

OPTO-MECHANICAL OPTICAL PATH RETARDATION MULTIPLIER FOR OPTICAL MEMS APPLICATIONS

BACKGROUND OF THE INVENTION

Technical Field of the Invention

5 The present invention relates in general to optical MEMS, and in particular, to optical path retardation multiplier devices using MEMS technology.

Description of Related Art

10 Micro Electro-Mechanical Systems (MEMS) refers to the integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate through microfabrication technology. For example, the microelectronics are typically fabricated using an integrated circuit (IC) process, while the micromechanical components are fabricated using compatible micromachining processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical components. MEMS devices are attractive candidates for use in spectroscopy, profilometry, environmental sensing, 15 refractive index measurements (or material recognition), as well as several other sensor applications, due to their low cost, batch processing ability and compatibility with standard microelectronics. In addition, the small size of MEMS devices enables the integration of equipment incorporating MEMS devices into mobile and hand held devices.

20 Recently, MEMS devices have been utilized in a number of optical applications that require large optical displacement by transforming a mechanical distance into an equivalent much larger optical distance. For example, MEMS technology can provide adequate resolution in many Fourier Transform spectrometers and Michelson interferometers. As another example, MEMS devices can produce sufficient scanning depths in various Optical Coherence Tomography (OCT) applications. In addition, MEMS devices can also be used to achieve 25 dynamic optical focusing through the manipulation of the optical beam working distance by a moving MEMS mirror.

30 In the area of spectrometry in particular, silicon-MEMS Fourier-transform spectrometers have been introduced that achieve a resolution of about 50 nm around 1500 nm in the NIR (220 cm^{-1}). In addition, MEMS-based Fourier transform-IR spectrometers for use in the 2–13.5 μm spectral range have also been proposed. The resolution targeted for such an IR spectrometer is 10 cm^{-1} , which requires a mirror motion on the order of 0.5 mm. However, even higher

resolutions are needed in future MEMS based Fourier transform spectrometers. In order to achieve these higher resolutions, the optical path difference or optical path retardation must be increased. Unfortunately, such an increase is not compatible with the small mechanical displacements in existing compact size MEMS devices.

5 Therefore, what is needed is an optical MEMS device that allows obtaining a much longer optical path difference for a given mechanical displacement.

SUMMARY OF THE INVENTION

Embodiments of the present invention provide an optical Micro Electro-Mechanical System (MEMS) device providing an optical path retardation multiplier. The MEMS device
10 includes a moveable corner cube reflector, a fixed mirror and a MEMS actuator. The moveable corner cube reflector is optically coupled to receive an incident beam on one edge of the corner cube reflector and operable to reflect the incident beam from another edge of the corner cube reflector. The fixed mirror is optically coupled to receive the incident beam reflected from the moveable corner cube reflector and operable to reflect the incident beam back towards the
15 moveable corner cube reflector as a reflected beam along a reverse path of the incident beam. The MEMS actuator is coupled to the moveable corner cube reflector to cause a displacement of the moveable corner cube reflector perpendicular to a plane of the fixed mirror to extend an optical path length of the reflected beam.

In an exemplary embodiment, the optical path difference between a first position of the
20 moveable corner cube reflector and a second position of the moveable corner cube reflector is four times a displacement of the moveable corner cube reflector between the first position and the second position.

In a further embodiment, the moveable corner cube reflector includes a moveable array of corner cube reflectors and the fixed mirror includes an array of fixed mirrors offset from the
25 moveable array of corner cube reflectors such that the reflected beam is parallel to the incident beam. In addition, each fixed mirror in the array of fixed mirrors can be a corner cube reflector coupled to receive the incident beam on one edge thereof from a first corresponding corner cube reflector in the moveable array of corner cube reflectors and to reflect the reflected beam on another edge thereof towards a second corresponding corner cube reflector in the moveable array
30 of corner cube reflectors. Furthermore, a flat mirror can be coupled to an end of the moveable array of corner cube reflectors and optically coupled to receive the incident beam from a last one of the corner cube reflectors in the array of fixed mirrors and to reflect the reflected beam back

towards the last one of the corner cube reflectors in the array of fixed mirrors to direct the reflected beam along the reverse path.

In this embodiment, an optical path difference between a first position of the moveable array of corner cube reflectors and a second position of the moveable array corner cube reflector is equal to a displacement of the moveable array of corner cube reflectors between the first position and the second position multiplied by a sum of four times a number of corner cube reflectors in the moveable array of corner cube reflectors plus two.

