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BEAM-STEERING OPTICAL-SWITCHING APPARATUS

FIELD OF THE INVENTION

This invention relates to a beam-steering optical-switching apparatus, particularly to a free-space optical cross-connect switching apparatus with mechanical actuation, for example, with a piezoelectric or another suitable solid state material, or any micro-optical positioning or beam-steering device with actuation of this type.

BACKGROUND OF THE INVENTION

All-optical free-space cross-connect switches typically consist of a fabric of optical emitters that launch a collimated beam, and another fabric of optical receivers. The emitters can be selectively connected to the receivers by varying the direction of the collimated beams so as to impinge on the selected receiver.

All-optical free-space cross-connect switches have been reported that either redirect a collimated beam that is launched in a fixed direction, or control the direction of a collimated beam. Switches that redirect a collimated beam typically rely on an arrangement of micro-mirrors that can be tilted, typically by applying an electrostatic force. Conversely, switches that control the beam direction have optical emitters that rotate or tilt in response to an applied actuation signal or change, the position of an optical emitter, such as a fiber tip, relative to the optical axis of a collimating lens, which varies the angle of the beam. Both types of optical switches can advantageously employ Micro-Electro-Mechanical Systems (MEMS) technology, with actuation provided by mechanical, electromagnetic, piezoelectric, photoactive ceramic or polymer, thermal, chemically-active polymer, electrostrictive, shape-memory alloy or ceramic, hydraulic and/or magnetostrictive actuators and other types of actuators known in the art.

Micro-mirror devices are typically etched from a silicon (Si) wafer, with the mirror elements formed as hinged reflection-coated platelets which have a poorly defined rest position and tend to flex when actuated, causing the redirected beam to loose
collimation. The mirror devices are also essentially undamped which limits their response time.

Recently, optical emitters with a controlled beam pointing direction have been proposed that incorporate piezoelectric actuators. Piezoelectric actuators advantageously provide a fast response, produce large forces, have a high characteristic frequency for fast switching, and have a well-defined rest position. Additionally, they are low-cost and have low susceptibility to vibration. Movement of the piezoelectric actuator can be controlled by applying electrical charges to electrodes. For example, US patent 4,512,036 describes bending the free end of a fiber in two directions perpendicular to the longitudinal axis of the fiber, with the fiber tip moving relative to a stationary lens. Other devices propose using piezoelectric actuators to move a lens in front of a stationary fiber in a plane perpendicular to the longitudinal axis of the fiber. However, practical piezoelectric actuators tend to have a limited displacement range, which limits the attainable tilt angle of the optical beam.

It has been proposed to amplify the displacement or stroke produced by piezoelectric actuators to increase the beam tilt angle. For example, US patent 4,303,302 describes a simple lever arm with an optical fiber attached to the arm which is supported on its fixed end and mechanically coupled to a piezoelectric bimorph bending element near the fixed end of the lever arm. The free end of the lever arm with the end of the optical fiber could thereby move in a plane and be aligned with different optical fibers located on an arc. A different lever mechanism for increasing the tilt angle of a Gimbals-mounted fiber holder with a fiber/lens assembly emitting a collimated optical beam is proposed in PCT/GB01/00062. Such lever mechanisms, however, increase the mass to be moved by the piezoelectric transducer and hence disadvantageously reduce the characteristic frequency of the optical assembly. Reducing the frequency reduces the achievable the switching speed of the cross-connect switch and increases sensitivity to vibration.

The aforementioned piezoelectric actuation mechanisms with levers are unlikely to benefit from inexpensive and reproducible batch fabrication processes, such as
MEMS technology. With MEMS, mechanical elements, sensors, actuators, and electronics can be integrated on a common substrate using the micromachining technology derived from IC fabrication processes. Reliable high-performance products can be designed and optimized using computer automated design tools, such as AutoCAD and the like.

The size of MEMS devices can range from several micrometers to millimeters, and can be precisely controlled by lithographic and etching processes that are standard in the semiconductor industry. Such miniaturization is particularly attractive for accurate actuation as well as optical sensing and positioning. In particular, miniaturization reduces size and increases port density of an all-optical switch, and can be extended to other tunable and/or programmable optical components in optical networks.

It would therefore be desirable to provide a piezoelectrically actuated motion transformer for beam-steering and positioning in all-optical cross-connect switches that has a sufficiently large beam deflection angle for a high port count and fast switching speed and that can be manufactured reproducibly and inexpensively by conventional MEMS fabrication processes.

SUMMARY OF THE INVENTION

The present invention describes micromachined motion transformers as well as their integration and/or assembly, for use in the positioning of small optical elements for creating a variety of tunable optical components. Together with different types of small sized actuators, in particular piezoelectric actuators, the motion transformers allow dense packing into compact arrays of movable optical elements, which can in turn be used separately or together to implement higher-level optical functions, such as large port count all-optical switches for telecommunication networks.

According to one aspect of the invention, an optical positioning device is provided which includes an actuator for generating a mechanical movement, a moveable optical component, and a unitary assembly with a first connection to an actuator, a second connection to the optical component, and a third connection to a support
housing. The unitary assembly imparts motion to the optical element relative to the support housing, in response to motion of the actuator.

According to another aspect of the invention, an optical switch with an optical positioning device is provided, wherein the optical positioning device includes an actuator for generating a mechanical movement, a moveable optical component, and a unitary assembly. The unitary assembly has a first connection to an actuator, a second connection to the optical component, and a third connection to a support housing. The unitary assembly imparts motion to the optical element relative to the support housing, in response to motion of the actuator.

According to yet another aspect of the invention, an optical positioning device of a type that employs an actuator for moving an optical component is provided, wherein the optical positioning device includes a unitary assembly with a first connection to an actuator, a second connection to the optical component, and a third connection to a support housing. The unitary assembly imparts motion to the optical element relative to the support housing, in response to motion of the actuator.

According to still another aspect of the invention, a unitary assembly for use in an optical positioning device that employs an actuator for moving an optical component is provided, wherein the unitary assembly includes a first connection to an actuator, a second connection to the optical component, and a third connection to a support housing. The unitary assembly imparts motion to the optical element relative to the support housing, in response to motion of the actuator.

