to realise a MOEMS modulator that acts as a micro-shutter array.

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According to a first aspect of the present invention there is now proposed a micro-opto-electro-mechanical systems (MOEMS) optical modulator having an optical resonator comprising an asymmetric Fabry-Perot etalon incorporating a mirror resiliently biased with respect to a substrate and moveable in relation thereto in response to a voltage
5   applied there-between.

Preferably, the optical modulator is capable of modulating electromagnetic radiation having a plurality of wavelengths and /or angles of incidence. Alternatively, the optical modulator is capable of modulating electromagnetic radiation having a single
10   wavelength.

By way of explanation, in a conventional Fabry-Perot etalon, each mirror usually comprises a dielectric stack of material of contrasting refractive index, with each layer approximately a quarter optical wavelength in thickness. The resonant cavity formed
15   by the air gap between the mirrors is conventionally a multiple of a half optical wavelength (at the design wavelength) in thickness. Thus by shifting the moveable mirror from the case where it is a half-wavelength to a quarter wavelength in thickness it is possible to achieve two contrasting optical states, since in the latter case the entire stack is in essence a broad-band reflector. These two states are denoted open and
20   closed respectively. The problem with such a design is that the spectral response of the open state is relatively narrow and such a device would be unsuitable as a broadband light modulator across a wide spectral range $(0.75 < w_0 < 1.2)$ where w_0 is the design wavelength. In the present approach, the cavity thickness is reduced to a level close to zero, so that the ensuing interference stack becomes in essence a broad-band
25   transmission filter.

In a preferred embodiment, the optical modulator is adapted to modulate transmission of infrared radiation and, more preferably, of at least one of the short wave infrared (SWIR) radiation ($0.8-2.5\mu m$), medium wave infrared (MWIR) radiation ($3-5\mu m$) and
30   long wave infrared (LWIR) radiation ($8-14\mu m$) atmospheric windows.

Conveniently, the optical modulator substrate is substantially transmissive to SWIR, MWIR and LWIR radiation. This characteristic refers to the transmission properties of a substrate layer in the optical modulator before the fabrication of the optical resonator
35   thereon.

Advantageously, the modulator is substantially transmissive to MWIR radiation in an optically open state and substantially non-transmissive to MWIR radiation in an optically closed state.

5

Preferably the optical modulator has a maximum transmittance greater than 40%, preferably greater than 50%, even more preferably greater than 60%, advantageously greater than 70%, even more advantageously greater than 80%, optimally greater than 95% in an optically open state and a minimum transmittance of less than 5%, preferably less than 4%, even more preferably less than 3%, advantageously less than 2%, even more advantageously lass than 1% in an optically closed state for MWIR radiation.

Conveniently, the optical modulator has a multilayer stack comprising the following plurality of contiguous layers; silicon moveable mirror layer, air gap, silicon layer, a first dielectric layer, and a silicon layer. The first dielectric layer may comprise one of silicon dioxide, silicon nitride, silicon oxynitride, or a gas, for example air or nitrogen.

Alternatively, the optical modulator may have a multilayer stack comprising the following plurality of contiguous layers; silicon moveable mirror layer, air gap, a second dielectric layer, silicon layer, a first dielectric layer, and a silicon layer. In this case, the second dielectric layer may comprise one of silicon dioxide, silicon oxynitride and silicon nitride.

In another preferred embodiment, the optical modulator is adapted to modulate reflectively visible radiation.

Preferably, the mirror is moveable within the asymmetric Fabry-Perot etalon between a substantially stable first position distal to the substrate and a substantially stable second position proximate the substrate.

Conveniently, the mirror is adapted to respond to applied voltage to move non-linearly between the first and second positions. Without limitation, the term non-linear used herein shall refer to the positional response of the mirror as a function of the voltage

- 6 -

applied to the optical modulator rather than the velocity with which the mirror moves or the acceleration thereof.

5   Advantageously, the mirror is adapted to move from the first position upon application of a force thereto having a magnitude which exceeds a first threshold and is adapted to move from the second position upon reduction of the magnitude of the applied force below a second threshold, the two thresholds being arranged to be substantially different.

10   Preferably, the force is the resultant of an electrostatic attractive force having a magnitude substantially proportional to the square of the applied voltage and a mechanical restoring force having a magnitude substantially proportional to the mirror displacement. Alternatively, or in addition, the spring can be designed to be a non-linear component.

15

Even more preferably, the mirror has a positional response which exhibits hysteresis.

According to a second aspect of the present invention there is now proposed a spatial optical modulator comprising a two-dimensional array of optical modulators according

20   to the first aspect of the invention.

In a preferred embodiment, the spatial optical modulator has a first layer of electrodes and second layer of electrodes, and wherein the optical modulators are arranged in an array with each modulator having an electrode in the first layer and an electrode in the

25   second layer.

Conveniently, the spatial optical modulator has a plurality of row electrodes and plurality of column electrodes and wherein the optical modulators are addressable individually using a passive matrix row-column addressing scheme. Such a passive

30   addressing scheme does not require a semiconductor device (transistor etc.) to switch each optical modulator within the spatial optical modulator. In the interests of clarity a row electrode includes all the moveable mirrors within the optical modulators of said row, whereas a column electrode includes all the fixed plate electrodes within the optical modulators of said column.

35

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Preferably, the optical resonator within each of the optical modulators comprises at least one of the first and second layer of electrodes.

Even more preferably, at least one of the first and second layer of electrodes is 5 substantially transmissive to incident radiation.

Preferably, the optical modulators are arranged regularly in the array with a pitch (measured between the same points on adjacent modulators) in the range 5 - 200μm, preferably in the range 20 – 50μm, optimally 30μm pitch.

10

Conveniently, at least one of the optical modulators within the spatial optical modulator is apodized. The at least one apodized optical modulator may comprise a profiled mirror.

15 Advantageously, the spatial optical modulator includes an array having a plurality of micro-lenses arranged in optical communication with the array of optical modulators therein. Preferably, each micro-lens within the micro-lens array cooperates with an optical modulator within the spatial optical modulator to focus electromagnetic radiation thereon.

20

According to a third aspect of the present invention there is now proposed a method of addressing a spatial optical modulator comprising a plurality of row electrodes and a plurality of column electrodes having a plurality of bistable MOEMS optical modulators arranged in an array with each optical modulator in the array disposed at an 25 intersection between a row electrode and a column electrode, the method comprising the steps of:

(i) applying a column drive voltage to each column electrode,

30   (ii) applying a row drive voltage to each row electrode,

whereby the optical modulator at each intersection is operable in response to the potential difference between the column drive voltage and the row drive voltage at said intersection.

35

A key feature of the addressing scheme is that the whole row can be set in parallel when a given column is enabled. In practice, columns are enabled sequentially, all the rows being set in parallel for each given column.

5   Preferably, the method comprises setting an optical modulator to a latched position incorporating the steps of:

(i) arranging the column drive voltage applied to all column electrodes to be equal to a hold voltage reference V_{ref},

10

(ii) increasing the column drive voltage applied to the column electrode corresponding with the modulator to be set by a set voltage V_{set}, wherein $V_{ref} + V_{set}$ is less than a latch voltage V_{pi} required to latch the optical modulator,

15   (iii) arranging the row drive voltage applied to the row electrode corresponding with the modulator to be set to be equal to a row-set voltage $-V_{row-set}$, wherein the potential difference $V_{ref} + V_{set} + V_{row-set}$ is greater than the latch voltage V_{pi},

(iv) removing the row drive voltage from the row electrode corresponding with the
20   modulator to be set, and

(v) reducing the column drive voltage applied to the column electrode corresponding with the modulator to be set by the set voltage V_{set} back to V_{ref}

25   Preferably, the method comprises resetting an optical modulator from a latched position comprising the steps of:

(i) arranging the column drive voltage applied to all column electrodes except the column corresponding with the modulator to be reset to be equal to a hold
30   voltage reference V_{ref} plus a set voltage V_{set}, wherein $V_{ref} + V_{set}$ is less than a latch voltage V_{pi} required to latch the optical modulator, the column corresponding with the modulator to be reset remains at V_{ref}.

(ii) arranging the row drive voltage applied to the row electrode corresponding with
35   the modulator to be reset to be equal to a row-reset voltage $+V_{reset}$, wherein the

potential difference $V_{ref} - V_{reset}$ is less than a release voltage V_{po} required to release the optical modulator,

(iii) removing the row drive voltage from the row electrode corresponding with the
5   modulator to be reset, and

(iv) reducing the column drive voltage applied to the column electrode corresponding with the modulator to be set by the reset voltage V_{reset} back to V_{ref}.

10

In the interests of clarity, the foregoing steps of setting and resetting an optical modulator to and from a latched position enable an individual optical modulator on a particular row to be set without changing the state of any other optical modulators on that row.

15

Preferably, the method comprises setting all the optical modulators within the array to a latched position comprising the steps of:

(i) arranging the column drive voltage applied to all column electrodes to be equal
20   to a hold voltage reference V_{ref} plus a set voltage V_{set}, wherein $V_{ref} + V_{set}$ is less than a latch voltage V_{pi} required to latch the optical modulator and greater than a release voltage V_{po} ,

(ii) arranging the row drive voltage applied to all row electrodes to be equal to a
25   row-set voltage $-V_{row-set}$, wherein the potential difference $V_{ref} + V_{set} + V_{row-set}$ is greater than the latch voltage V_{pi},

(iii) removing the row drive voltage from the row electrode corresponding with the modulator to be set, and

30

(iv) reducing the column drive voltage applied to the column electrode corresponding with the modulator to be set by the set voltage V_{set} back to V_{ref}.

Preferably, the method comprises resetting all optical modulators within the array from
35   a latched position comprising the step of:

(i)   arranging the column drive voltage applied to all column electrodes to be
      substantially zero.

5   The skilled person will realise that sub-groups of optical modulators within the array
    can be reset in a similar manner by addressing sub-groups of column electrodes in
    order to control peak current.

    According to a fourth aspect of the present invention, there is now proposed an array of
10 MOEMS modulators for an adaptive coded aperture imaging (ACAI) system comprising
    an aperture mask having at least one spatial optical modulator according to the second
    object of the invention arranged so as to modulate electromagnetic radiation incident
    on a detector array.

15

The invention will now be described, by example only, with reference to the accompanying drawings in which;

Figures 1a shows a schematic perspective representation of a MOEMS optical
5   modulator having two support springs. Figure 1b shows a schematic perspective representation of an alternative MOEMS optical modulator having four support springs.

Figure 2 shows cross-sectional view of a MOEMS optical modulator according to one embodiment of the present invention.
10

Figure 3a illustrates a cross-sectional view of a MOEMS optical modulator according to the present invention comprising an asymmetric Fabry-Perot etalon having a tuneable cavity. Figure 3b shows a cross-sectional view of an MOEMS optical modulator having an asymmetric Fabry-Perot etalon of an alternative embodiment.
15

Figures 4a to 4c show typical performance characteristic for the optical modulator of figure 3a. Specifically, figure 4a shows transmittance against MWIR waveband for the optical modulator when the micro-mirror is in its upper equilibrium position and in its lower position at normal incidence. Figure 4b shows transmittance against MWIR
20   waveband for the optical modulator when the micro-mirror is in its upper equilibrium position and in its lower position for incident angles of 0 degrees and 50 degrees. Figure 4c shows transmittance against angle of incidence by polarisation.

Figure 5a shows a typical performance characteristic for the optical modulator of figure
25   3b optimised for maximum transmission in an optically open state in the 3.5 to 4.5μm waveband. Figure 5b shows a schematic representation of an adaptive coded aperture imaging (ACAI) system as described in our co-pending UK patent application GB 0510470 the content of which is hereby incorporated by reference thereto, including a two-dimensional array of MOEMS optical modulators according to the present
30   invention.