In still a further another embodiment, the optical MEMS device further includes a first small corner cube mirror coupled between the moveable array of corner cube reflectors and the flat mirror and a second small corner cube mirror coupled to the array of fixed mirrors on an end thereof that is opposite to the end of the moveable array of corner cube reflectors to which the flat mirror is coupled. The dimensions of each of the first and second small corner cube mirrors are smaller than the dimensions of each corner cube reflector within the moveable and fixed arrays of corner cube reflectors. In this embodiment, an optical path difference between a first position of the moveable array of corner cube reflectors and a second position of the moveable array corner cube reflector is increased by a factor equal to a number of circulations the incident beam travels through the moveable array of corner cube reflectors and the array of fixed mirrors, in which the number of circulations is based on the dimensions of the first and second small corner cube mirrors and a spot size of the incident beam.

Embodiments of the present invention further provide a Michelson interferometer fabricated as a Micro Electro-Mechanical System (MEMS) structure providing an optical path retardation multiplier. The interferometer includes first and second arrays of fixed mirrors, a moveable array of corner cube reflectors moveable in an area between the first and second arrays of fixed mirrors in a direction orthogonal to a plane of the first and second arrays of fixed mirrors, a detector, a beam splitter and an auxiliary mirror.

The beam splitter is optically coupled to receive an incident beam and to split the incident beam into a first incident beam and a second incident beam. The first incident beam is directed towards an initial corner cube reflector of the moveable array of corner cube reflectors to be reflected between a first side of the moveable array of corner cube reflectors and the first array of fixed mirrors along a first forward and reverse path and output as a first reflected beam from the initial corner cube reflector of the moveable array of corner cube reflectors back towards the beam splitter.

The auxiliary mirror is optically coupled to receive the second incident beam and to reflect the second incident beam towards an initial fixed mirror in the second array of fixed mirrors to be reflected between the second fixed array mirrors and a second side of the moveable array of corner cube reflectors along a second forward and reverse path and output as a second reflected beam from the initial fixed mirror of the second array of fixed mirrors. The auxiliary mirror is further optically coupled to receive the second reflected beam and reflect the second reflected beam towards the beam splitter. The beam splitter is further optically coupled to combine the first reflected beam and the second reflected beam to produce a combined beam that is directed towards the detector.

In this embodiment, an optical path difference between a first position of the moveable array of corner cube reflectors and a second position of the moveable array corner cube reflector is equal to a displacement of the moveable array of corner cube reflectors between the first position and the second position multiplied by twice a sum of four times a number of corner cube reflectors in the moveable array of corner cube reflectors plus two.

Embodiments of the present invention further provide a method for fabricating an optical Micro Electro-Mechanical System (MEMS) device providing an optical path retardation multiplier. The method includes providing a silicon on insulator (SOI) wafer including a top surface and a bottom surface and photolithographically defining within the top surface of the SOI wafer a moveable corner cube reflector optically coupled to receive an incident beam on one edge of the corner cube reflector and operable to reflect the incident beam from another edge of the corner cube reflector, a fixed mirror optically coupled to receive the incident beam from the moveable corner cube reflector and operable to reflect the incident beam back towards the moveable corner cube reflector as a reflected beam along a reverse path of the incident beam and a MEMS actuator coupled to the moveable corner cube reflector to cause a displacement of the moveable corner cube reflector perpendicular to a plane of the fixed mirror to extend an optical path length of the reflected beam. The method further includes etching between the top surface of the SOI wafer and the bottom surface of the SOI wafer using a deep reactive ion etching process to form the fixed mirror and the MEMS actuator and etching between the top surface of the SOI wafer and the bottom surface of the SOI wafer using an anisotropic alkaline wet etching process to form the moveable corner cube reflector.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention may be obtained by reference to the following detailed description when taken in conjunction with the accompanying drawings wherein:

5 FIGURE 1A is a diagram illustrating an exemplary optical MEMS device providing optical path retardation multiplication, in accordance with embodiments of the present invention;

FIGURE 1B is a diagram illustrating exemplary motion of the optical MEMS device, in accordance with embodiments of the present invention;

10 FIGURE 1C is a perspective view of an exemplary optical MEMS device, in accordance with embodiments of the present invention;

FIGURE 2 is a diagram illustrating another exemplary optical MEMS device providing optical path retardation multiplication, in accordance with embodiments of the present invention;

FIGURE 3 is a plan view of an exemplary optical MEMS device, in accordance with embodiments of the present invention;

15 FIGURE 4 is a diagram illustrating yet another exemplary optical MEMS device providing optical path retardation multiplication, in accordance with embodiments of the present invention;

FIGURE 5 is a diagram illustrating an exemplary Michelson interferometer implementing a MEMS optical path retardation multiplier, in accordance with embodiments of the present invention;

20 FIGURES 6A and 6B illustrate still another exemplary optical MEMS device providing optical path retardation multiplication, in accordance with embodiments of the present invention;

25 FIGURES 7A-7J illustrate exemplary fabrication process steps for a method of fabricating an optical MEMS device in accordance with embodiments of the present invention;

FIGURES 8A-8E illustrate exemplary fabrication process steps for another method of fabricating an optical MEMS device in accordance with embodiments of the present invention; and

30 FIGURES 9A-9F illustrate exemplary fabrication process steps for fabricating a shadow mask for use in fabricating an optical MEMS device in accordance with embodiments of the present invention.