Embodiments of the invention may include one or more of the following features. The optical component may include a component selected from the group consisting of a fiber, a lens, a mirror, a collimator, a prism, a filter, and a grating. The motion of the optical element may cause the formation and/or steering of an optical beam.

The unitary assembly may include a compliant coupling disposed between any combination of components selected from the group consisting of the actuator, the optical component, and support housing. The compliant coupling may include a bending flexure, a torsional flexure, an annular flexure, a membrane, a lever arm, a
rigid link, and/or a gimbal. The actuator may be a piezoelectric actuator, an
electrostrictive actuator, a magnetostrictive actuator, an electrostatic actuator, a
thermal actuator, an electromagnetic actuator, and/or an electroactive polymer. The
unitary assembly can be formed from one or more layers, such as a substrate. The
unitary assembly can include at least one microfabricated element and/or a plurality
of lever arms.

The optical positioning device may further include a stroke amplifier for amplifying
the mechanical movement generated by the actuator.

Insert discussion of the deformable fiber and planar waveguides here.

Further features and advantages of the present invention will be apparent from the
following description of preferred embodiments and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The following figures depict certain illustrative embodiments of the invention in
which like reference numerals refer to like elements. These depicted embodiments
are to be understood as illustrative of the invention and not as limiting in any way.

FIG. 1 is a schematic perspective view of an all-optical switch fabric;

FIG. 2 shows a fiber/lens assembly with rotation for beam tilting;

FIG. 3 shows a fiber/lens assembly with beam tilt achieved by moving a lens
relative to a stationary fiber;

FIG. 4 shows a fiber/lens assembly with beam tilt achieved by moving a fiber
relative to a stationary lens;

FIG. 5 shows a fiber/lens assembly with beam tilt achieved by rotating a fiber
relative to a stationary lens;

FIG. 6 shows schematically an embodiment of a motion transformer using the
fiber/lens assembly of FIG. 5;
FIG. 7A is a perspective view of a first embodiment of an exemplary unitary lever arm for the motion transformer of FIG. 6 in a rest position;

FIG. 7B is a perspective view of the lever arm of FIG. 7A in an actuated position;

FIG. 7C is a perspective view of a second embodiment of an exemplary unitary lever arm for the motion transformer of FIG. 6 in a rest position;

FIG. 7D is a perspective view of the lever arm of FIG. 7C in an actuated position;

FIG. 7E is a perspective view of a third embodiment of an exemplary unitary lever arm for the motion transformer of FIG. 6 in a rest position;

FIG. 7F is a perspective view of the lever arm of FIG. 7E in an actuated position;

FIG. 7G is a perspective view of a third embodiment of an exemplary unitary lever arm for the motion transformer;

FIG. 7H is a bottom view of the lever arm of FIG. 7C;

FIG. 8 shows schematically in cross-section another embodiment of a motion transformer using a double-membrane flexure and the fiber/lens assembly of FIG. 5;

FIG. 9 is a cross-sectional bottom view of the motion transformer taken along the line IX-IX of FIG. 8;

FIG. 10 shows the motion transformer of FIG. 8 in an actuated state;

FIG. 11 depicts a process for fabricating the bonded double-membrane flexure of the motion transformer shown in FIGS. 8 to 10;

FIG. 11A-F depict a process for fabricating the layers of the motion transformer containing the unitary lever arms;
FIG. 12 depicts exemplary piezoelectric actuator configurations useful for the embodiments of FIGS. 7 to 10;

FIG. 13A is a top view and a cross-sectional view taken along the line A-A of an exemplary subassembly forming the optical switch fabric of FIG. 1;

FIG. 13B is a perspective view (a) and a cross-sectional view (b) of an individual unit-cell, which together with other unit cells can form the optical switch fabric of FIG. 13A;

FIG. 13C shows schematically in cross-section a stacked assembly of mating layer, amplifier layer and lens mount of the assembly of FIG. 13A;

FIG. 13D is an exploded view of the switch fabric of FIG. 1 showing the various components and subassemblies;

FIG. 13E shows a cross-sectional view of the subassembly of FIG. 13A with bonding and wiring board and capillary tube for fiber attachment;

FIG. 13F shows a hermetically sealed package;

FIG. 14 shows optical elements to correct for axial offset of the optical emitters and receivers;

FIG. 15 shows schematically a setup for initial calibration of the switching apparatus;

FIG. 16 shows schematically a setup for active calibration and control feedback using fiber tap couplers;

FIG. 17 shows schematically a direction modulation of the emitter/receiver for active beam alignment;

FIG. 18 shows schematically optical power contours at two different wavelengths for optical power control and beam alignment;
FIG. 19A shows a piezoelectric actuator directly acting on a movable MEMS ferrule assembly to change fiber elongation for possible path length changes, optical phase delay, and tunable filter applications;

FIG. 19B shows a piezoelectric actuator acting to deform (elongate) a fiber though a MEMS motion transformation element comprising micro-fabricated pistons and hydraulic motion amplification; and

FIG. 20A shows a Mach-Zehnder interferometer formed in planar waveguides on a substrate and having hydraulic motion amplification; and

FIG. 20B shows a Mach-Zehnder interferometer formed in planar waveguides on a substrate and having piezoelectric actuation acting on the waveguide through mechanical motion transformation subassembly.

BEST MODE FOR CARRYING OUT THE INVENTION

The systems and methods described herein are directed to motion transformers as well as their integration and/or assembly, for use in directing optical beams and positioning of small optical elements for creating a variety of tunable optical components. More particularly, the systems and methods can be applied to a free-space optical cross-connect switching apparatus with electroactive actuation and deformable waveguide-based tunable components such as switches, variable attenuators and polarization and chromatic dispersion controllers.

The term "motion transformer" will be used to indicate amplification or conversion of motion in extent and/or direction.

The term "electroactive" as used herein refers to a range of materials that exhibit a mechanical response to applied electrical signals. Specifically, piezoelectric and electrostrictive materials are both electroactive, and can change their dimensions (strain) or apply force (stress) in the presence of an applied electric field or voltage. Henceforth the term "piezoelectric" may be used in place of "electroactive," with it to be understood that this language is not intended to be limiting, but to be
exemplary of the range of electroactive materials and geometries that can be employed in the current application.