Figure 6 illustrates the typical latching characteristic (hysteresis curve) for a MOEMS modulator according to the present invention.

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Figure 7a shows schematic representation of a spatial optical modulator according to one embodiment of the invention having an array of pixels, each pixel individually addressable using a plurality of row and column address lines. Figure 7b shows a schematic perspective view of the spatial optical modulator having an array of 30μm
5   pitch pixels incorporating a buried electrode for row addressing and an electrode disposed on the micro-mirrors for column addressing. Figure 7c shows a schematic cross-sectional representation of another embodiment of the invention comprising an encapsulated two dimensional array of optical modulators.

10   Figure 8 illustrates example waveforms and corresponding pixel states typical of a matrix (row-column) addressing scheme according to another embodiment of the invention used to control the present MOEMS spatial optical modulator. The upper graph shows row and column voltage states while the lower graph denotes whether a pixel is in the latched (1) or released (0) state.
15

Figure 9 shows predicted performance characteristics for MOEMS optical modulators according to the present invention. These show the general trends for rectilinear pixels of the form of figure 1. Specifically, figure 9a shows a plot of predicted resonant frequency vs. pixel thickness, figure 9b shows a plot of predicted resonant frequency
20   vs. plate size, figure 9c shows a plot of predicted drive voltage vs. plate size, and figure 9d shows a plot of predicted fill factor vs. plate size.

Figure 10 shows a schematic illustration of a large MOEMS spatial optical modulator array comprising multiple MOEMS spatial optical modulator chips linked by electronics
25   chips (driver ASIC) using direct chip attach technology (e.g. ball grid array / flip-chip). The illustration is shown in cross-section.

Figure 11 shows a schematic illustration of an infrared camera using an adaptive coded aperture (ACA) based calibration source comprising a MOEMS spatial optical
30   modulator according to the present invention.

Referring now to the drawings wherein like reference numerals identify corresponding or similar elements throughout the several views, Fig. 1 shows a schematic cross-sectional representation of large area MOEMS optical modulator as described in our co-pending UK patent application GB 0521251, the content of which is hereby incorporated by reference thereto.

By way of a brief explanation, the modulator described in GB 0521251 utilises optical interference effects to control the intensity and / or phase of a beam (or beams) of light and is based on a single MOEMS optical modulator or an array of MOEMS optical modulators in which one or more moveable micro-mirrors are suspended above a substrate. This arrangement may be used in transmission for wavelengths where the substrate (for example silicon) is optically transmissive, and may be used in reflection for a substantially larger range of wavelengths.

An individual optical modulator 2 comprises a moveable suspended layer 10, hereinafter referred to as a micro-mirror 10 which is suspended above a substrate 13 by a distance of between a fraction of a micron and a few microns. The micro-mirror is supported by springs 14, so that when a voltage is applied between the substrate 13 and the micro-mirror 10, electrostatic forces will pull the micro-mirror 10 from an equilibrium position towards the substrate 13.

The micro-mirror 10 may be any shape in plan form but is required to be flat and parallel to the substrate 13.

When light is directed onto this device, some of the light will be reflected and some will be transmitted to the substrate 13 and out the other side (for the case of wavelengths such that the substrate is transparent). Light reflected and transmitted by the suspended mirror 10 will interfere with light reflected and transmitted by the substrate 13, and the actual transmission and reflection of the device 2 will vary between a high and a low value depending on the angle of incidence of the light upon the device, on the spacing between the suspended mirror 10 and the substrate 13, and on other pre-determined characteristics of the system such as the thickness of the suspended micro-mirror 10, the refractive index of the material from which the micro-mirror 10 is made, and the wavelength of the incident light.

As the spacing between the micro-mirror 10 and the substrate 13 is adjusted, the transmission varies between a high and low value, providing a means of modulation of the incident light. The modulation can work in transmission or reflection modes. It is noted that the micro-mirror 10 is typically a fraction of a micron thick and will be semi-

5   transparent even in the visible region where silicon is highly absorbing, so a modulator made from silicon can be used in reflection for the visible band. Additionally, the micro-mirror may be coated to act as an even better reflector in the visible region.

The transmission and reflection properties of the optical modulator 2 can be described

10   by using the known formulae for transmission and reflection by a Fabry-Perot etalon. It is noted that the reflected and transmitted light experiences a phase shift as well as a change in amplitude. This can also be used in a device which communicates by modulating the phase of a beam of light.

15   The micro-mirrors 10 each have two stable positions in which one can be confident of ensuring the mirror 10 is located when being controlled. The first of these is an 'equilibrium position' in which the micro-mirror 10 is suspended at rest above the substrate 13 when no voltage is applied between the mirror 10 and the substrate 13, and there is no extension of the support springs 14. The second is the 'pull-down

20   position' in which the micro-mirror 10 is pulled firmly down towards the substrate 13 when the voltage applied to the substrate 13 exceeds a certain value. Insulating stops 22 may be provided between the substrate 13 and the micro-mirror 10 so that when the voltage exceeds a certain value the mirror 10 is pulled hard against the stops 22 but cannot be pulled any further towards the substrate 13. These pull-down stops 22

25   thereby prevent undesirable electrical contact between the micro-mirror 10 and the substrate 13, since electrical contract would lead to a short circuit and electrical damage.

A cross-sectional view of the MOEMS optical modulator 2 discussed above is shown in

30   Fig. 2. The MOEMS optical modulator 2 comprises a simple structure having an etalon comprising a polysilicon-air-silicon configuration. The optical modulator 2 may be fabricated on the silicon substrate 13 using only four deposition steps (silicon nitride layer 18, a polysilicon layer to produce the micro-mirror 10 and the supporting springs 14, and two phosphorous-doped silicon oxide layers which are subsequently removed

35   from the device, the removal of the lower of the phosphorous-doped silicon oxide

layers providing an air gap within the Fabry-Perot etalon). Accordingly, the simple structure results in a low cost device. Further optional layers may be included, such as an additional fixed polysilicon layer 16 as an improved etch stop and a metal layer 20 to reduce track resistance to control RC delays as the array size grows.

The micro-mirrors 10 described above may be produced as an array with an extended area covered by a tiling of closely packed optical modulators 2, in which case it becomes a spatial optical modulator. The stress is low and so a suspension of the form shown in Fig. 2 may be employed and tessellated to make a large area array. This form of design has springs 14 on two opposite or all four sides of a central substantially square or rectangular mirror plate. It represents a good compromise between plate flatness on displacement and fill factor (for good optical performance), acceptable speed and drive voltage (electromechanical performance), and scalability to large area coverage. The device utilises the substrate 13 as a global electrode and so all the optical modulators 2 are driven in parallel. Although described above in terms of a square or rectangular configuration, the mirror plate 10 (and associated two-dimensional array) may take other shapes, e.g. circular, hexagonal etc. Similarly, the springs 14 are not limited to a rectilinear configuration but could be curved. They could be also positioned relative to the mirror to facilitate connectivity and fill factor within the associated two dimensional array.

Using this approach with a MOEMS optical modulator has demonstrated data rates in excess of 200kbps with a contrast ratio in excess of 7:1 (50:1 double pass) at 24V, at 1.55µm.

Hitherto, the MOEMS optical modulator 2 described above has been used in a transmissive mode of operation at a single wavelength (1.55µm) in the SWIR. A low-finesse optical cavity has been employed to provide wide angle operation.

Referring now to Fig. 3a, a cross-sectional view of a MOEMS optical modulator according to the present invention comprises an asymmetric Fabry-Perot etalon having moveable mirror over a tuneable cavity. In this embodiment of the invention, the asymmetric etalon comprises a polysilicon-air-polysilicon-oxide-silicon configuration.

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The MOEMS optical modulator shown in Fig. 3a comprises a silicon substrate 13 upon which is fabricated a layer 30 of silicon oxide, followed by a fixed polysilicon layer 26. The fixed polysilicon layer 26 provides the fixed electrode which is separated from the moveable micro-mirror 10 by air gap 24. In this embodiment of the invention, the etalon

5   comprises a polysilicon-air-polysilicon-oxide-silicon configuration.

In an alternative embodiment shown schematically in Fig. 3b, a dielectric layer 28 is provided on top of the fixed polysilicon layer 26. In this embodiment of the invention, the etalon comprises an asymmetric polysilicon-air-dielectric-polysilicon-dielectric-

10   silicon configuration. The upper polysilicon-air layers provide the tuneable etalon in combination with the fixed dielectric layer 28, the polysilicon layer 26, the dielectric layer 30 and the silicon substrate 13. The dielectric layer 28 preferably comprises silicon oxide, silicon oxy-nitride or most preferably silicon nitride. The dielectric layer 30 preferably comprises silicon oxide. Alternatively, the dielectric layer 30 could comprise

15   silicon nitride or silicon oxynitride. In a further alternative, a more complex structure could be used with a polysilicon-air-polysilicon moveable upper mirror to increase the finesse of the device.

As will be appreciated by the skilled reader, the above-mentioned architecture may be

20   fabricated by employing oxide layers which have different relative etch rates during the removal of the sacrificial layer, in this case phosphorous doped deposited silicon oxide. For example, thermal silicon oxide etches much more slowly in hydrofluoric acid than deposited doped oxide layers by a factor of between 5 and 100. However, an improved fabrication route is to avoid having exposed silicon oxide layers during a release etch.

25

The foregoing embodiments shown in figures 3a and 3b utilise silicon dioxide as the dielectric within layer 30 and silicon oxide, silicon oxy-nitride or silicon nitride as the dielectric within layer 28, however the skilled person will be aware that other dielectric materials may be chosen to give good performance.

30

Using a dielectric layer 28 in figure 3b confers an addition benefit by providing electrical isolation between the polysilicon micro-mirror (used as the upper electrode in the device) and the lower polysilicon layer 26 (the lower electrode within the device). This configuration facilitates fabrication of an array of optical modulators 2 (where the fixed

35   polysilicon layer is divided into a plurality of separate electrodes) since the silicon

nitride layer protects the underlying silicon oxide layer from being etched away during the process to realise the air gap within the modulator.

Similarly, other structural layers / substrates may be used with appropriate optical /
5   mechanical material properties, e.g. polysilicon-germanium, germanium, single crystal silicon etc.

An anti-reflective coating (ARC), such as SiO or Ta_2O_5/SiO_2, is typically added on the back of the silicon substrate 13 to optimise throughput and reduce the likelihood of
10   spurious etalon effects.

To achieve good closed-state performance, a narrow air gap is required (e.g. 30-100nm) that is challenging without the use of additional stand-off dimples 22 to prevent large area contacts. One alternative to use the blanket insulating dielectric layer 28
15   over the polysilicon electrode (with appropriate optical design) to allow touching and define the stand-off. The design is optimized to ensure the moveable micro-mirror overcomes stiction forces and returns to its equilibrium position.

The MOEMS optical modulator according to the present invention enables operation in
20   the SWIR, MWIR, LWIR and some parts of the visible spectrum in transmission by adjusting the gap of the optical cavity.

Optionally, the device is useable in reflection in other optical bands (e.g. visible) provided sufficient travel is allowed (defined by the gap). Optionally, a thin upper
25   reflective coating is used to improve performance.

Digital operation of the optical modulator is sufficient, in which case the micro-mirror is positioned either in its upper equilibrium position, or in its lower position in close proximity to the lower fixed electrode. The upper equilibrium position and the lower
30   position shall include those positions adopted by the mirror with a reference voltage V_{ref} applied to the modulator. The modulator is preferably used in transmission rather than reflection to improve system design. When used as a transmissive modulator, the optical modulator substantially blocks transmission of electromagnetic radiation there-through when the micro-mirror is positioned in its upper equilibrium position and

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substantially transmits electromagnetic radiation there-through when the micro-mirror is positioned in its lower position in close proximity to the substrate.