DETAILED DESCRIPTION OF THE DRAWINGS

An optical MEMS device in accordance with embodiments of the present invention realizes a large optical path retardation (optical path difference) for only a small mechanical displacement of a MEMS moving mirror. The MEMS moving mirror includes a corner cube reflector arranged in a manner to realize the extended optical path difference required. The optical MEMS device can be used to extend the range of resolution achieved by MEMS FTIR spectrometers an order of magnitude higher than existing solutions, enabling them to compete with high resolution traditional lab instrument spectrometers. The optical MEMS device can be also used to increase the scanning depth measurement range in Optical Coherence Tomography (OCT) applications. In addition, the optical MEMS device may also be used other MEMS applications that require large optical path distances achieved by small physical displacements.

Turning now to FIGURE 1A, there is illustrated an exemplary optical Micro Electro-Mechanical System (MEMS) device in accordance with embodiments of the present invention. The optical MEMS device 10 can be fabricated using, for example, conventional MEMS technology with one lithography step and classical metallization, as described in more detail below in connection with FIGURES 7-9.

The optical MEMS device 10 includes a moveable reflector 20, a fixed mirror 30, a light source 40 and a MEMS actuator 50. The light source 40 may be, for example, a laser source, a collimated LED, an optical fiber, or any other type of optical source. The light source 40 may produce visible, Infra Red (IR), Ultra Violet (UV), X-ray or Microwave radiation. The MEMS actuator 50 may be an electrostatic comb-drive actuator or other type of MEMS actuator. The moveable reflector 20 shown in FIGURE 1A is a corner cube reflector that includes two mirrors placed at right angles to one another such that a beam incident from any direction in the plane perpendicular to both mirrors is reflected through 180 degrees. However, in other embodiments, the moveable reflector 20 may include two mirrors placed at different angles with respect to one another, as described in more detail below in connection with FIGURES 6A and 6B.

The moveable reflector 20 is optically coupled to receive an incident beam 70 from the light source 40 and to reflect the incident beam 70 through 180 degrees. More specifically, the moveable reflector 20 receives the incident beam 70 on one edge 22 of the corner cube reflector 20 and reflects the incident beam from another edge 24 of the corner cube reflector 20 towards the fixed mirror 30, which is shown in FIGURE 1 as a flat mirror oriented orthogonal to a direction of the incident beam 70. The fixed mirror 30 reflects the incident beam back to the moveable reflector 20 as a reflected beam 75 that propagates along a reverse path of the incident

beam 70. The MEMS actuator 50 causes a displacement of the moveable reflector 20 perpendicular to a plane of the fixed mirror 30 to extend an optical path length of the reflected beam 75.

For example, as shown in FIGURE 1B, as the corner cube reflector 20 is mechanically
5 displaced a distance x parallel to the direction of the incident beam 70, the optical path difference between the two light paths (i.e., when the corner cube reflector is in an initial position 60a and when the corner cube reflector is in another position 60b) is $4x$, where x is the mechanical displacement of the corner cube reflector 20. Thus, utilizing a single cube corner reflector 20 produces an optical path difference twice that of a conventional flat mirror normally used in
10 MEMS devices.

A perspective view of an exemplary optical MEMS device incorporating the optical path retardation multiplier is shown in FIGURE 1C. As can be seen in FIGURE 1C, the moveable reflector 20 and fixed mirror 30 are each fabricated on a substrate 80. The fixed mirror 30 overlies a buried oxide (BOX) layer 82 in the substrate 80, while an air gap 86 separates the
15 substrate 80 from the moveable reflector 20 to enable the moveable reflector 20 to slide above the surface of the substrate 80. A metallization layer 84 covers the substrate 80, the first and second edges 22 and 24 of the moveable corner cube reflector 20 and an opposing edge of the fixed mirror 30.

To compensate for any tilt or shear angles in the incident beam and to ensure that the
20 reflected beam travels back parallel to the incident beam independent of the angle of the reflector, the corner cube reflector 20 in FIGURE 1C can be seen to include three perpendicular edges: the two moving edges 22 and 24 and the metallized substrate 25 functioning as the third reflector edge. All three corner cube reflector edges 22, 24 and 25 are formed and metallized in one step, as described below in connection with FIGURES 7-9, but only the two moving edges
25 22 and 24 move together, while the substrate edge 25 remains fixed. As such, the arrayed corner cube reflector 20 can be positioned as shown, where incident light beams are parallel to the plane of the substrate 80, or the reflector 20 may be placed in a different manner to accommodate for the usage of the third edge 25 to compensate for shear and tilt.