The use of electroactive materials results in actuators that can apply high force, react quickly to an applied field, and require low power dissipation. High force can be translated into large deflections by the use of mechanical amplification structures or converted from linear into rotary or other types of motion by appropriate mechanisms. Appropriate mechanisms may consist of levers, linkages, flexures, compliant mechanisms, etc. Compliant mechanisms incorporating flexures provide reduced mechanical loss and backlash as compared to linkages. High speed is the result of the rapid piezoelectric response of the crystal lattice to applied fields. Low power dissipation is the result of the device being largely capacitive, requiring electric current flow to initiate motion, but not to maintain position. Actuators using these materials can have high stiffness and thus be used in structures having high resonant frequencies of vibration, making them relatively immune to environmental vibrations. This in turn makes these actuators more capable of maintaining their positional stability in open-loop operation.

Referring first to FIG. 1 an all-optical switch assembly 10 directs optical beams 15, 17 from optical emitters 12, 14 located on a first image plane 11a to receivers 16, 18 located on a second image plane 11b. The exemplary image planes 11a, 11b are shown as each having a 9-element switch matrix arranged symmetrically about a center axis CL to facilitate beam addressing and control. Emitters 12, 14 and receivers 16, 18 can be placed on either image plane 11a, 11b and can be intermixed. The illustrated configuration is therefore merely illustrative and not limiting in any way. For example, any combination of active and/or passive emitters and/or receivers can be combined to form 1 x N, N x 1, or N x N, or M x N switch assemblies. For nonblocking NxN and MxN implementations both transmit and receive elements should be active. In a practical application, an optical fiber can be connected to a respective beam-steering device located in emitter/receiver locations in the corresponding image plane 11a, 11b. The optical beam emerging, for example, from emitter 14 in image plane 11a can be directed by the beam-steering device to any port in the image plane 11b. Actuation stroke of the beam-steering
devices can be reduced by passive alignment of the beam emerging from any emitter in one image plane, for example, image plane 11a, onto the centrally located receiver 18 on the opposite image plane 11b, as indicated by beam path 17. In this way, each emitter 12, 14 will require approximately the same beam deflection angle to reach all receivers 16, 18 on the opposing image plane regardless of the emitter location on the first image plane 11a. The exemplary ports are shown as being coupled to optical fibers, although other light emission and receiving devices known in the art could also be employed. Details of suitable methods for actively steering the optical beams 15, 17 will now be described. The actuation mechanism has been omitted from the figures for sake of clarity.

Referring now to FIGS. 2 to 5, the trajectory 26 of an optical beam emitted, for example, by an end 25 of an optical fiber 22 located in the focal plane of a collimator (lens) 24 and collimated by the collimator 24 relative to a fixed axis A can be adjusted with a fiber/lens assembly 20, 30, 40, 50 by different methods. As shown in FIG. 2, the fiber 22 can be secured to the collimator 24, and the fiber 22 and lens 24 can be tilted together about a pivot point 23, as indicated by arrow 21. The beam tilt angle is equal to the tilt angle of the fiber/lens assembly 20. The fiber tip can be cleaved at an angle and/or anti-reflection coated and/or lensed to reduce back reflections and/or improve optical performance. Alternatively, as depicted in FIG. 3, the lens 24 can be displaced a distance $y$ relative to the stationary fiber tip 25 on the free end of the fiber 22 in a direction substantially perpendicular to the fixed axis A. The beam angle $\Theta$ in this embodiment is equal to \( -\frac{y}{f} \), wherein $f$ is the focal length of the lens. The first two approaches involve moving relatively heavy elements which tends to reduce the characteristic response/switching frequency.

Those of skill in the art will understand that other optical elements, such as prisms and gratings, can also be displaced relative to an optical emitter/receiver element to effect beam-steering.

Conversely, as shown in FIG. 4, the fiber tip 25 can be displaced a distance $y$

\[
\Theta = -\frac{y}{f}
\]

relative to the stationary lens 24, which also gives Fiber translation
requires displacement of the fiber by quite a large distance, depending on the focal length of the collimating lens and the desired deflection angle. Although the beam tilt angle \( \Theta \) can be increased by using lenses with a shorter focal length to provide more "optical leverage", the required beam quality (wavefront distortion) for efficiently imaging the collimated beam onto the receiver 16, 18 sets lower limits for a practical focal length.

An alternative beam-steering/tilting mechanism 50 shown in FIG. 5 uses a holder or collet 52 holding the fiber 22 that can pivot about an "effective" pivot point 53. The term "effective" pivot point refers to the fact that the pivot point can move in relation to a stationary support depending on the tilt position of the holder 52. An actuator (not shown) can be connected to the holder 52 at attachment point 56 a distance \( \Delta \) from the effective pivot point 53. The fiber acts as a lever arm to convert the angular motion into an amplified motion of the fiber tip on an arcuate path about the pivot point. For small rotation angles, the arcuate path can be viewed as being pseudo-linear, with the small deviations from a truly linear path correctable by an aspheric lens design. A lateral displacement \( \varepsilon \) of the attachment point from a rest position will displace the fiber tip 25 by \( y \). The magnitude of \( y \) will in turn determine the beam angle \( \Theta \), as discussed above. The last two approaches advantageously involve moving only the relatively light fiber.

Returning to FIG. 5, the beam tilt angle \( \Theta \) is related to the lateral displacement \( y \) of the fiber tip 25 from its rest position by:

\[
\Theta_{\text{max}} = \frac{-y}{f},
\]

wherein \( f \) is the focal length of the lens. \( y \) is related to the lateral excursion \( \varepsilon \) at the attachment point 56 by the equation:

\[
y = \frac{L \ast \varepsilon}{\Delta},
\]
wherein \( L \) is the distance of the fiber tip 25 from the pivot point 53 of the fiber holder, \( \Delta \) is the distance between the attachment point 56 on the fiber holder and the pivot point 53, and \( \varepsilon \) is the lateral displacement of the fiber holder at the attachment point 56.

Accordingly,

\[
\Theta = \frac{L_{\text{Fiber}} \cdot \varepsilon}{f \cdot \Delta}
\]

i.e., the beam angle \( \Theta \) can be increased by increasing the length of the free end of the fiber (\( L_{\text{Fiber}} \)) (which is impractical above a certain fiber length due to inherent flexing of the fiber); increasing the achievable actuator motion ("stroke") of the piezoelectric actuator or attaching a passive lever arm to the actuator (which has certain disadvantages discussed above); and/or by decreasing the distance \( \Delta \) between the attachment point 56 and the pivot point 53.