The present MOEMS modulator is particularly applicable to MWIR and SWIR imaging applications where other conventional modulator solutions cannot be applied for reasons of performance (e.g. LCD) or cost (e.g. multi-quantum well devices). Moreover, since the modulator may be fabricated exclusively from silicon, thermal bi-material effects are reduced or eliminated, and hence the behaviour of the modulator is largely unaffected by operational temperature (e.g. ranges in excess of -40°C to +70°C are readily accessible). This means that is suitable for cooling so that the micro-mirror does not add noise to an image. Accordingly, the modulator may be advantageously employed in IR imaging applications and adaptive coded aperture imaging applications (ACIA).

Figures 4a to 4c show typical performance characteristic for the tuneable cavity of Fig. 3b. Specifically, Fig. 4a shows transmittance in the MWIR waveband for the optical modulator when the micro-mirror is in its upper equilibrium position and in its lower position at normal incidence. Fig. 4b shows transmittance against MWIR waveband for the optical modulator when the micro-mirror is in its upper equilibrium position and in its lower position for incident angles of 0 degrees and 50 degrees. Fig. 4c shows transmittance against angle of incidence by polarisation. In practice, incident angles in the range 15 degrees to 20 degrees may be used to minimise angular effects. In situations involving modulation of radiation from the atmosphere, it is beneficial to arrange transmission peaks to coincide with atmospheric transmission windows.

The dimensions of the optical stacks within the etalon may be optimised across the spectral and angular range to maximise contrast ratio – moving away slightly from conventional half/quarter wave optical stacks for a single wavelength device.

Fig. 5a shows a typical performance characteristic for the tuneable cavity of Fig. 3b optimised for maximum transmission in an optically open state in the 3.5μm to 4.5μm waveband using the following layer sequence:

polysilicon micro mirror-air-silicon nitride-polysilicon-silicon dioxide-silicon substrate.

In this particular embodiment, the two states of the optical modulator (optically open –
substantially transmissive / optically closed – optically non-transmissive) are achieved
by moving the micro-mirror so as to adjust the air gap in the modulator. Standard
positions would be ~1μm and ~50nm .

5

For specific imaging applications, e.g. adapted coded aperture imaging (ACAI), it is
desirable to produce a two-dimensional array of MOEMS optical modulators wherein
each optical modulator is individually addressable. This enables individual optical
modulators within the array (also referred to hereinafter as picture elements or pixels)
10   to be set in the optically closed or optically open position (reflect "0" or transmit "1"). For
example, see figure 5b which shows a schematic representation of an adaptive coded
aperture imaging (ACAI) system as described in our co-pending UK patent application
GB 0510470 the content of which is hereby incorporated by reference thereto,
including a two-dimensional array of MOEMS optical modulators according to the
15   present invention.

Hence, according to another embodiment of the present invention, a spatial optical
modulator comprises a two dimensional array of optical modulators of Figs. 1 to 3
addressable using a passive matrix row / column addressing scheme without the need
20   for sub-pixel control electronics that would reduce fill factor unacceptably in a
transmissive device. A critical aspect for the transmissive architecture is that the lower
electrode is transparent and part of the optical design. A key benefit is that this
embodiment of the invention enables a MEMS-only chip to be addressed using an off-
chip drivers and means an integrated MEMS process is not necessary. This approach
25   enables separate optimisation of the MEMS architecture and the pixel control
electronics, reduces costs and provides a two-dimensional array which is scaleable to
any size.

Passive matrix addressing of the two dimensional array is achieved in this embodiment
30   of the invention by making the constituent optical modulators bistable using appropriate
voltages.

In order to achieve this bistable characteristic, the micro-mirrors are arranged such that
when the voltage applied to the optical modulator exceeds a certain value, the micro-
35   mirror will snap down from the equilibrium position to the 'pull in' (or 'latch down')

position. Non-linear effects in MOEMS optical modulators have hitherto been considered to be detrimental to the operation of the device and efforts have been made to eliminate such effects, for example see patent US 5,838,484 which describes a MOEMS optical modulator with linear operating characteristic.

5

Accordingly, in the present invention each optical modulator 2 within the array is arranged so that the micro-mirror 10 therein will only latch down (pull in) when the applied potential difference across a pair of electrodes exceeds a threshold voltage (V_{pi}), in which condition the electrostatic attraction force is greater than the mechanical

10   restoring force provided by the supporting springs 14. The optical modulator exhibits hysteresis so that the pull off voltage (V_{po}) is significantly lower than the pull in voltage. The degree of hysteresis may be tailored by appropriate design.

In order to enable passive matrix addressing, the pull off (or release) voltage is

15   arranged to be significantly lower (e.g. a factor of 2) than the pull in voltage. See for example Fig. 6 which shows schematically the hysteresis characteristic of one of the optical modulators within the array of the present embodiment.

In the present embodiment, the two dimensional array of optical modulators are

20   arranged in a matrix between a plurality of column address electrodes 32, and a plurality of underlying row address electrodes 34, see Fig. 7. The upper column address electrodes 32 comprise the moveable micro-mirrors 10 within the optical modulators whereas the row address electrodes 34 comprise the fixed electrode plate 36 in each optical modulator and accessed via the edge, Fig. 7b refers.

25

Figure 7c shows a schematic cross-sectional representation of another embodiment of the invention comprising an encapsulated two dimensional array of optical modulators. Here, the optical modulator array is enclosed by a cap 31 attached using a wafer / chip scale encapsulation technique to the substrate 13 by a bond layer 29. In figure 7c, the

30   cap is has a rebate formed therein. Alternatively a planer cap may be used if the thickness of the bond layer 29 is increased accordingly. Encapsulation in this manner enables the pressure within a sealed device to be controlled, thereby allowing the mechanical damping of the micro-mirrors to be controlled. This technique simplifies processing as devices are released wafer scale, bonded and sawn – avoiding debris

35   issues and simplifying handling during packaging / integration into system. The cap 31

is provided with appropriate antireflection (AR) coatings and an appropriate spacing to the moveable mirror (e.g. > coherence length of light in application to avoid unwanted etalon effects). This spacing may be achieved by a rebate in the cap (as shown in the figure) and/or a bond spacer between the modulator wafer and the cap wafer. It is

5   possible to actively use the gap between upper cap 31 and moveable mirror 10 in some way to further tune optical performance and exploit etalon effects with small gap.

Through wafer vias could also be incorporated into the substrate or cap (or even the electronic chips) to enable direct mounting of the electronic driver chips without flipping.

10

Optionally, the cap may be shaped to provide an element or elements having an optical functionality or optical power, for example the cap may have a lensing function.

In the present arrangement, the voltage applied to a given optical modulator within the

15 array is the sum of the voltage applied to the moveable micro mirror (the column voltage) and the voltage applied to the fixed electrode (row voltage). This configuration enables each optical modulator or pixel within the array to be set individually in a row / column address scheme.

20 An addressing scheme according to one embodiment of the invention is now described which enables each pixel to be set and reset individually in a row / column addressing scheme (the whole array does not need to be reset to unlatch a pixel).

Those skilled in the art will appreciate that there are other ways of changing the column

25 / row voltages to achieve the same functionality of moving the net potential difference applied to each pixel to fall within the hysterisis zone (hold), below the pull off voltage (reset) or above the pull in voltage (set) as described in detail herein. For example, during the reset function, the voltage of the column containing mirrors to be reset needs to be lower than that of the other columns such that the sum of the column

30 voltage and the row voltage falls below the pull-off voltage. This may be achieved by reducing the voltage of the column of interest below the reference voltage (such that $V_{ref} - V_{reset} > V_{po}$ for other columns) or by increasing the voltage of the other columns above the reference voltage by V_{set2} such that their potential remains above the pull off voltage whilst the column of interest (at V_{ref}) in conjunction with the row voltage fall

35 below the pull off threshold. Similarly, the row and column voltages could be

- 22 -

interchanged such that rows would be sequentially addressed whilst all the columns are set in parallel.

The addressing scheme according to the present embodiment of the invention is based
5   on electrostatic hysteresis (see Fig. 6) where V_{pi} is the latch (pull in) voltage and V_{po} is the release (pull off) voltage. With reference to the prior art, the addressing scheme of EP 1 341 025 resets the entire modulator array by removing the latch voltage. EP 1 341 025 also uses a separate latch electrode. This makes only changing small parts of the array, whilst leaving the remainder unaffected, difficult and is potentially inefficient
10   (requiring higher addressing speeds to adapt the array pattern in a given time).

The addressing scheme described in this embodiment is best illustrated by the sequences shown in Fig 8. Referring to Fig. 8, the row location is denoted by R row no., the column location by C column no. and pixel location by P row no., column no.
15   For this example, let V_{pi} = 14V, V_{po} = 10V. The upper graph in Fig. 8 denotes row voltage states (e.g. up = -2V ($-V_{row-set}$), down = +2V ($V_{row-set}$), centre = 0V) and column voltage states (e.g. up = 13V ($V_{ref}+V_{set}$), centre = 11V (V_{ref}) and down = 0V). The drive voltage for a given pixel is given by ($V_{column} - V_{row}$). The lower graph in Fig. 8 denotes whether a given pixel is in latched (1) or released (0) state. The voltages used here are
20   typical of a 25μm micro-mirror with a 1.2μm gap designed to modulate in the SWIR at 100kbps.

The operations are performed by setting the appropriate combination of voltages as follows:
25

Set pixel – all columns at hold voltage reference, V_{ref}, except column with pixels to be set at $V_{ref} + V_{set} < V_{pi}$. Row voltages with pixels to be latched set to $-V_{row-set}$ so that potential difference, $V_{ref} + V_{set} + V_{row-set} > V_{pi}$ (other columns at $V_{ref} + V_{row-set} < V_{pi}$ so do not latch). $V_{row-set}$ removed from row and all columns returned to V_{ref} to hold pixels in
30   latched state.

Reset pixel – all columns at $V_{ref} + V_{set}$ ($<V_{pi}$) except column with pixels to be reset (released) at V_{ref}. Row voltages with pixels to be released set to $+V_{reset}$ so potential difference across pixels is $V_{ref} - V_{reset} < V_{po}$ (other columns at $V_{ref} + V_{set} - V_{reset} > V_{po}$ so if

latched remain so). V_{reset} removed from rows and all columns returned to V_{ref} to hold desired pixels in latched state.

Reset/Set all – All columns to 0V to reset all. All columns to V_{ref} + V_{set} and all rows to
5    $V_{row-set}$ to set all.

A complete column may be addressed in parallel in this way (i.e. all the row voltages are set to change the entire column when the column voltage is set. Columns are addressed sequentially.
10

The terms row and column used above are not limiting but may be interchanged without affecting the addressing scheme.

In principle, using this approach the spatial optical modulator array is scaleable to any
15   size. For an imaging scenario, the individual pixel micromirror pitch is likely to fall in the range 15-100µm. When used in an imaging application, preferably the pitch matches the pitch of pixels in the imaging array of the detector. The array must comprise independent columns and, in practice, the size will be limited by resistance / capacitance (RC) time constant considerations. This is mitigated by only switching one
20   column at any time. The resistance of individual pixels will be dominated by the spring width and length – for example, in 0.5µm thick polysilicon with a 2µm spring, the pixel array resistance is of the order of 500KΩ/cm whilst the capacitance of the array is of the order of 50pF/cm (for a 100µm pixel plate) giving an RC constant of 2.5µs/cm. A stepper field size as used in lithography is typically of the order of 2x2cm and so this
25   would be a practical size limit for a tile to build up larger arrays whilst maintaining good control and yield. However, employing a buried layer or a second layer of lower resistance polysilicon interconnect above the spring could reduce the resistance significantly (>10x). Alternatively or additionally, a thin metal layer could reduce track resistance by 2-3 orders of magnitude if speed / resistive voltage drop is an issue. For
30   example, this could be deposited when the device is partially released using a combination of shadow masking from the structure itself and/or lift-off to protect areas where no Au is required (e.g. transmissive region of pixel). Where the modulator comprises additional polysilicon and metal conductor layers, said layers may be arranged to form an optically blocking layer in parts of device to maintain optimal
35   contrast. This is particularly beneficial in low fill factor devices.