In FIGURE 2, instead of using a single corner cube reflector as the moveable reflector
30 20, an array of corner cube reflectors 100 is provided. In addition, instead of using a single flat mirror as the fixed mirror 30, an array of fixed mirrors 110 is provided. The array of fixed mirrors 110 is offset from the moveable array of corner cube reflectors 100, such that the reflected beam 75 is parallel to the incident beam 70. More specifically, each fixed mirror in the

array of fixed mirrors 110 is also a corner cube reflector coupled to receive the incident/reflected beam on one edge thereof from a first corner cube reflector in the moveable array of corner cube reflectors 100 and to reflect the incident/reflected beam on another edge thereof towards a second corner cube reflector adjacent to the first corner cube reflector in the moveable array of corner cube reflectors 100. Each corner cube reflector in the moveable array of corner cube reflectors 100 introduces an additional $4x$ optical path difference.

In addition, a flat mirror 105 is coupled to an end of the moveable array of corner cube reflectors 100 and optically coupled to receive the incident beam 70 from a last one of the fixed mirrors in the array of fixed mirrors 110 and to reflect the reflected beam 75 back towards the last one of the fixed mirrors in the array of fixed mirrors 110 to direct the reflected beam along a reverse path of the incident beam 70. This adds an extra $2x$ to the optical path difference (OPD), or optical path retardation, due to reflection from the flat mirror 105. In general, the formula for the OPD when an array of N corner cube reflectors moves a mechanical displacement x is:

$$\text{OPD} = (4N+2)x. \quad (\text{Equation 1})$$

For example, if the travel distance (x) of the moveable array of corner cube reflectors 100 is approximately $100\text{ }\mu\text{m}$, and there are four (4) corner cube reflectors in the array 100, the OPD between the two beams (at the first position 60a and the second position 60b) is 1.8 mm , corresponding to an optical resolution of 5.55 cm^{-1} .

FIGURE 3 is a plan view of an exemplary optical MEMS device, in accordance with embodiments of the present invention. In FIGURE 3, the MEMS actuator 50 is an electrostatic comb-drive actuator coupled to the moveable reflector 20. The moveable reflector 20 includes an array of corner cube reflectors 100 and a fixed mirror 105 coupled to the end of the array of corner cube reflectors 100. The fixed mirror 30 includes an array of fixed mirrors 110 (also corner cube reflectors) offset from the moveable array 100 to enable an incident beam 70 to be reflected through the arrays 100 and 110 along a forward and reverse path and exit as a reflected beam 75 from the entrance of the arrays 100 and 110. The MEMS actuator 50 causes a displacement of the entire moveable array 100 in a direction away from the incident beam 70 (i.e., parallel to the incident beam and perpendicular to the plane of the fixed array 100), which results in an increase in the optical path length of the reflected beam 75. As such, motion of the MEMS actuator 50 multiplies the optical path retardation of the reflected beam 75 by several orders of magnitude.

Turning now to FIGURE 4, another exemplary optical MEMS device providing optical path retardation multiplication by an additional order of magnitude is shown. In FIGURE 4, two small corner cube mirrors 120 and 125 are added onto opposing ends of the moveable and fixed corner cube arrays 100 and 110. More specifically, the first small corner cube mirror 120 is coupled between the moveable array of corner cube reflectors 100 and the flat mirror 105, while the second small corner cube mirror 125 is coupled to the array of fixed mirrors 110 on an end thereof that is opposite to the end of the moveable array of corner cube reflectors 100 to which the flat mirror 105 is coupled. The dimensions (i.e., the length of each of the edges) of each of the first and second small corner cube mirrors 120 and 125 are smaller than respective dimensions of each corner cube reflector within the moveable array of corner cube reflectors 100 and the array of fixed mirrors 110.

The small corner cube reflectors 120 and 125 guide the incident beam to circulate inside the structure (i.e., between the moveable and fixed reflectors 100 and 110) until the incident beam hits the flat mirror 105, which produces the reflected beam that propagates back in the reverse path of the incident beam. As shown in FIGURE 4, the incident beam propagates through three circulations before it hits the flat mirror 105 and reflects back. The addition of the small corner cube reflectors 120 and 125 multiplies the optical path distance by a factor M, where M is the number of circulations the beam travels and M is determined by the dimensions of the two small corner cube reflectors 120 and 125 and the beam spot size.