With modern MEMS fabrication techniques, \( \Delta \) can be reduced to a length of several tens of micrometers or less. A typical piezoelectric actuator can generate a stroke of \( \varepsilon = 10 \, \mu m \), so that a tilt angle \( \Theta \sim 3^\circ \) be obtained with \( \Delta \sim 60 \, \mu m \). Tilt assemblies with such attachment point to pivot point spacing can be easily fabricated using MEMS technology. Motion transformers of two different designs will now be described.

FIG. 6 depicts schematically a motion transformer 60 that transforms a linear (left-to-right) motion of the piezoelectric actuators 65, 66 into an (up/down) motion of optical fiber tip 25 located in the focal plane of a collimator lens 24 that is attached to a housing or support structure 61. The piezoelectric actuators 65, 66 are supported on a fixed end by the housing 61, with the free end of the piezoelectric actuators 65, 66 pushing against corresponding levers 63, 64 at attachment points 67, 68. The levers have flexures and are attached with one end to the support structure 61 and with the other free end to a holder/collet 62 that holds the fiber 22. As described above with reference to FIG. 5, the up-and-down motion of fiber tip behind the lens changes the trajectory and the beam angle \( \Theta \) of the collimated beam.
Referring now to FIGS. 7A to 7F, the design of the lever arms of the motion transformer amplification mechanism determines the mechanical function, range of motion, amplification factor, and required forces. In the exemplary embodiment of FIG. 7A, a lever mechanism 70A includes three lever arms 73, 74, 75 that are spaced apart by 120° around the central fiber/lens optical axis 71. Three piezoelectric actuators (not shown) are coupled to the lever arms 73, 74, 75 at an attachment point 76 that is close to a lever arm's pivot (or flexing) point 771 where the lever arms are attached to the support structure 78, for example, a Si layer. The lever mechanism amplifies the linear motion of the piezoelectric actuators and converts the amplified linear motion into a tilt motion of the fiber. Hence any small deflection applied by a piezoelectric actuator, for example, to the lever arm 73 at the attachment point 76 is magnified by the ratio of the length of the lever arm to the distance between the attachment point and the attachment point to the support structure 78. A lever mechanism of this type can also be viewed as a stroke amplifier. The three arms 73, 74, 75 can be connected at their free ends by a common center structure, e.g., the fiber collet 72 that holds the optical fiber.

Typically piezoelectric stacks are significantly weaker in tension than in compression. To maximize the operating range of the device a preload is applied to the fiber during assembly. The preload causes a compressive load in the piezoelectric actuators, thus increasing the operating range of the device.

In the exemplary embodiment shown in FIG. 7A, each of the three lever arms 73, 74, 75 has three independent flexure elements 771, 772 and 773. Two of the three flexures 771, 772 serve strictly as lever pivot bending points allowing each lever arm to amplify translational motion of the piezoelectric actuator. The third flexure 773 on each lever arm is oriented perpendicular to the other two flexures. This third flexure allows bending in a direction perpendicular to the other two flexures. Since the three lever arms 73, 74, 75 can be coupled through the center fiber/lens structure and the lever arms can be actuated independently, each lever arm is subjected to coupled motion and bending from another lever arm. The third flexure 773 provides compliance for this motion, which generates the angular tilt. Actuating each of the levers independently controls the position of three points of the center fiber/lens
structure plane. Controlling three points of the fiber/lens plane provides the ability to position the fiber/lens, and therefore the optical beam, at any angle desired within the constraints of mechanical stops built into the layer structure. Actuating the levers in unison moves the fiber and/or lens along the optical axis (z-axis) and can be used to change the collimation of the beam as well as to stress the fiber, which will be described below.

FIG. 7B shows the mechanism of FIG. 7A in an actuated state, for example, by pushing against attachment point 76'. The fiber tilt 71' is determined by the difference in the excursion between the lever arms 73, 74, 75.

The exemplary lever arm structure 70A can be manufactured from a commercially available silicon wafer. Each of the lever arms is between 1 and 2 mm long. Other typical dimensions of the exemplary lever arm structure 70 are as follows:

- Si wafer thickness = 625 µm
- Trench width = 70 µm
- Trench depth = 545 µm
- Flexure arm width = 30 µm
- Push point width = 70 µm
- Fiber hole diameter = 140-190 µm

With these dimensions and the positions of the actuator push points shown in the exemplary design, a translational motion amplification of about a factor of five (5x) can be easily achieved at the center of the fiber attachment structure. As mentioned above, the tilt action is produced by differentially energizing the actuators.

A process for manufacturing the exemplary lever arm structure 70A is depicted in FIGS. 11A and 11B. Details of the assembly will be described below with reference to FIGS. 13A and 13B, wherein layer 134 includes the lever arm structure described herein. Layer 134 (see FIG. 13A) is formed by a series of deep reactive ion etches (DRIE) on both sides of the wafer to form the trenches. Careful control of the front-to-back alignment of the masks is essential to the formation of the flexures. Side-
wall straightness and fillet control at the bottom of the trenches is also crucial in
achieving the desired strength from the structure. FIGS. 11A and 11B show the
detailed steps of the fabrication process flow (steps A through K). The mask layouts
used in the process are conventional and not shown. In step A, a surface oxide is
grown on the top (T) side of the wafer and patterned to define the through holes. In
step B, photoresist (PR) is spun on and the pattern for the holes that do not extend
through the wafer are defined. In step C, openings are etched through the oxide layer
using a buffered oxide etch (BOE), followed in step D by a DRIE etch of 425 \( \mu \text{m} \)
(plus an additional depth to counter Aspect Ratio Dependent Etching (ARDE)) to
produce almost the entire trench depth. In step E, the PR mask is stripped and an
additional depth of 100 \( \mu \text{m} \) is etched to complete the top side of the wafer.