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For the electrode layer, the fixed polysilicon acts as the electrical conduit. This is significantly wider than the spring in the moveable array layer and so less likely to limit performance. To reduce its resistance further, the electrode array could be connected to the substrate with implanted tracks periodically using vias. The tracks in the

5   substrate are isolated using reverse biased pn diodes as a result of the implants. For the most aggressive resistance control, a silicide or metal tracks could also be defined on the substrate but care would be needed that it did not interfere with the optical path.

A metal-nitride process is an interesting alternative in this circumstance as both the

10   electrode and moveable micro mirror layer would contain low resistance metal tracking. The drive voltage would likely be higher due to the need to fabricate the majority of the micro mirror as PECVD nitride only to allow transmission (unless an IR transmissive metallization were employed). In practice, metallization may applied to the top and the bottom of the PECVD nitride layer so as to reduce thermal bi-material effects and to

15   reduce the drive gap (thereby reducing the drive voltage).

Optionally, a micro-lens array may be used in conjunction with the spatial optical modulator of the present invention to maintain the efficiency of the optical modulator in circumstances where the fill factor of modulators within the spatial optical modulator

20   array is reduced.

According to further embodiment of the invention a process of optical apodization can be used within the present spatial optical modulator to reduce edge effects and hence diffraction. The pixel can be apodized by suitably profiling one of the cavity mirror

25   elements within the optical modulators of the array. For example, the mirror may be imparted with a monotonically increasing profile, a stepped profile etc designed so as to reduce the optical transmission of the individual Fabry-Perot elements. Most practically, this would be constrained to near the periphery of the micro mirror. Alternatively, or in addition, to achieve apodization, metallization is added to the

30   edge(s) of the cavity mirror. The metallization may comprise a layer or layers of metal (e.g. gold). The thickness of the metallic layer may be graduated. In addition, or alternatively, the metallization is applied using a grey scale pattern (half-tone pattern) etc. to vary the optical density of the metallic layer .

In terms of MEMS design, the main features of interest are the speed, voltage (power) and micro mirror size. With reference to the figures, Fig. 9a shows a plot of predicted resonant frequency vs. pixel thickness, Fig. 9b shows a plot of predicted resonant frequency vs. plate size, Fig. 9c shows a plot of predicted drive voltage vs. plate size,

5   and Fig. 9d shows a plot of predicted fill factor vs. plate size. Figs. 9a to 9d highlighting the following trends; larger pixels reduce the drive voltage and increase the fill factor whilst reducing speed, the four spring design is faster but requires a larger drive voltage and has a lower fill factor, thinner pixels reduce the drive voltage and the speed.

10

It will be appreciated by the skilled person that large areas can be tiled from smaller MOEMS spatial optical modulator arrays according to the present invention. In another embodiment of the invention hybrid integration employing direct chip attach techniques is used to flip and bond a thinned driver electronics chip 40 onto two sides of a

15   MEOMS spatial optical modulator array chip for column and row addressing respectively (e.g. using fine geometry solder bump technology). When scaled to a two dimensional array of tiles (modulator chips), this results in a MEMS chip surrounded on all 4 sides by driver chips. A dummy chip may be used for the blank edges around the periphery of the tile array. The driver chips may alternatively contain electronics for two

20   neighbouring chips, requiring a driver chip on a 4 edges of every tile. Using this technique, two MOEMS modulator chips are attached by each electronics chip as shown in Figure 10.

Building large arrays out of small tiles is the most effective way to reduce cost as yield

25   deceases with chip area. It also controls the number of columns and rows each driver chip needs to address (and hence RC / resistive loss and power/current considerations). For example in a 2x2cm chip, if the pixel pitch were 20µm, there would be 1000 rows and 1000 columns. This requires 10 bit addressing. Such as chip could be realised in a 0.35µm mixed CMOS technology if the drive voltage were below 3.3V

30   or 0.8µm mixed CMOS technology if the drive voltage were below 5V. Higher drive voltages would require a high voltage (20 – 50V) process variant and / or larger geometry process, resulting in a highly specialised design of drive electronics. Transistor sizes in high voltage processes are also larger, meaning that this approach may cease to be viable using simple layouts and architectures. Configurations using

35   combinations of driver chips operating at different drive voltages are also feasible. For

- 26 -

example in a column and row addressing scheme, the column address driver may comprise a standard CMOS driver chip, whereas the row address driver may comprise a high voltage driver chip. In this example, the high voltage driver chip is capable of operating up to 40v for small pixel pitches.

5

Using such a tiling arrangement, it is also possible to realise non-flat shapes, such as a geodesic dome to give added rigidity. Figure 10 also illustrates an optional support frame which has elements 42 arranged to increase the rigidity of the tiled array. The support frame may advantageously be thermally conductive (e.g. metallic) and may be

10   used to control the temperature of the tiled array. For example, the whole array may be cooled by removing heat from the edges via the support frame. Optionally, the support frame comprises a hollow cross-section through which a cooling fluid is passed. Alternatively, the data and /or power connections may be routed through or on the support frame to the tiled plurality of MOEMS arrays.

15

A 50x50 array of 2cm chips may be further multiplexed to enable/disable a particular chip for setting and give a 1x1m mask. If using a single element, this would require 16 bit addressing on a 2.5Gpixel array.

20   The speed to update a tiled large area array is a major design consideration. The voltage drives a capacitive load and so the electrical speed is limited by RC considerations. For a typical design, the RC time constant is of the order of 2.5μs/cm length – compatible with a 10μs/pixel switching speed for a 2x2cm chip. In the above configuration, this is limited by the resistance of the polysilicon in the column path and

25   to a lesser extent the rows. Both could be reduced by adding a more conductive path in parallel with a slight addition in process complexity as previously described. The mechanical response is determined by the resonant frequency of the device and the damping (pressure). The frequency is dependent on the thickness of the moving layer, the spring design and the pitch. With appropriate design, it is predicted to be of the

30   order of 1-10μs. With potentially a 1000x1000 array (20μm pitch on a 2cm chip), an array update time of below 10ms results using the addressing scheme proposed herein wherein pixels within a whole column are set in parallel. By using tiles of this size, and driving / addressing all modulator tiles in parallel, an array of any size may be set at the same speed as an individual tile.

35

- 27 -

The drive voltage depends on the pixel area, spring geometry and gap. For an optical design with a 35μm pixel, it is of the order of 5V and it would be capable of responding at up to 200kHz. Power consumption is a function of the voltage in combination with the capacitance, number and frequency of pixels changing states and the efficiency of

5   any charge recovery schemes employed.

The MOEMS optical modulator according to any of the foregoing embodiments of the present invention is fabricated by successive depositing of material layers on a silicon substrate. Alternatively the device is manufactured using the device layer of a SOI

10   wafer that is patterned and transferred to the MEMS wafer in place of the polysilicon structural layer. This could be advantageous as high temperature processing steps would not be required to control the stress in the polysilicon layer and enable conventional CMOS electronics on the substrate.

15   It is possible to post-process the present MOEMS optical modulator on a substrate containing CMOS using a low temperature technology, such as polysilicon-germanium micromachining (e.g. IMEC or UC Berkeley) or a metal-nitride process (e.g. QinetiQ). The latter would use a PECVD nitride film as the main optical/structural element with low resistance metal tracking as previously described. It is also possible to incorporate

20   the standard polysilicon process into a modified large geometry (2-3μm) CMOS or BiCMOS process flow with slightly degraded transistor characteristics.

One particular application of the MOEMS spatial optical modulator array of the present invention is as a reconfigurable mask within an adaptive coded aperture imaging

25   (ACAI) system. Referring to figure 5b, the reconfigurable mask comprising at least one of the present MOEMS spatial optical modulator arrays is used in front of a two-dimensional detector array and arranged to modulate the amplitude and / or phase of electromagnetic radiation incident thereon from a scene. The mask provides a plurality of individually addressable apertures or pin-holes.. Typically the pitch of apertures

30   within the mask is ~15 - 50μm. In practice, a plurality of optical modulators may be grouped together to act as a larger modulator having a greater effective aperture. For example, four individual optical modulators each having a 50μm^2 sub aperture may be grouped to form a single optical modulator having a 200μm^2 effective aperture.

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Alternative applications of a MOEMS spatial optical modulator of the present invention include, but are not limited to, in-use calibration of infrared detector arrays, electro-optical protection and scanning detector applications.

5   Calibration of infrared detector arrays is an important application of the present MOEMS spatial optical modulator since, due to variations in the manufacturing process, the output signal from an infrared detector varies considerably from detector to detector. This is true even in a two-dimensional array of detectors made at the same time. Individual elements on a two-dimensional array of infrared detectors are normally

10   accessed by bump bonding the array on to a silicon readout circuit which can act as a multiplexer. Variations in the properties of the silicon transistors add to the variation in the outputs and in general make the output vary non-linearly with input flux.

It is therefore essential to calibrate the output from each pixel in an array as a function

15   of flux. Due to the non-linear nature of the variation, it is necessary to do this calibration at a significant number of fluxes if high quality imaging is needed over a range of scene temperatures (such as viewing sky and ground).

The conventional solution is to use a thermo-electrically controlled calibration black-

20   body plate and measure the output as a function of the plate temperature. The disadvantage of this technique is that allowing for settling time at each temperature it can take up to seven minutes to complete this procedure. Ideally a source is required which can produce a stable range of fluxes rapidly. As well as reducing the time-to-operation, this will enable more frequent calibration cycles. This will help reduce drift in

25   the calibration settings due to effects such as variation in the array temperature. Furthermore, since silicon and polysilicon have the same temperature coefficient of expansion, heating and cooling does not add additional stresses in the spatial optical modulator which may otherwise adversely effect performance.

30   A fast calibration source may be produced by combining a conventional fixed temperature black-body plate and a reconfigurable adaptive coded aperture (ACA) mask comprising a MOEMS spatial optical modulator according to the present invention. As before, the ACA mask consists of an array of openings in a mask plate which can be opened or closed to vary the flux falling on the detector. Ideally, the ACA

mask would be cooled, however this may not be necessary if the switching goes from a transmissive to a reflective state.

A range of calibrated fluxes can be generated by varying the number of openings from
5   fully closed to fully open. As switching of the mask can be done relatively quickly, it should be possible to get multipoint calibrations in a short time. A possible configuration of a camera using this system is shown in figure 11. The infrared camera system 50 of figure 11 employs an ACA mask 52 arranged on a paddle and a thermo-electrically (TE) controlled black body plate 54 arranged on a paddle. During
10   calibration, the ACA mask 52 and the TE controlled plate are rotated by rotation means 56 into a position between the camera lens 58 and the two-dimensional infrared detector array. During calibration, the two-dimensional infrared detector array images the thermo-electrically (TE) controlled black body plate 54 rather than receiving infrared radiation from a scene outside the camera. For a conventional imaging system, the
15   mask is not at an imaged position and hence the illumination of the focal plane will be uniform – however this can be improved by spreading out the openings uniformly on the ACA mask.