FIGURE 5 is a diagram illustrating an exemplary Michelson interferometer 200 implementing a MEMS optical path retardation multiplier, in accordance with embodiments of the present invention. In FIGURE 5, the two mirrors of the interferometer are combined into one structure having two fixed mirrors 30a and 30b, which are both fixed corner cube arrays and one moveable reflector 20, which is a moveable corner cube array.

The interferometer 200 is designed such that the motion of the moving mirror 20 results in an increase of the optical path in one interferometer arm and a decrease of the optical path in the other interferometer arm of the same amount. For example, as the moveable reflector 20 moves away from fixed mirror 30a, the optical path length between them is increased, while the optical path length between the moveable reflector 20 and fixed mirror 30b is reduced. This arrangement doubles the optical path difference compared to that achieved by a single corner cube array. For example, the optical path difference (OPD) for the interferometer 200 shown in FIGURE 5 can be expressed as:

$$\text{OPD} = 2(4N+2)x, \quad (\text{Equation 2})$$

which means that for the same previous example of 4 corner cube reflectors and an actuator motion of only 100 μm , the interferometer 200 achieves an optical path difference of 3.6 mm, which is equivalent to a spectrometer resolution of 2.77 cm^{-1} .

Turning now to the details of the interferometer 200, the Michelson interferometer includes an optical source 210, a beam splitter 220, an auxiliary mirror 230, a detector 240, the moveable reflector 20 (moveable array of corner cube reflectors) and the two fixed mirrors 30a and 30b (arrays of fixed mirrors). In an exemplary operation, the beam splitter 220 is optically coupled to receive an incident beam 70 from the optical source 210 and to split the incident beam 70 into a first incident beam 70a and a second incident beam 70b. The first incident beam 70a is directed towards an initial corner cube reflector of the moveable array of corner cube reflectors 20 to be reflected between a first side 26 of the moveable array of corner cube reflectors 20 and the first array of fixed mirrors 30a along a first forward and reverse path and output as a first reflected beam 75a from the initial corner cube reflector of the moveable array of corner cube reflectors 20 towards the beam splitter 220.

The auxiliary mirror 230 is optically coupled to receive the second incident beam 70b and to reflect the second incident beam towards an initial fixed mirror in the second array of fixed mirrors 30b to be reflected between the second array of fixed mirrors 30b and a second side 28 of the moveable array of corner cube reflectors 20 along a second forward and reverse path and output as a second reflected beam 75b from the initial fixed mirror of the second array of fixed mirrors 30b. The auxiliary mirror 230 is further optically coupled to receive the second reflected beam 75b and reflect the second reflected beam towards the beam splitter 220. The beam splitter 220 operates to split the first reflected beam 75a and second reflected beam 75b and transmit a combined first and second reflected beam towards the detector 240.

Although FIGURE 5 is directed to a Michelson interferometer, it should be understood that in other embodiments, a similar structure can be provided to implement a Fourier Transform spectrometer or other type of optical device.

FIGURES 6A and 6B illustrate still another exemplary optical MEMS device providing optical path retardation multiplication, in accordance with embodiments of the present invention. In FIGURES 6A and 6B, the moving mirror 20 and fixed mirror 30 each include an array of reflectors 100 and 110, as in FIGURE 2. However, the reflectors within the arrays 100 and 110 are not corner cube reflectors. Rather, the reflectors each have a non-orthogonal angle between the two edges of the reflectors. As shown in FIGURE 6A, the angle is 109.47 degrees between the two edges of each reflector.

As can be seen in FIGURE 6B, the reflectors can be fabricated using, for example, anisotropic alkaline wet etching of the (110) device layer 300 of the SOI wafer, as described in more detail below in connection with FIGURES 8A-8E, which enables vertical anisotropic etching as well as smooth surfaces at the $\langle 111 \rangle$ planes 310 of the device layer. As a result of the wet etching, the angle of the reflectors is approximately 109.47° due to the angle between the $\langle 111 \rangle$ vertical planes 310.

Since the reflected beam is still reflected in a path parallel to the input beam 70, after two consecutive reflection cycles from the corner cube-like mirrors, the moving mirror 20 and fixed mirror 30 will still operate in the same manner. However, a slight modification of the formula for beam path retardation or optical path difference (OPD) is required to include the non-perpendicular path of the beam due to the $\langle 111 \rangle$ planes angle.

Turning now to FIGURES 7-9, there are illustrated exemplary fabrication processes for fabricating an optical MEMS device incorporating an optical path retardation multiplier, in accordance with embodiments of the present invention. FIGURES 7A-7J illustrate a first exemplary fabrication process. The first fabrication process involves the fabrication of an integrated device that includes the corner cube reflectors, fixed mirrors, beam splitters as well as the MEMS actuator and mechanical springs.