In step F (FIG. 11B), the bottom (B) side of the wafer is selectively patterned with
oxide. The B side includes also the bond regions with subassembly 132 (FIG. 13A)
and actuator push points 76 (FIG. 7). In step G, the B side is patterned with PR for
both the through-hole and non-through-hole trenches. As before, a DRIE etch with a
depth of 515 \( \mu \text{m} \) (plus an additional depth to counter ARDE) is performed in step H,
whereafter the PR is stripped in step I to expose the nested mask of step A for
creating the recessed features on the B side. In step J, an additional 10 \( \mu \text{m} \) is DRIE-
etched to create the push point contact regions and bond regions that are distinct
from other recessed surfaces. All regions that separate the levers from the rest of the
wafer have been removed at this process step. In step K, all mask residues and other
protective layers are stripped, leaving only the silicon structure of the lever arm
layer 134.

FIG. 7C depicts another lever arm mechanism 70B wherein the flexure 773 has been
replaced with a thin arm 778 that absorb the torsion forces produced by the other
lever arms. The arm(s) can then twist, as shown in FIG. 7D when the lever arm is
actuated at attachment point 76'. As illustrated in FIG. 7H, in a preferred
embodiment, the push point 76 in FIG. 7C includes two push points 76a, 76b that
are spaced apart in a direction perpendicular to the longitudinal extent of the arm
778. FIG. 7H shows a bottom view of layer 134 (FIG. 13A) for the lever arm
mechanism 70B depicted in FIG. 7C, with the two push points 76a and 76b clearly
visible. Having two push points adds stiffness to the design near the actuator, with bosses 1376 (see layer 1325 in FIGS. 13A and 13C) transferring the actuating force from the actuators 1320 to the push points 76a, 76b. The boss layer is part of the mating interface that is discussed below with reference to FIG. 13A and more particularly, subassembly 134.

FIG. 7E depicts yet another embodiment 70B of the lever arm mechanism wherein the flexures 780, 782 and 784 are formed by etching through the entire wafer thickness rather than to a certain trench depth which has to be carefully monitored, which simplifies the manufacturing process. The attachment point 76 of the actuators is located proximate to the stationary support 78, as in the embodiments described above with reference to FIGS. 7A to 7D. As shown in FIG. 7F, the fiber and/or beam direction tilts when the lever arm is actuated at attachment point 76'.

Other designs of actuation mechanisms can have at least one arm, two arms, and potentially four or more arms. In general, symmetric designs like the three-arm embodiment described above are preferred because they are insensitive to a thermal expansion mismatch between the arms and the housing and because they provide for high angular output due to the capability for differential actuation. Different modes of motion (translation, plunge, etc.) can be achieved by different linkage designs.

The lever arms are typically about 625 μm thick (the thickness of a bulk micromachined 150-mm diameter silicon wafer), with arm lengths of one to two millimeters. When some actuators are energized and others are not, the tilt action is accomplished. With the dimensions shown, about a ±3° angular swing can be achieved in this structure for about 5 μm of translational motion of any one of the piezoelectric actuators, independently actuated, at the attachment point 76. The effective pivot point for the angular motion lies within the thickness of the structural layer containing the lever arms. The limiting factor in this performance is the peak stress within the flexures, which restricts the maximum bending they can accommodate prior to failure. It should be noted that the three actuators can be extended and/or contracted in concert (in common) to effect not tipping but plunging, z axis motion perpendicular to the plane of the device to accomplish
amplified extension of or positioning of the center fiber contact point to accomplish for instance motion of a fiber tip into and out of a focal plane of a lens oriented parallel to the plane of the device. This motion can effect changes to the focus and degree of collimation of an emergent beam from the device.

In order to maximize the amplification and tilt motion, the flexures should have a high stiffness in the direction of the actuation force, while allowing the holder to tilt freely. This can be accomplished with the flexure 773 of the three-jointed hinge mechanism of FIG. 7A or alternatively with the thin vertical flexures 778, 782 of FIGS. 7C and 7E. This mechanism can also be understood as a compliant actuation mechanism or gimbal allowing free angular movement, such as tilting over a solid angle, of the holder. In general, making the flexure elements long and thin in cross section will provide more compliance and reduce the stress the flexures undergo. However, in a practical switch application, this would increase the overall radial dimension of each port in the switch fabric, which would disadvantageously also increase the center-to-center spacing between ports and the required beam-steering angle.

FIG. 7G shows an alternative motion amplification mechanism, wherein the lever arms curve around to reach the opposite side of the center structure. As before, each arm has three flexures. The flexures allow for movement of the arms such that the center structure can tip and tilt. In this design, the flexures close to the center structure experience less bending for a given tilt angle, thus allowing increased range for the motion transformer by approximately a factor of 2.

Unlike the embodiments illustrated in FIGS. 7A to 7G which employ several linear piezoelectric actuators for each fiber port, an amplified tilt motion can also be obtained by using a single bending-type piezoelectric actuator that bends along its longitudinal (z) axis. The detailed design of an embodiment using double-membrane flexures will now be described with reference to FIGS. 8 to 10.

FIG. 8 is a cross-sectional view of a motion transformer mechanism 80 with a piezoelectric bending actuator 85 that is supported on the bottom support 81 of a
housing or support structure having side-walls 83. Various designs for the piezoelectric actuator 85 and the electrode arrangement will be discussed in more detail below. Upon actuation by an electrical charge and/or voltage, the free end of the piezoelectric actuator 85 moves sideways in the direction of arrows 86. A double-membrane flexure 810 is supported laterally by the side-walls 83. The double-membrane flexure 810 is fabricated of two separate layers 812 and 814 that are bonded together along at least a portion of their periphery 816 and at the center 817. It will be understood by those skilled in the art that various other optical elements, such as a lens, a mirror and/or an optical grating may be attached to the motion transformer. It will also be understood that the membrane need not be contiguous, but can include slots and other types of radial and/or annular openings, as long as the membrane provides enough stiffness for transmitting the lateral forces.

In the illustrated embodiment, the double-membrane flexure 810 is made of silicon or silicon-on-insulator (SOI) wafers, but other materials, such as metals, can also be used. A thin annular membrane 820, 822 is located between the bonded sections 816 and 817 in the plane of each layer 812, 814. The membranes can be continuous or segmented. The radially inward portion of the upper membrane 822 is attached to the fiber holder 82, whereas the radially outward portion of the upper membrane 822 is fixedly secured to the wall 83. The radially inward portion of the lower membrane 820 is attached to the fiber holder 82, whereas the radially outward portion of the lower membrane 820 is connected to an annular ring 824 that is resiliently supported for movement in the direction of the arrows 86 by flexures 818 disposed between the annular ring 824 and the portion 826 of the layer 812 that is fixedly secured to the wall 83. An additional optional annular structure 830 can be disposed between the free end of the piezoelectric actuator 85 and the resiliently supported ring 824 to accommodate fabrication tolerances when connecting the free end of the piezoelectric actuator 85 to the ring 824. The compliant upper membrane can also be viewed as a gimbal mount for the holder 82.