In an adaptive coded aperture imaging (ACAI) system as described above, an ACA
20   mask is already included and hence the abovementioned calibration scheme can be implemented without additional cost. A particular application is in a lens-less adaptive coded aperture imaging (ACAI) system. In a lens-less ACAI imaging system, the flux falling on each detector is expected to be relatively uniform (due to averaging flux from all the openings) and good imaging will depend on accurate calibration over a relatively
25   small range of flux. A range of fluxes around this value could again be generated by opening different patterns on the mask. A more complex scheme may be implemented which can calibrate out variations in the transmission of the individual openings on the mask.

30   In view of the foregoing description it will be evident to a person skilled in the art that various modifications may be made within the scope of the invention.

The scope of the present disclosure includes any novel feature or combination of features disclosed therein either explicitly or implicitly or any generalisation thereof
35   irrespective of whether or not it relates to the claimed invention or mitigates any or all of

the problems addressed by the present invention. The applicant hereby gives notice that new claims may be formulated to such features during the prosecution of this application or of any such further application derived there from. In particular, with reference to the appended claims, features from dependent claims may be combined

5   with those of the independent claims and features from respective independent claims may be combined in any appropriate manner and not merely in the specific combinations enumerated in the claims.

Claims

1. A micro-opto-electro-mechanical systems (MOEMS) optical modulator having an optical resonator comprising an asymmetric Fabry-Perot etalon incorporating a mirror resiliently biased with respect to a substrate and moveable in relation thereto in response to a voltage applied there-between.

2. An optical modulator according to claim 1 adapted to modulate transmission of at least one of short wave infrared radiation (SWIR), medium wave infrared radiation (MWIR) and long wave infrared (LWIR).

3. An optical modulator according to claim 1 or 2 wherein the substrate is substantially transmissive to SWIR, MWIR and LWIR radiation.

4. An optical modulator according to claim 2 or 3 wherein the modulator is substantially transmissive to MWIR radiation in an optically open state and substantially non-transmissive to MWIR radiation in an optically closed state.

5. An optical modulator according to claim 4 having a maximum transmittance greater than 50% in an optically open state and a minimum transmittance of less than 5% in an optically closed state for MWIR radiation.

6. An optical modulator according to any of the preceding claims having a multilayer stack comprising the following plurality of contiguous layers; silicon moveable mirror layer, air gap, silicon layer, a first dielectric layer, and a silicon layer.

7. An optical modulator according to claim 6 wherein the first dielectric layer comprises one of silicon dioxide, silicon oxynitride, and silicon nitride.

8. An optical modulator according to claim 6 having a multilayer stack comprising the following plurality of contiguous layers; silicon moveable mirror layer, air gap, a second dielectric layer, silicon layer, a first dielectric layer, and a silicon layer.

9. A optical modulator according to claim 8 wherein the second dielectric layer comprises one of silicon dioxide, silicon oxynitride, and silicon nitride.

10. An optical modulator according to any of the preceding claims adapted to modulate reflection of visible radiation.

11. An optical modulator according to any of the preceding claims wherein the mirror is moveable within the asymmetric Fabry-Perot etalon between a substantially stable first position distal to the substrate and a substantially stable second position proximate the substrate.

12. An optical modulator according to claim 11 wherein the mirror is adapted to respond to applied voltage to move non-linearly between the first and second positions.

13. An optical modulator according to claim 11 or 12 wherein the mirror is adapted to move from the first position upon application of a force thereto having a magnitude which exceeds a first threshold and is adapted to move from the second position upon reduction of the magnitude of the applied force below a second threshold, the two thresholds being arranged to be substantially different.

14. An optical modulator according to claim 13 wherein the force is an electrostatic force having a magnitude substantially proportional to the square of the applied voltage.

15. An optical modulator according to claim 13 wherein the mirror has a positional response which exhibits hysteresis.

16. A spatial optical modulator comprising a two-dimensional array of optical modulators according to any of the preceding claims.

17. A spatial optical modulator according to claim 16 having a first layer of electrodes and second layer of electrodes, and wherein the optical modulators are arranged in an array with each modulator having an electrode in the first layer and an electrode in the second layer.

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18. A spatial optical modulator according to claim 17 having a plurality of row electrodes and a plurality of column electrodes and wherein the optical modulators are addressable individually using a passive matrix row-column addressing scheme.

19. A spatial optical modulator according to claims 17 or 18 wherein the optical resonator within each of the optical modulators comprises at least one of the first and second layer of electrodes.

20. A spatial optical modulator according to any of claims 17 – 19 wherein at least one of the first and second layer of electrodes is substantially transmissive to incident radiation.

21. A method of addressing a spatial optical modulator comprising a plurality of row electrodes and a plurality of column electrodes having a plurality of bistable MOEMS optical modulators arranged in an array with each optical modulator in the array disposed at an intersection between a row electrode and a column electrode, the method comprising the steps of:

    (i)   applying a column drive voltage to each column electrode,

    (ii) applying a row drive voltage to each row electrode,

whereby the optical modulator at each intersection is operable in response to the potential difference between the column drive voltage and the row drive voltage at said intersection.

22. A method of addressing a spatial optical modulator according to claim 21 so as to set an optical modulator to a latched position comprising the steps of:

    (i)   arranging the column drive voltage applied to all column electrodes to be equal to a hold voltage reference V_{ref},

    (ii) increasing the column drive voltage applied to the column electrode corresponding with the modulator to be set by a set voltage V_{set}, wherein $V_{ref} + V_{set}$ is less than a latch voltage V_{pi} required to latch the optical modulator,

(iii) arranging the row drive voltage applied to the row electrode corresponding with the modulator to be set to be equal to a row-set voltage $-V_{row\text{-}set}$, wherein the potential difference $V_{ref} + V_{set} + V_{row\text{-}set}$ is greater than the latch voltage V_{pi},

(iv) removing the row drive voltage from the row electrode corresponding with the modulator to be set, and

(v) reducing the column drive voltage applied to the column electrode corresponding with the modulator to be set by the set voltage V_{set}.

23. A method of addressing a spatial optical modulator according to claim 21 so as to reset an optical modulator from a latched position comprising the steps of:

(i) arranging the column drive voltage applied to all column electrodes to be equal to a hold voltage reference V_{ref} plus a set voltage V_{set}, wherein $V_{ref} + V_{set}$ is less than a latch voltage V_{pi} required to latch the optical modulator,

(ii) arranging the row drive voltage applied to the row electrode corresponding with the modulator to be reset to be equal to a row-reset voltage $+V_{reset}$, wherein the potential difference $V_{ref} - V_{reset}$ is less than a release voltage V_{po} required to release the optical modulator,

(iii) removing the row drive voltage from the row electrode corresponding with the modulator to be reset, and

(iv) reducing the column drive voltage applied to the column electrode corresponding with the modulator to be set by the reset voltage V_{reset}.

24. A method of addressing a spatial optical modulator according to claim 21 so as to set all the optical modulators within the array to a latched position comprising the steps of:

(i)   arranging the column drive voltage applied to all column electrodes to be equal
        to a hold voltage reference V_{ref} plus a set voltage V_{set}, wherein $V_{ref} + V_{set}$ is less
        than a latch voltage V_{pi} required to latch the optical modulator,

(ii)   arranging the row drive voltage applied to all row electrodes to be equal to a
        row-set voltage $-V_{row-set}$, wherein the potential difference $V_{ref} + V_{set} + V_{row-set}$ is
        greater than the latch voltage V_{pi},

(iii)   removing the row drive voltage from the row electrode corresponding with the
        modulator to be set, and

(iv)   reducing the column drive voltage applied to the column electrode
        corresponding with the modulator to be set by the set voltage V_{set}.

25. A method of addressing a spatial optical modulator according to claim 21 so as to
reset all optical modulators within the array from a latched position comprising the step
of:

(i)   arranging the column drive voltage applied to all column electrodes to be
        substantially zero.

26. An adaptive coded aperture imaging (ACAI) system comprising an aperture mask
having at least one spatial optical modulator according to any of claims 16 – 20
arranged so as to modulate electromagnetic radiation incident on a detector array.

27. A spatial optical modulator according to any of claims 16 – 20 wherein at least one
of the optical modulators therein is apodized.

28. A spatial optical modulator according to claim 27 wherein the at least one apodized
optical modulator includes a profiled mirror.

Fig.1a.

Fig.1b.

Fig.2.

Fig.3a.

Fig.3b.

10
24
28
30
13

26

Fig.4a.

Transmittance (%) vs Wavelength (μm)

Fig.4b.

Transmittance (%) vs Wavelength (μm)

Fig.4c.

Transmittance (%) vs Angle (deg)

Fig.5a.

Transmittance (%) vs Wavelength (μm)

Fig.5b.

CMOS array   Coded aperture array

imagery data

FPGA /
Modular ASIC /
ASIC

To machine

To display(s)