In Figure 7A, an aluminum sputtering step is performed over an SOI wafer (layers 400-420) to form an aluminum layer 430, which functions as a mask for a subsequent etching of the top silicon layer 420 of the SOI wafer using DRIE, as shown in Figure 7E. In Figure 7B, a photo-resist material 440 is spun over the aluminum layer. In Figure 7C, a lithography step is performed for realizing the MEMS device. One lithography step is sufficient for realizing the moving reflectors and fixed mirrors as well as the electrostatic actuator. The lithography pattern in the photo-resist material 440 is transferred to the aluminum mask 430 by plasma chlorine etching of the aluminum layer, as shown in Figure 7D. DRIE is then applied to the wafer until reaching the oxide etch stop layer 410 of the SOI, as shown in Figure 7E. Then, as shown in Figure 7F, the remaining aluminum mask 430 is removed using an Alu etch.

As shown in FIGURE 7I, moving structures such as the MEMS actuator and moveable reflectors are released by etching the buried SiO_2 layer 410 using HF, while fixed structures are not released due to the wider area of the SiO_2 beneath.

Turning now to Figure 7J, a shadow mask 470 is used for the selective metallization 460 of the micromirrors and reflecting surfaces, as well as metallizing the substrate beneath the vertical corner cube edges to perform as the third edge of the corner cube mirror and creating

connection pads. As shown in Figure 7J, the shadow mask 470 is placed over the SOI substrate 400-420 to selectively sputter Cr/Au 460 onto desired portions of the top silicon layer 420.

In embodiments in which the Bosch process is used for DRIE etching (shown in Figure 7E), rough mirror surfaces may result due to the periodic nature of the process. Thus, as shown in Figure 7G, growing a thin oxide layer 450 on the surfaces and then removing it by HF, as shown in Figure 7H, can be useful before structure release to ensure a smoother mirror surface. However, if a cryogenic DRIE process is used in Figure 7E, the process steps shown in Figures 7G and 7H would be unnecessary since a smoother surface is obtained directly after etching. In addition, the aluminum mask shown in Figure 7A may not be necessary, as the process tends to have better selectivity between a photo-resist material and silicon at cryogenic temperatures.

FIGURES 8A-8E illustrate exemplary fabrication process steps for another method of fabricating an optical MEMS device in accordance with embodiments of the present invention. FIGURE 8A illustrates the resulting structure after a lithography step realizing the fixed mirrors as well as the electrostatic actuator of the MEMS device and DRIE etching of the top silicon layer 420 until reaching the oxide etch stop layer 410 of the SOI wafer, as similarly described above in connection with FIGURES 7A-7F. In FIGURE 8B, a hard mask layer 480 is applied to the wafer (e.g. by oxidation) to define the corner cube reflectors during a subsequent alkaline wet etching (e.g., KOH etching) step, as shown in FIGURE 8C.

After the wet etching process shown in FIGURE 8C, the large angled moving and fixed reflectors shown in FIGURES 6A and 6B are formed. Thereafter, as shown in FIGURE 8D, moving structures, such as the actuator and moving reflectors are released by etching the buried SiO₂ layer 410 using HF, while fixed structures are not released due to the wider area of the SiO₂ beneath. In FIGURE 8E, a shadow mask 470 is used for the selective metallization 460 of the moving and fixed mirrors, as well as for metallizing the substrate beneath the vertical corner cube edges to perform as the third edge of the corner cube reflector and creating connection pads. Although this fabrication process involves two etching steps, as well as extra steps for protection and lithography, it ensures the smoothness and verticality of the corner cube-like mirrors, which minimizes optical losses due to the multiple reflections that the beam will undergo during its propagation in the structure.

An exemplary process for creating the shadow mask is shown in Figures 9A-9F. As described above in connection with Figure 7E and FIGURE 8D, the shadow mask is used for the selective metallization of the wafer to ensure an adequate metallization for the mirrors, while at the same time protecting some surfaces from metallization. As shown in Figure 9A, to create the

shadow mask, first a metallic layer 510 is formed over a silicon wafer 500 using, for example, aluminum sputtering. Then, in Figure 9B, a photo-resist material 520 and 530 is spun on both sides of the wafer 500. The top photo-resist material 520 is used for lithography, and the bottom photo-resist material 530 functions as an etch stop.

5 Subsequently, as shown in Figure 9C, lithography is carried out on the top layer 520, followed by chlorine plasma etching of the aluminum layer 510, as shown in Figure 9D. In Figure 9E, using DRIE, etching through the silicon wafer 500 is performed until reaching the photo-resist material 530 on the bottom of the wafer 500. Finally, as shown in Figure 9F, the photo-resist material 520 and 530 on the top and bottom of the wafer are removed to complete
10 the shadow mask.

As will be recognized by those skilled in the art, the innovative concepts described in the present application can be modified and varied over a wide range of applications. Accordingly, the scope of patents subject matter should not be limited to any of the specific exemplary teachings discussed, but is instead defined by the following claims.