FIG. 9 is a cross-sectional view, viewed from the bottom 81, of the double membrane flexure motion transformer taken along the line IX-IX of FIG. 8. In the depicted exemplary embodiment, three flexures 818 are arranged between and
connecting the annular ring 824 and the fixed portion 826 of the layer 812 to allow essentially uniform lateral displacement of the annular ring 824 for all actuation directions of the free end of piezoelectric actuator 85. These flexures 818 are not required for ultimate function of the device. They are designed to be compliant so as to maintain position of the ring until it is bonded to the actuator and to not reduce performance of the device during operation.

FIG. 10 shows the motion transformer mechanism 80 in an activated state, with the free end of piezoelectric actuator 85 laterally displaced by a distance ε in the direction of the arrows 96. This displacement ε urges the annular ring 824 towards the left section of wall 83 by compressing flexure 918a and away from the right section of wall 83 by expanding the flexure 918b. As a result, a force is applied to the attachment point 94 of the lower membrane 820 which pulls the attachment point 94 towards the compressed flexure 918a and thereby pivots the fiber holder 82 about the essentially stationary pivot point 93 of the holder 82. This pivoting motion of the fiber holder 82 causes the trajectory of a beam emitted by a fiber tip (not shown) to be changed by an angle Θ, as described above with reference to FIG. 5. The membranes can be manufactured very precisely by MEMS technology, wherein a spacing between the attachment point 94 and the pivot point 93 of, for example, 50 - 100 μm can be easily achieved. A small displacement ε of the piezoelectric actuator 85, on the order of 5 μm, can then effect a large change in Θ.

FIG. 11 illustrates the MEMS fabrication steps of double-membrane flexure 810. Precise control of the layer thickness, in particular of the thin membranes 820, 822, is made possible by using precisely engineered, commercially available SOI (silicon-on-insulator) wafers. A SOI wafer typically consists of a handle wafer to which a thin SiO₂-Si layer structure is wafer-bonded, with the SiO₂ layer facing the handle wafer. The thicknesses of both the Si and the SiO₂ layer can be well controlled, ranging from extremely thin (10 nm) to as thick as several tens of micrometers, with a thickness uniformity of better than ±5%. In the present embodiment, the handle wafer provides structural support, whereas the membranes are essentially formed from the thin Si layer.
Referring now to FIG. 11, and in particular to process step A, the top MEMS layer 814 is made of an SOI wafer with a Si layer thickness of 60μm on the device side 1104. The Si layer 1104 is supported by a handle layer 1101 via an intermediate SiO₂ layer 1102. A stepped recess 1105 with a residual layer thickness of approximately 10 μm is etched on the device side 1104. This residual layer will later form the membrane 822. A center portion 1103 is etched through the Si device layer 1104 and the intermediate SiO₂ layer 1102 partially into the handle layer 1101.

The bottom MEMS layer 812 is etched in a separate process step B. Beginning with an SOI wafer having the same dimensions as the top wafer described above, a recess 1115 with a residual layer thickness of approximately 10 μm is etched on the device side 1104'. This residual layer will later form the membrane 820. A center portion 1113 and an annular portion 1117 are etched through the Si device layer 1104' and the intermediate SiO₂ layer 1102' partially into the handle layer 1101'.

In process step C, the bottom layer 812 is bonded, for example, by fusion or wafer bonding, to the top layer 814. In process step D, metallization layers 1132, 1132', 1134, and 1134' made, for example, of Ti/Pt/Au or Ti/Ni/Au are deposited and patterned on the respective handle surfaces 1101, 1101' of the bonded membrane layers. The metallization layers 1132 are provided for subsequent attachment of the formed double-membrane structure 810 to a holder or housing, whereas metallization layer 1132' is provided for attachment of the fiber extending through the center opening of collet 817. Metallization layer 1134' attaches, either directly or via an intermediate layer, to the piezoelectric actuator (not shown). In process step E, a DRIE etch is performed on both the top handle 1101 and the bottom handle 1101' of the bonded membrane layers to etch through the collet 817 and to the buried SiO₂ layer to form the two membranes 820 and 822, and the vertical flexures. To relieve the stress at the corners of the handle side after DRIE etching, the width of the stepped recesses 1105 and 1115 on the device is narrower by at least several μm than the width of the DRIE etched recess on the handle side opposite the recesses 1105 and 1115.
FIG. 12 shows different embodiments of piezoelectric actuators capable of providing the movement for the exemplary motion transformers described above. Fig. 12 (a) shows a piezoelectric stack 1210 with sequentially arranged interdigitated electrodes 1212, 1214 which expands/contracts in the direction of the arrow upon application of an external voltage to the interdigitated electrodes 1212, 1214. FIG. 12(b) shows a piezoelectric tube 1220 with an inner electrode 1222 and an outer electrode 1224 which also expands/contracts in the direction of the arrow upon application of an external voltage to the electrodes 1222, 1224. FIG. 12(c) shows a tube 1230 with an inner electrode 1232 and segmented electrodes 1234, 1236, 1238 disposed of the outer surface of the tube 1230 along its longitudinal axis. This tube can bend in the direction of the arrow upon application of different voltages between the inner electrode 1232 and the electrodes 1234, 1236, 1238. FIG. 12(d) shows an alternate embodiment of a piezoelectric bender 1240 having separately addressable piezoelectric bending elements 1242, 1244, … arranged on a support structure 1248. The piezoelectric tube can also be made of a material, for example, a metal tube, that is coated with a piezoelectric material.

Typical piezoelectric compositions used in engineering applications are of the PZT-type (Lead Zirconate Titanate). Within this type of family, there exist many variations that have different performance and mechanical properties. The changes are determined by the amount of chemical dopants in the source powders. PZT materials are typically characterized by large actuation strains, linear response, and good temperature stability, but also have high creep and hysteresis and need to be poled prior to operation. This is the first and most common type of piezoelectric actuator that would be chosen for actuator experiments.