2D/3D scene

Adaptive control
(steering, power conservation,
foveation, windowing,
3D mode etc.)
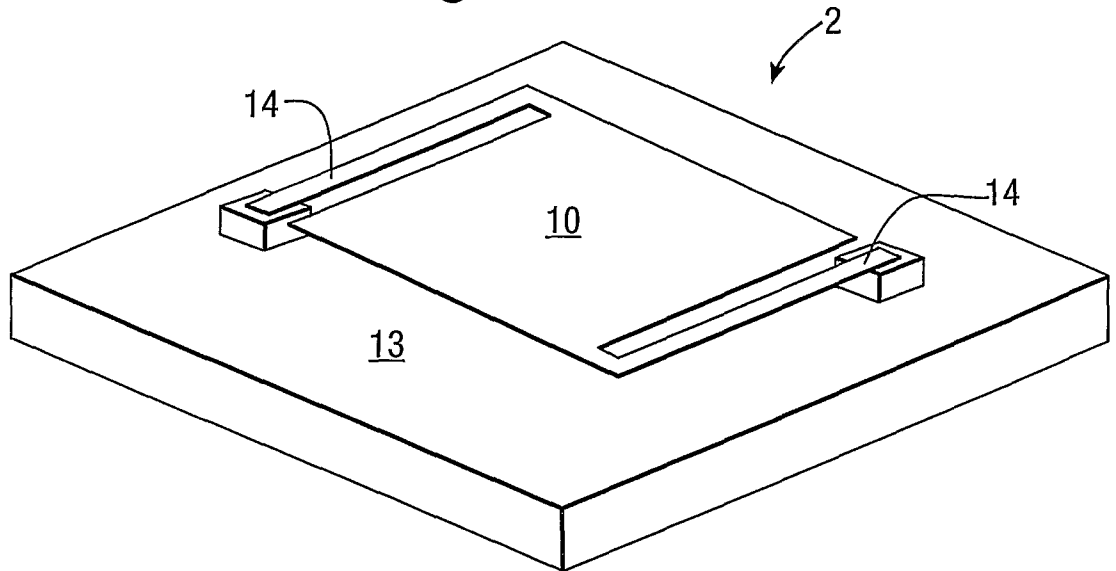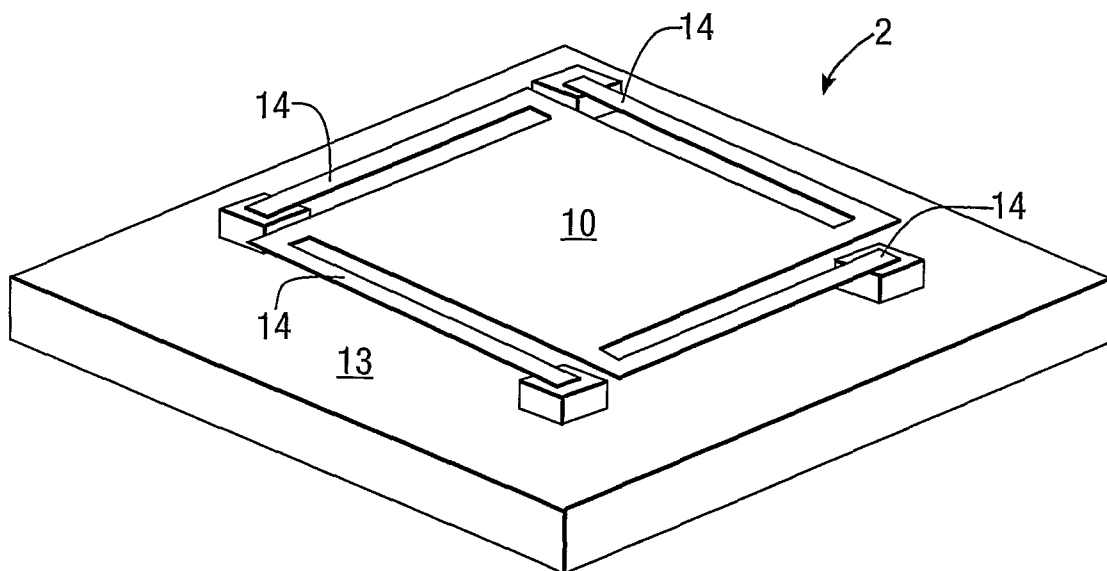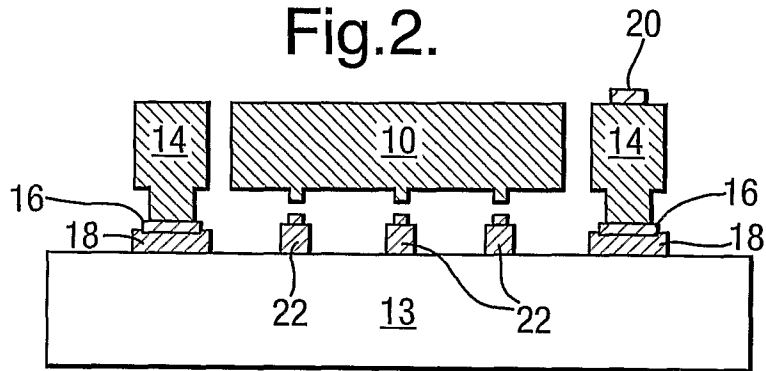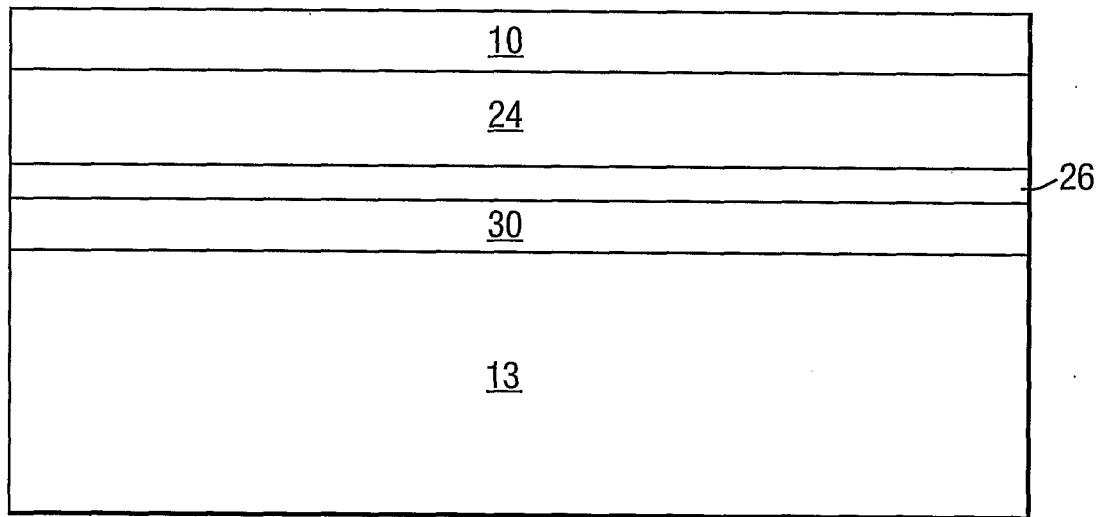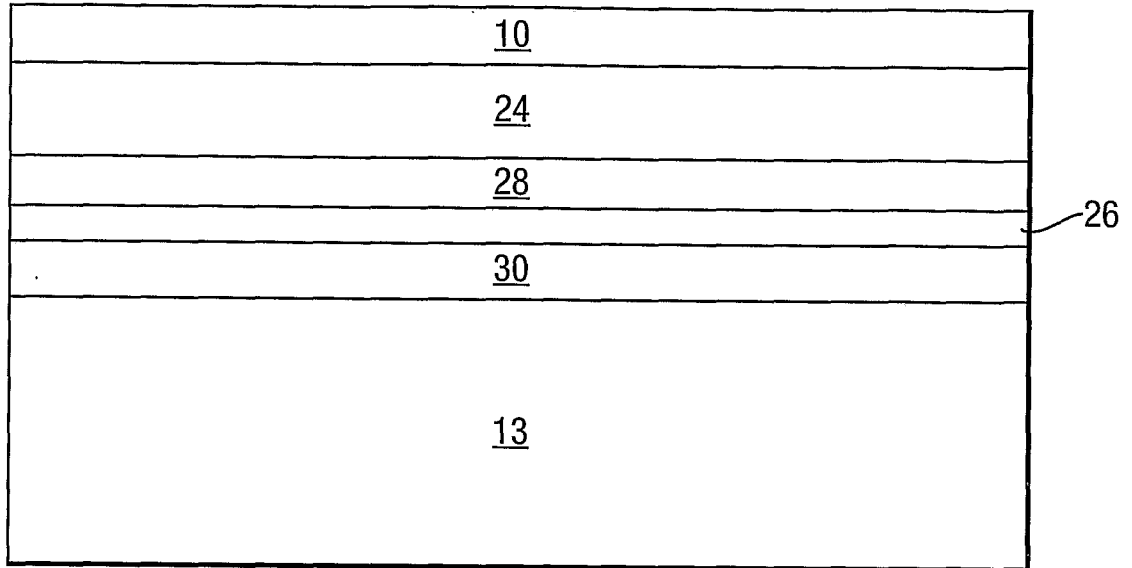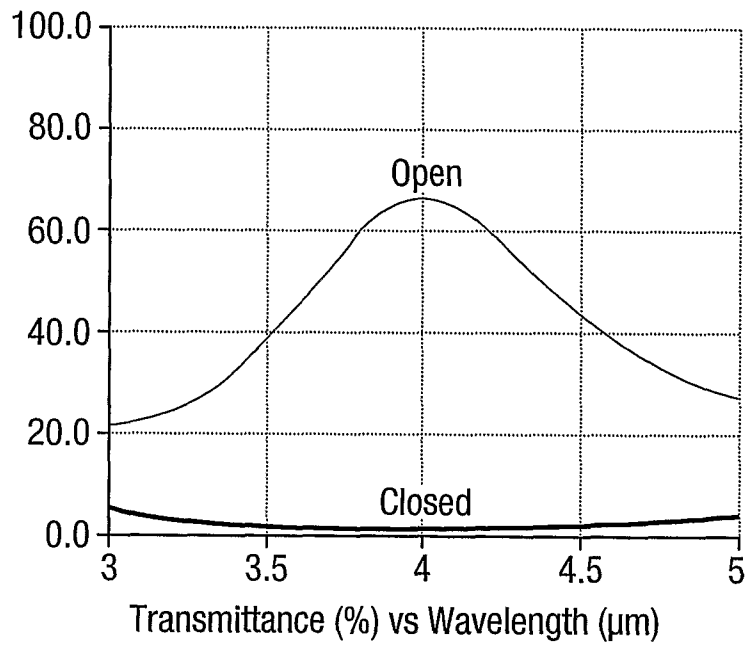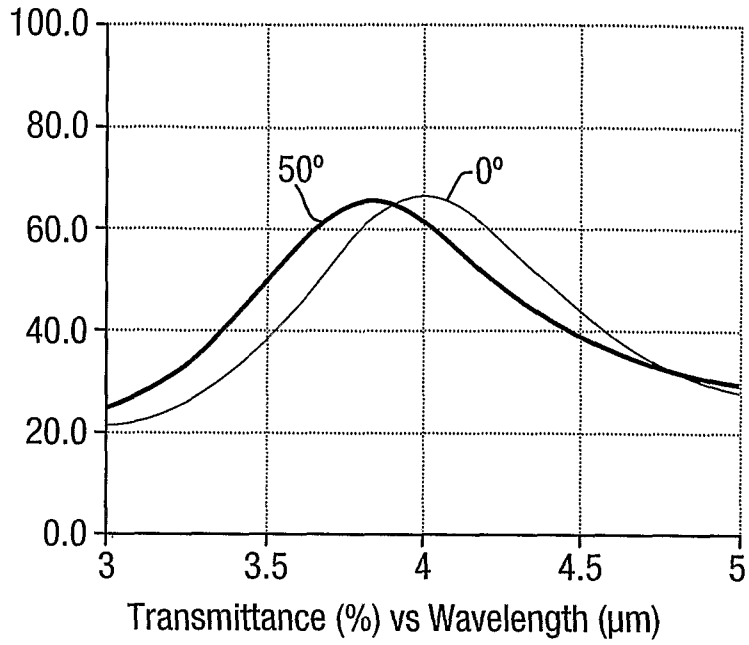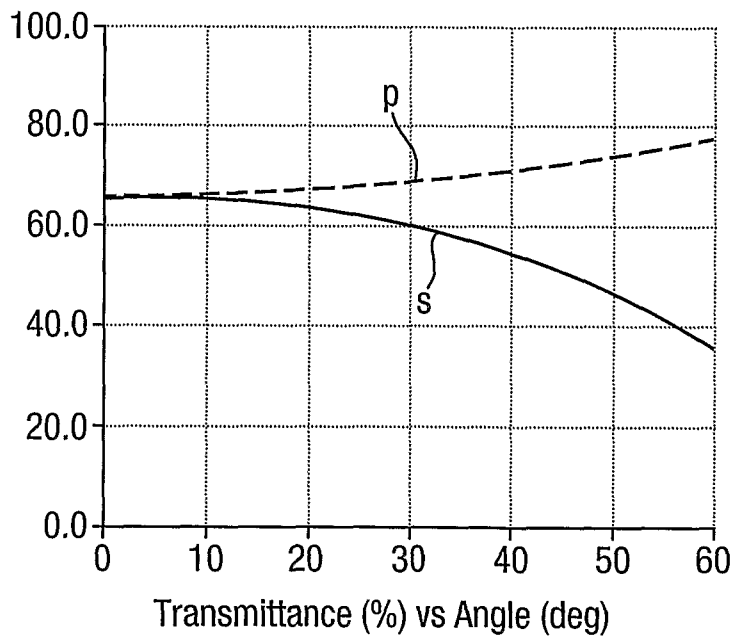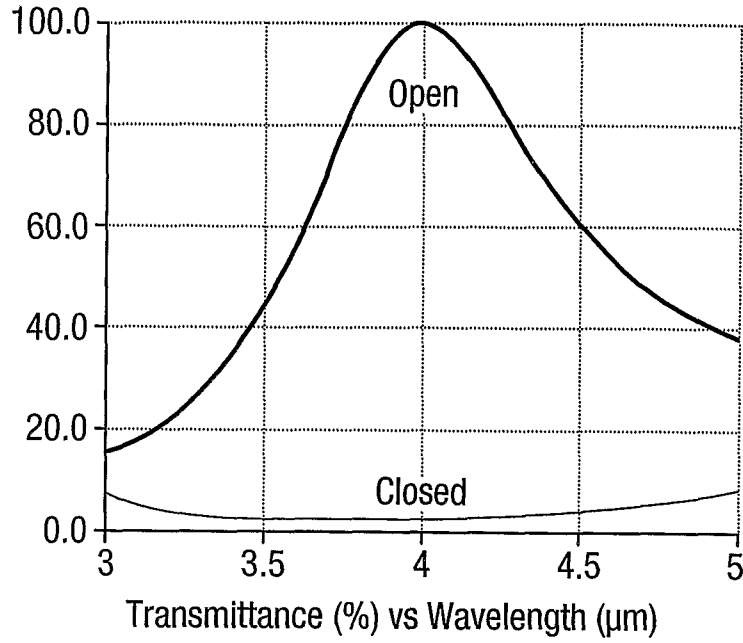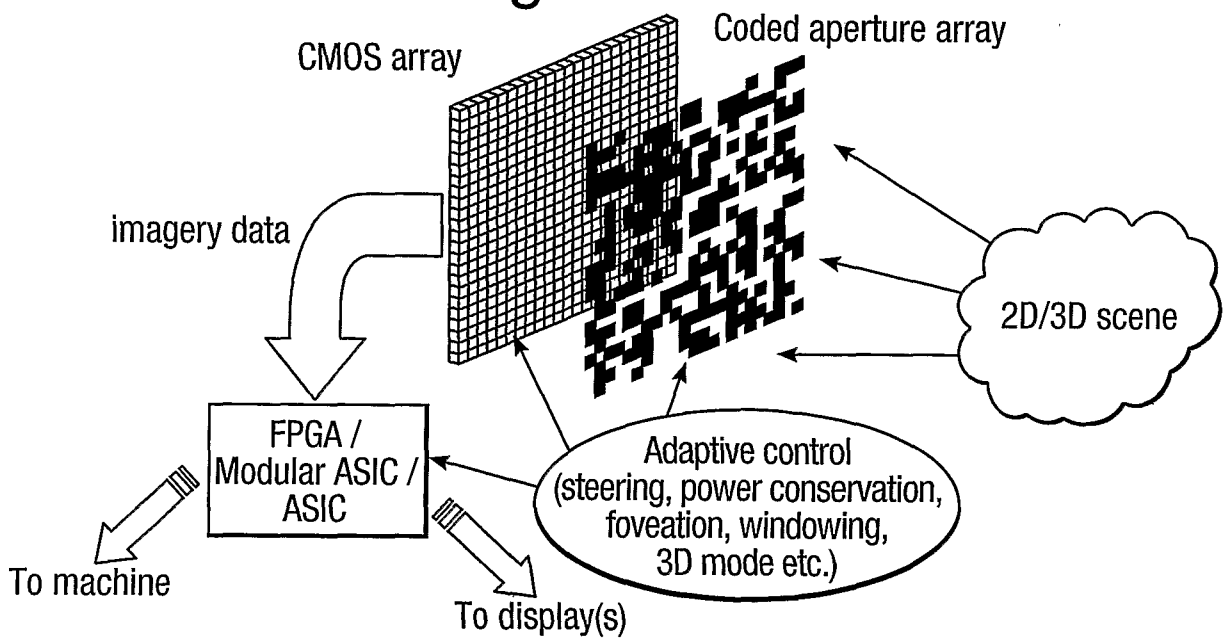
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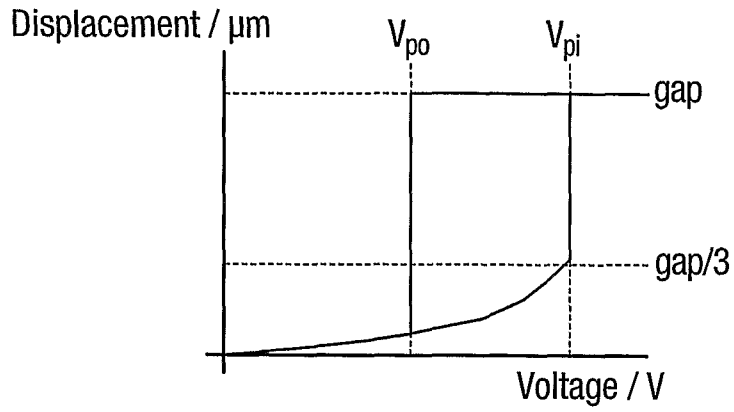
Fig.7a.
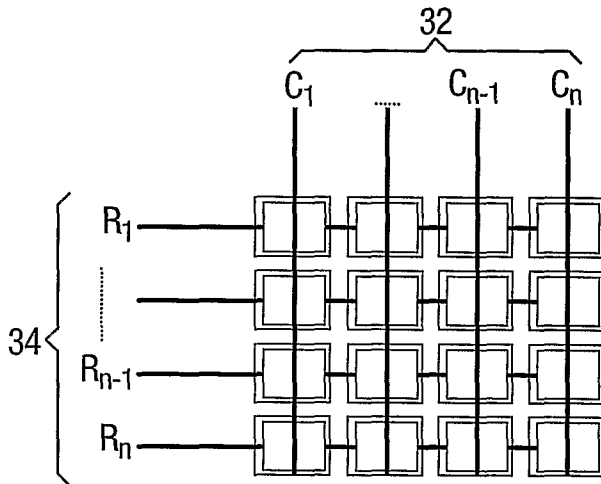
Fig.7b.