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REPLACEMENT SHEETS

1. An optical Micro Electro-Mechanical System (MEMS) device providing an optical path retardation multiplier, comprising:

a substrate;

a corner cube reflector including a first edge, a second edge and a third edge, the substrate acting as the third edge, the first and second edges being separated from the substrate by an air gap to enable movement of the first and second edges while the third edge remains stationary, the corner cube reflector being optically coupled to receive an incident beam on the first edge and operable to reflect the incident beam from the second edge;

a fixed mirror formed on the substrate and optically coupled to receive the incident beam reflected from the corner cube reflector and operable to reflect the incident beam back towards the corner cube reflector as a reflected beam along a reverse path of the incident beam; and

a MEMS actuator formed on the substrate and coupled to the corner cube reflector to cause a displacement of the first and second edges of the corner cube reflector perpendicular to a plane of the fixed mirror to extend an optical path length of the reflected beam.

2. The MEMS device of Claim 1, wherein the fixed mirror is a flat mirror oriented orthogonal to a direction of the incident beam.

3. The MEMS device of Claim 1, wherein an optical path difference between a first position of the corner cube reflector and a second position of the corner cube reflector is four times a displacement of the corner cube reflector between the first position and the second position.

4. The MEMS device of Claim 1, wherein the corner cube reflector includes an array of corner cube reflectors and the fixed mirror includes an array of fixed mirrors offset from the array of corner cube reflectors such that the reflected beam is parallel to the incident beam.

5. The MEMS device of Claim 4, wherein an optical path difference between a first position of the array of corner cube reflectors and a second position of the array corner cube reflectors is equal to a displacement of the array of corner cube reflectors between the first position and the second position multiplied by a sum of four times a number of corner cube reflectors in the array of corner cube reflectors plus two.

6. The MEMS device of Claim 4, wherein each fixed mirror in the array of fixed mirrors is a corner cube reflector coupled to receive the incident beam on one edge thereof from a first corresponding corner cube reflector in the array of corner cube reflectors and to reflect the reflected beam on another edge thereof towards a second corresponding corner cube reflector in the array of corner cube reflectors.

7. The MEMS device of Claim 6, further comprising:

a flat mirror coupled to an end of the array of corner cube reflectors and optically coupled to receive the incident beam from a last one of the corner cube reflectors in the array of fixed mirrors and to reflect the reflected beam back towards the last one of the corner cube reflectors in the array of fixed mirrors to direct the reflected beam along the reverse path.

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REPLACEMENT SHEETS

8. The MEMS device of Claim 7, further comprising:

a first small corner cube mirror coupled between the array of corner cube reflectors and the flat mirror; and

a second small corner cube mirror coupled to the array of fixed mirrors on an end thereof that is opposite to the end of the array of corner cube reflectors to which the flat mirror is coupled;

wherein respective dimensions of each of the first and second small corner cube mirrors are smaller than respective dimensions of each corner cube reflector within the array of corner cube reflectors and each fixed mirror within the array of fixed mirrors.

9. The MEMS device of Claim 8, wherein:

an optical path difference between a first position of the array of corner cube reflectors and a second position of the array of corner cube reflectors is increased by a factor equal to a number of circulations the incident beam travels through the array of corner cube reflectors and the array of fixed mirrors;

the number of circulations is based on the dimensions of the first and second small corner cube mirrors and a spot size of the incident beam.

10. The MEMS device of Claim 4, wherein the MEMS device is a Fourier Transform spectrometer or Michelson interferometer and the array of fixed mirrors is a first array of fixed mirrors, and further comprising:

a second array of fixed mirrors;

a detector;

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REPLACEMENT SHEETS

a beam splitter optically coupled to receive the incident beam and to split the incident beam into a first incident beam and a second incident beam, the first incident beam being directed towards an initial corner cube reflector of the array of corner cube reflectors to be reflected between a first side of the array of corner cube reflectors and the first array of fixed mirrors along a first forward and reverse path and output as a first reflected beam from the initial corner cube reflector of the array of corner cube reflectors;

an auxiliary mirror optically coupled to receive the second incident beam and to reflect the second incident beam towards an initial fixed mirror in the second array of fixed mirrors to be reflected between the second array of fixed mirrors and a second side of the array of corner cube reflectors along a second forward and reverse path and output as a second reflected beam from the initial fixed mirror of the second array of fixed mirrors;

wherein the auxiliary mirror further optically coupled to receive the second reflected beam and reflect the second reflected beam towards the beam splitter;

wherein the beam splitter is further optically coupled to receive the first reflected beam and combine the first reflected beam and the second reflected beam to produce a combined beam that is directed towards the detector.