Typical electrostrictive compositions are of the PMN (Lead Magnesium Niobate) type. These compositions do not need to be poled, a characteristic that has positive implications on device integration and operation (allows for higher processing and operating temperatures). PMN materials are generally characterized by good actuation strains, extremely low hysteresis and creep, however exhibit highly nonlinear response and are very sensitive to temperature.
Electromechanical actuator properties can be further tailored by forming compounds or solid solutions of PZT and PMN compositions with other perovskite structured materials. For example, the composition of general formula \((A_1A_2)(B_1B_2)O_3\) may be used to represent simple compounds such as BaTiO\(_3\), BaZrO\(_3\), KNbO\(_3\), or SrTiO\(_3\), mixed A-site compounds such as \((Na_{1/2}Bi_{1/2})TiO_3\) or \((K_{1/2}Bi_{1/2})TiO_3\), mixed B-site compounds such as \(Pb(Zn_{1/3}Nb_{2/3})O_3\) or \(Pb(SC_{1/3}Ta_{1/3})O_3\) or defect compounds such as \((La_{2/3}□_{1/3})TiO_3\) where □ is a site vacancy. The optimum composition is chosen for its actuation performance, reliability, environmental stability, and processing compatibility.

A tubular actuator of the type depicted in FIG. 12 (c) and (d) is particularly suited for the embodiment of FIGS. 8-10. The sideways motion is transferred by the double-membrane motion transformer 810 to the fiber collet 82.

Although the motion transformer and beam deflection mechanism have been described above with reference to a single unit, such devices can be conveniently integrated to form a multi-port switch fabric, which will now be described.

FIG. 13A shows a top view and a cross-sectional view taken along the line A-A of an exemplary switch fabric 130 having multiple emitters/receivers that can be arranged in form of a two-dimensional array, as shown in the top view and described above with reference to FIG. 1. The switch fabric 130 can be assembled from layered subassemblies, such as an actuator subassembly 132, a motion transformer subassembly 134 and a lens/collimator subassembly 136, 24. Each part of the device can advantageously be independently tested and its performance verified before final mating, thereby increasing the overall process yield.

An actuator sub-assembly 132 includes a base or substrate layer 1310 with electrical leads 1305, piezoelectric actuators 1320 and a spacer (housing) layer 1330. The base layer 1310 forms the support layer for the piezoelectric actuators. The base layer 1310 can include seating surfaces for the piezoelectric actuators, holes for the optical fiber 22, and holes for the electrical leads 1305 to the actuators or other electronic components. This layer should be stiff to provide support for the actuators and can be made, for example, of a silicon-on-insulator (SOI) wafer, or a multi-layer
ceramic. Alternatively, a multi-chip module substrate commonly used in electrical chip technologies can be employed. Wafer level electrical components, such as switches and transistors, for electrically connecting and/or addressing the individual actuators can also be incorporated.

As described above, the embodiment described above with reference to FIGS. 6 and 7A to 7F and using the linear actuator motion transformer has preferably three piezoelectric actuators per optical port, while the dual-membrane flexure motion transformer of FIGS. 8-10 requires only a single piezoelectric actuator (FIG. 12(e)) or actuator assembly (FIG. 12(d)) per optical port. The actuators 1320 are located in holes extending through the spacer layer 1330 and formed by a number of drilling or milling processes known in the art, including laser beam machining and ultrasonic abrasive milling. The spacer layer 1330 layer can provide additional structural and spacer support for precisely locating the actuators relative to the amplification mechanism and the fiber/lens and also provides structural support, such as the wall 83 of FIG. 8, for the actuators to react against. The actuators can be piezoelectric, electrostrictive, thermal, or magnetostrictive in composition or any of a variety of other actuators known in the art, and can optionally be capped on their free ends to facilitate interfacing with a layer above. The spacer material has a thickness comparable to the actuator length (in the present embodiments approximately 10 to 11 mm) and can be, for example, PYREX glass or a ceramic material to achieve optimal thermal expansion matching with the piezoelectric actuator(s). The holes should be oriented and arranged so as to place the beam ports as close together as possible to allow close-packed arrays of beam ports in a fiber-optic beam-steering switch application. A center-to-center spacing or pitch of the beam ports of 1-4 mm can be easily achieved with commercially available piezoelectric actuators having diameters of 2.2 mm or less. The thickness of the spacer layer is in part determined by desired and available amounts of strain or throw from the actuators for a given drive voltage. Both layer 1310 and 1330 should be configured to provide a high stiffness load return path to react the loads at the base of the actuators to the motion transformation stage 134. Any compliance in layers 1310 and 1330 tends to diminish the actuation and motion capability of the completed assembly.
The second sub-assembly 134, the motion transformer sub-assembly, includes a single or plurality of layers 1324, 1325, 1326 which together accomplish the tasks of attaching to and causing articulation of the moving optical element in the beam-steering unit based on relative motion between the electroactive actuator element and the housing or based on relative motion between two or more actuator elements. The sub-assembly 134 has an actuator layer 1324 that mates on its bottom side with interface or mating layer 1325 to allow for positioning tolerances onto the piezo actuators 1320 and housing/spacer 1330. Attached to the top surface of the actuator layer 1324 of subassembly 134 is a lens mount layer 1326 allowing positioning and attachment of the collimating lens 24. It should be noted that the switch or actuator fabric 130 depicted in FIG. 13A is exemplary only, and that the dimensions and shapes of the various layers and subassemblies can be adapted for specific applications.

The subassembly 134 can be made, for example, of a micro-machined (MEMS) Silicon-On-Insulator (SOI) wafer and can include a push point beam or the annular ring 824 (FIG. 8) that can be bonded directly to the etched mechanisms on other layers in the subassembly. The subassembly 134 and or its constituent layers can be used to route signals to the piezo actuators, for example in a row/column addressing scheme in which row address lines could run on layer 1310 and column address lines could run on the bottom surface of subassembly 134. Furthermore, sensors such as piezo-resistive, piezoelectric, or capacitive sensors, could also be incorporated into subassembly 134 to allow sensing and feedback for accurately positioning and controlling the actuator.