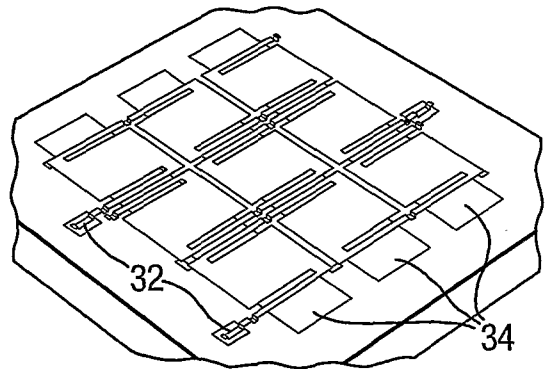
Fig.7c.
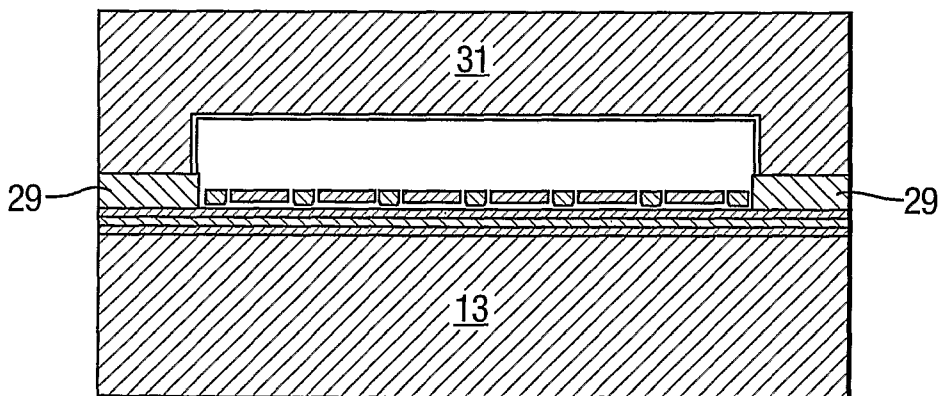
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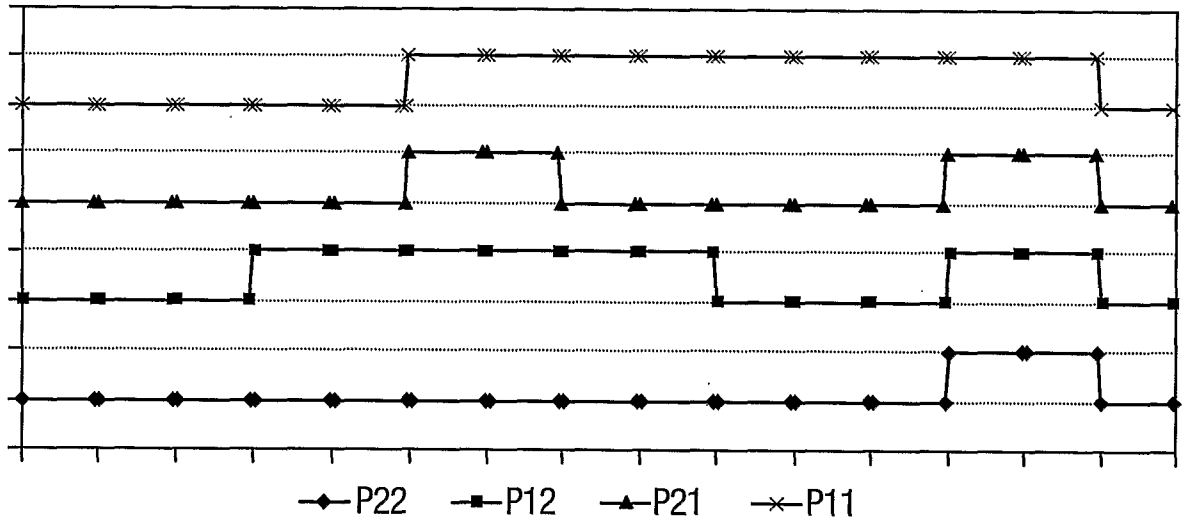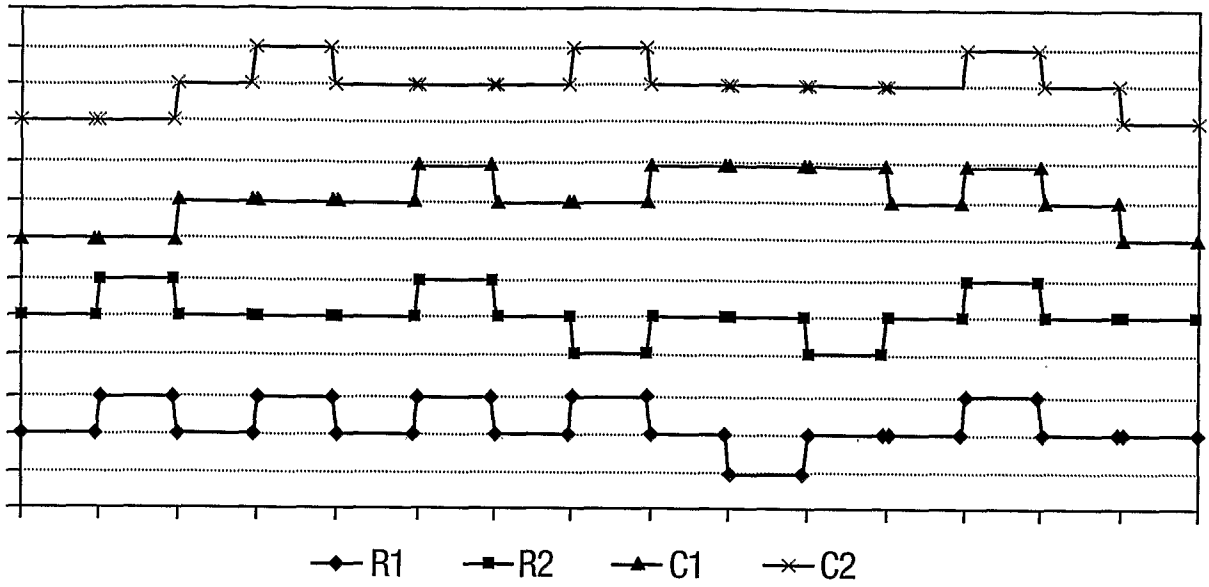
Fig.9a.
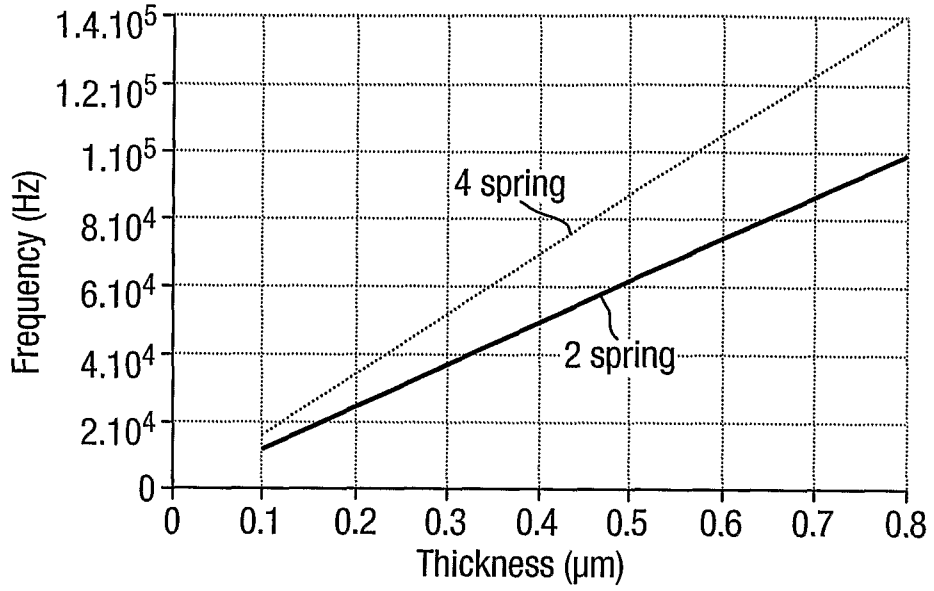
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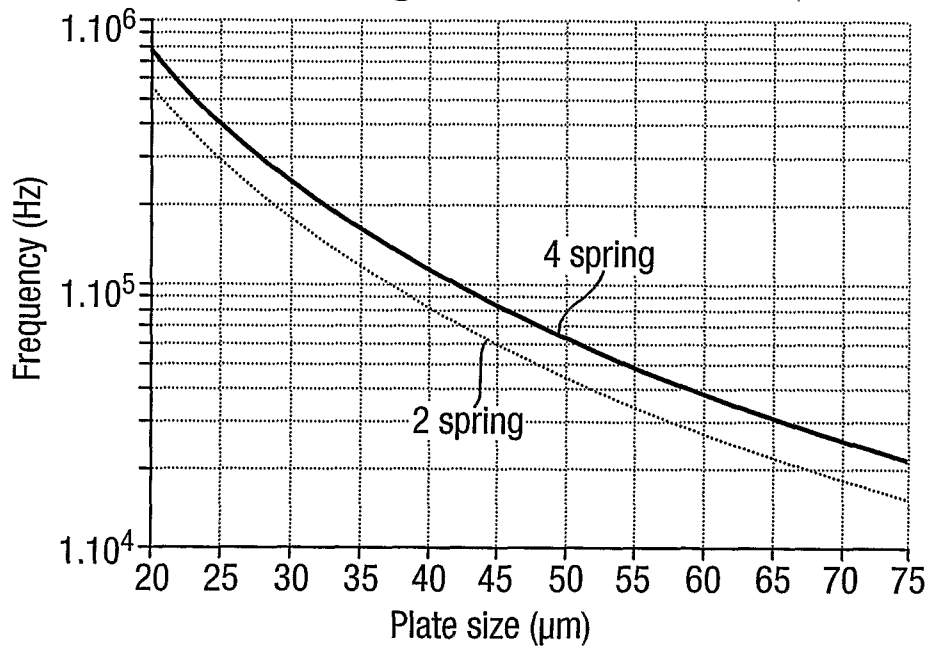
Fig.9c.
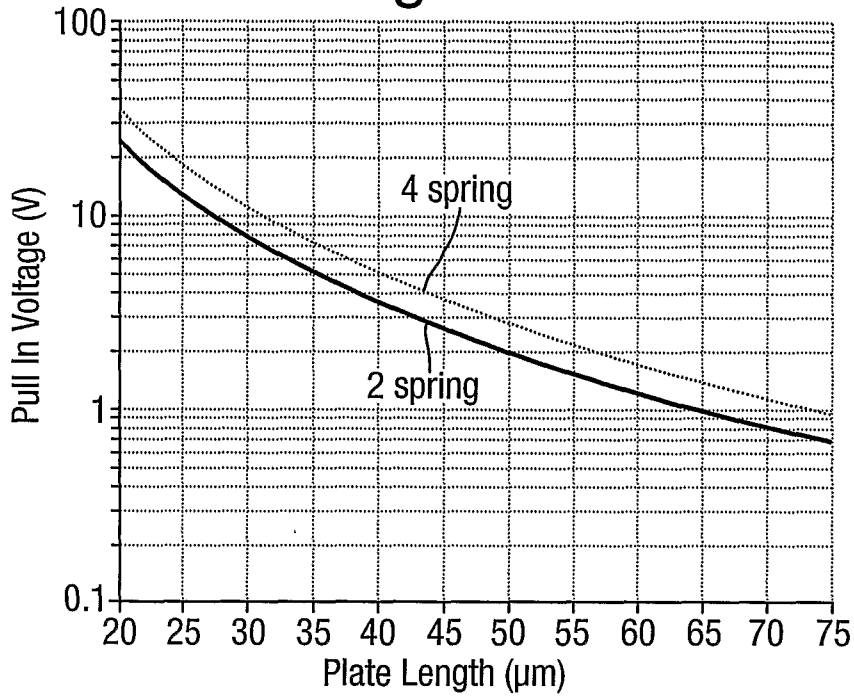
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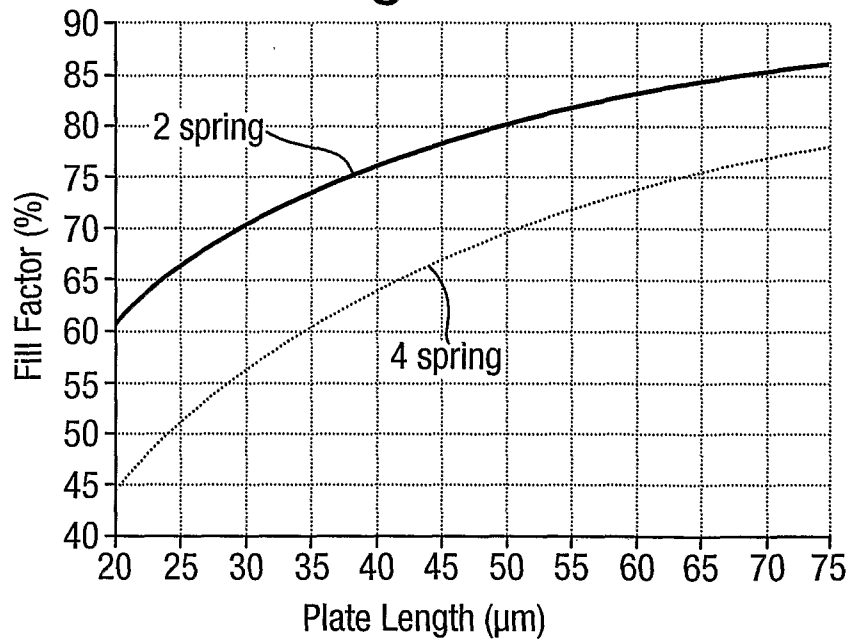
Fig.10.
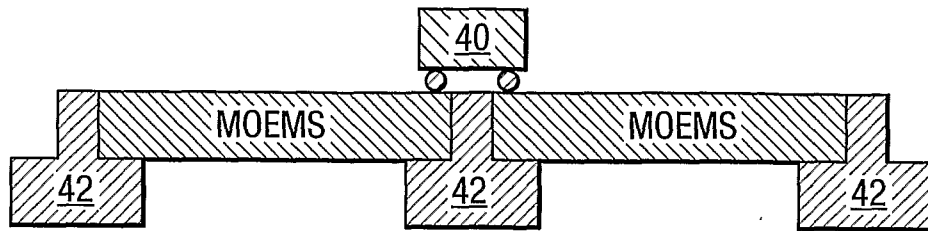
Fig.11.
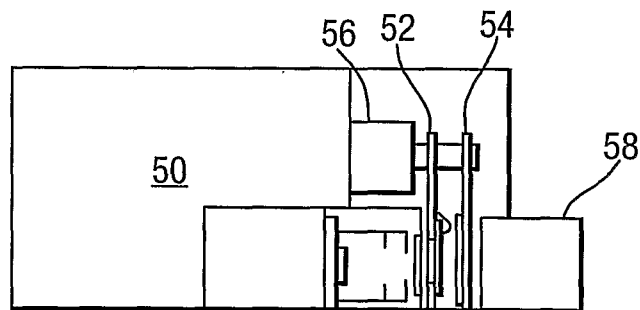
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02B5/28   G02B26/00