11. The MEMS device of Claim 10, wherein an optical path difference between a first position of the array of corner cube reflectors and a second position of the array of corner cube reflectors is equal to a displacement of the array of corner cube reflectors between the first position and the second position multiplied by twice a sum of four times a number of corner cube reflectors in the array of corner cube reflectors plus two.

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12. The MEMS device of Claim 4, wherein each corner cube reflector in the array of corner cube reflectors has an angle between 90 degrees and 120 degrees and each fixed mirror in the array of fixed mirrors has a corresponding angle.

13. The MEMS device of Claim 12, wherein the angle is approximately 110 degrees.

14. The MEMS device of Claim 12, wherein the array of fixed mirrors and the MEMS actuator are fabricated using a deep reactive ion etching process and the array of corner cube reflectors is fabricated using an anisotropic alkaline wet etching process.

15. The MEMS device of Claim 4, further comprising:
an optical source for directing the incident beam towards an initial corner cube reflector in the array of corner cube reflectors.

16. The MEMS device of Claim 1, wherein:
the first edge and the second edge are perpendicular to one another; and
the third edge is perpendicular to the first edge and the second edge.

17. The MEMS device of Claim 16, wherein the incident beam is not parallel to a plane of the substrate.

18. The MEMS device of Claim 1, wherein the incident beam is parallel to a plane of the substrate.

19. A Michelson interferometer fabricated as a Micro Electro-Mechanical System (MEMS) structure providing an optical path retardation multiplier, comprising:

first and second arrays of fixed mirrors;

an array of corner cube reflectors, each of the corner cube reflectors including a first edge, a second edge and a third edge, the substrate acting as the third edge, the first and second edges being separated from the substrate by an air gap to enable movement of the first and second edges while the third edge remains stationary in an area between the first and second arrays of fixed mirrors in a direction orthogonal to a plane of the first and second arrays of fixed mirrors, each of the corner cube reflectors being optically coupled to receive a beam on the first edge and operable to reflect the beam from the second edge;

a detector;

a beam splitter optically coupled to receive an incident beam and to split the incident beam into a first incident beam and a second incident beam, the first incident beam being directed towards an initial corner cube reflector of the array of corner cube reflectors to be reflected between a first side of the array of corner cube reflectors and the first array of fixed mirrors along a first forward and reverse path and output as a first reflected beam from the initial corner cube reflector of the array of corner cube reflectors;

an auxiliary mirror optically coupled to receive the second incident beam and to reflect the second incident beam towards an initial fixed mirror in the second array of fixed mirrors to be reflected between the second fixed array mirrors and a second side of the array of corner cube reflectors along a second forward and reverse path and output as a second reflected beam from the initial fixed mirror of the second array of fixed mirrors;

wherein the auxiliary mirror further optically coupled to receive the second reflected beam and reflect the second reflected beam towards the beam splitter;

wherein the beam splitter is further optically coupled to receive the first reflected beam and combine the first reflected beam and the second reflected beam to produce a combined beam that is directed towards the detector.

20. The Michelson interferometer of Claim 19, further comprising:

an optical source for directing the incident beam towards the beam splitter.

21. The Michelson interferometer of Claim 19, wherein an optical path difference between a first position of the array of corner cube reflectors and a second position of the array of corner cube reflectors is equal to a displacement of the array of corner cube reflectors between the first position and the second position multiplied by twice a sum of four times a number of corner cube reflectors in the array of corner cube reflectors plus two.

22. The Michelson interferometer of Claim 19, further comprising:

a MEMS actuator coupled to the array of corner cube reflectors to cause a displacement of the first and second edges of the array of corner cube reflectors.

23. A method for fabricating an optical Micro Electro-Mechanical System (MEMS) device providing an optical path retardation multiplier, comprising:

providing a silicon on insulator (SOI) wafer including a top surface and a bottom surface;

photolithographically defining within the top surface of the SOI wafer a corner cube reflector optically coupled to receive an incident beam on a first edge of the corner cube reflector and operable to reflect the incident beam from a second edge of the corner cube reflector, a fixed mirror optically coupled to receive the incident beam reflected from the corner cube reflector and operable to reflect the incident beam back towards the corner cube reflector as a reflected beam along a reverse path of the incident beam and a MEMS actuator coupled to the corner cube reflector to cause a displacement of the first and second edges of the corner cube reflector with respect to the SOI wafer perpendicular to a plane of the fixed mirror to extend an optical path length of the reflected beam;

etching between the top surface of the SOI wafer and the bottom surface of the SOI wafer using a deep reactive ion etching process to form the fixed mirror and the MEMS actuator; and

etching between the top surface of the SOI wafer and the bottom surface of the SOI wafer using an anisotropic alkaline wet etching process to form the corner cube reflector.