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

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GOOSSEN K W ET AL: "SILICON MODULATOR BASED ON MECHANICALLY-ACTIVE ANTI-REFLECTION LAYER WITH 1 MBIT/SEC CAPABILITY FOR FIBER-IN-THE-LOOP APPLICATIONS" IEEE PHOTONICS TECHNOLOGY LETTERS, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 6, no. 9, 1 September 1994 (1994-09-01), pages 1119-1121, XP000468079 ISSN: 1041-1135 cited in the application the whole document	1-5,10, 11,13-15
A	US 5 825 528 A (GOOSSEN KEITH WAYNE [US]) 20 October 1998 (1998-10-20) column 3, line 54 - column 4, line 16	1

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| X | Further documents are listed in the continuation of Box C. | | X | 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 document 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	Date of mailing of the international search report
23 April 2007	06/07/2007

| Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016 | Authorized officer Mollenhauer, Ralf |

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 500 761 A (GOOSSEN KEITH W [US] ET AL) 19 March 1996 (1996-03-19) column 4, line 27 - column 5, line 5	1
A	US 5 636 052 A (ARNEY SUSANNE C [US] ET AL) 3 June 1997 (1997-06-03) cited in the application column 4, line 26 - column 5, line 30	1
A	WO 02/44788 A (QINETIQ LTD [GB]; LEWIS KEITH LODER [GB]; SMITH GILBERT WILLIAM [GB];) 6 June 2002 (2002-06-06) abstract	1

INTERNATIONAL SEARCH REPORT

Box 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.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box 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:

    see additional sheet

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 fee, this Authority did not invite payment of any additional fee.

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.:

    see annex

Remark on Protest   ☐ The additional search fees were accompanied by the applicant's protest.

                              ☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (January 2004)

INTERNATIONAL SEARCH REPORT

FURTHER INFORMATION CONTINUED FROM   PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-15

    MOEMS optical modulator having a multilayer stack comprising a predetermined sequence of contiguous layers

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2. claims: 16-20,27,28

    A spatial optical modulator comprising a two-dimensional array of optical modulators

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3. claims: 21-25

    Method of addressing a spatial optical modulator comprising a plurality of row electrodes and a plurality of column electrodes

    ---

4. claim: 26

    Adapted coded aperture imaging system

FURTHER INFORMATION CONTINUED FROM   PCT/ISA/ 210

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 5825528	A	20-10-1998	NONE		
US 5500761	A	19-03-1996	CA	2137063 A1	28-07-1995
			EP	0667548 A1	16-08-1995
			US	5654819 A	05-08-1997
			US	5589974 A	31-12-1996
US 5636052	A	03-06-1997	EP	0695959 A1	07-02-1996
			JP	8211847 A	20-08-1996
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			DE	60110455 D1	02-06-2005
			DE	60110455 T2	23-02-2006
			EP	1337888 A1	27-08-2003
			JP	2004514945 T	20-05-2004
			TW	556001 B	01-10-2003
			US	2004057144 A1	25-03-2004