Subassembly 134 is the primary motion transformer subassembly which includes layers containing the lever arm structures 70A, 70B, 70C (FIGS. 7A – 7F) or the flexure membrane structure 810 (FIG. 8) with the fiber holder described earlier. The mechanism converts the vertical elongation/lateral bending motion of the piezoelectric actuators into an angular tilt of the fiber and (optionally) the lens for controlling the beam trajectory. Alternatively, the subassembly can include a layer or portion thereof which can also be coupled to the fiber/lens tilting mechanism depicted in FIG. 2.
As mentioned before, layers comprising subassembly 134 can be formed by a series of deposition and etch processes (wet etching, DRIE) on both sides of a Si or Si-SiO₂-Si wafer to form the resilient flexures (either lever beams or membranes), with careful control of the front-to-back alignment of the masks. Side-wall straightness and fillet control at the bottom of the trenches is also important for achieving the desired strength and fatigue-resistance of the structure. The formations of the layer(s) and their subsequent assembly into a unified subassembly can be accomplished by a wide variety of processes including but not limited to those commonly used in the fabrication and assembly of micro-electro-mechanical systems (MEMS). These can include DRIE and/or KOH wet etching processes as well as Si-Si wafer bonding and/or thermo-compression wafer or die bonds using gold and and/or other metal interlayers. Alternately, the layers comprising the subassembly can be individually fabricated and mechanically joined and held together during overall device assembly and operation.

Sub-assembly 134 can also include layers or portions of layers which serve the primary mating function with the moving optical element, for example providing features for mating to and/or holding or bonding a moving optical element such as: a fiber, a lens, pre-assembled fiber/lens assembly, a fiber with integrally lensed tip, a prism, an optical wavelength filter element, or grating element. For example, the lens and fiber could be assembled together and bonded directly to a portion of the layers comprising subassembly 134, similar to the fiber/lens arrangement of FIG. 2.

It will be understood by those skilled in the art that various other optical elements, such as a lens, a mirror and/or an optical grating may be attached to the motion transformer.

FIG. 13C shows schematically in greater detail in a cross-sectional view the amplifier subassembly 134 which can be preassembled as a unit. Clearly indicated is the mating layer 1325 with bosses 1376 that push against the push points 76, 76a, 76b of the lever arms. The process for fabricating the actuator layers 1324 and 810 has been described above. The layout and fabrication steps for the intermediate or
mating layer 1325 used with the embodiments depicted in FIG. 7 will now be
described.

FIG. 11C shows the mating layer 1325 which is made of a bulk micromachined
Silicon-On-Insulator (SOI) wafer. The etched features include a transfer column (not
shown) that mates with the piezoelectric actuator, a thin diaphragm 1105
surrounding and holding the transfer column that allows vertical displacement but
not lateral displacement, and a push point beam 1376 on top of the transfer column.
This push point beam is bonded directly to the etched amplifier mechanisms on the
next layer, the amplification layer 1324. The beam is where the actuator
displacement is transferred to the amplification and tilting mechanism. Layer 1325
allows for imprecise positioning of the piezo actuators and makes the contact to the
precise push point on the amplifier layer 1324.

Layer 1325 could potentially be used to route signals to the piezo actuators, for
example in a row/column addressing scheme in which row address lines could run
on layer 1310 and column address lines could run on layer 1325. Furthermore,
sensors such as piezoresistive, piezoelectric, or capacitive sensors may be
incorporated into layer 1325 to allow sensing and feedback for the actuator position.

These features are formed by deep reactive ion etching (DRIE) of the silicon wafer.
The handle side of the SOI wafer is 400 to 600 μm. This is etched down to the
insulator to form the top side of the diaphragm. The etch is controlled to create
nominally straight side-walls. The device side is 25 to 50 μm thick. An isotropic
etch is used to etch back the device side until the desired membrane thickness is
achieved.

The fabrication process for layer 1325 is depicted in FIG. 11D. Starting with a
double-side polished SOI wafer with device side 1101 Si thickness of about 40 μm.
A thermal oxide is deposited to protect the surfaces. The handle side is then
optionally patterned and DRIE etched to a designed depth to define a 2 μm deep
seating surface 1115 of the push bar (see FIG. 7H). Isotropic dry etch is performed
to form the drive membranes of 10 μm thick with gradual fillet, which are somewhat
narrower than the later applied deep DRIE etch on the handle side so as to prevent
stress points in the membrane layer 1105. This state of the wafer is shown as step A in FIG. 11D. Also partially formed from the device side is fiber hole 1103.

The wafer is then processed from the handle side by forming a nested oxide mask which is used to etch down the recesses 1127 which allow the actuators to move freely while limiting their excursion (Step B). A thin portion of Si is left in the fiber hole which together with any Si left in the handle-side trenches is cleared in step C. The layer can be protected with SiO₂ after step C for protection during final assembly with layer 1326.

Layer 1326 is likewise an SOI wafer bulk micro-machined layer. It is provided mechanically spacing the optical lens the correct distance from the front tip of the optical fiber. This spacing is necessary to produce the desired optical configuration for the optical beam. A spacer/holder is etched for each lens. This silicon spacer is bonded to the center fiber silicon structure on the amplifier layer, layer 1324. The spacer mates the lens and fiber and allows them to tilt as a unit. An alternative configuration is to make this spacer structure out of something other than silicon in more of a macro fabrication process, (glass for example). Then the spacer would be assembled to the lens and bonded to the amplifier layer. In still another configuration, this layer 1324 could be omitted and a lens and fiber assembled together as a unit could be directly bonded to the amplifier layer 1324.

The lens holder is shown in a perspective view in FIG. 11E. As seen in FIG. 11E, the three-leaf lens holder is detached from the sides of the wafer and once attached/bonded to the actuator collet, can freely move and tilt with the actuator(s).

The process to create layer 1326 is depicted in FIG. 11F. It also includes a series of DRIE etches in an SOI wafer having a device layer 1104, a SiO₂ layer 1102 and a handle layer 1101. The wafer is patterned with SiO₂ and a recess is cut from the device side for the fiber hole, step A. A trench is cut from the handle side to the buried oxide layer to define the outside of the lens mount, step B. In addition, the cavity to accommodate the fillet on the fiber/lens assembly is cut, and the fiber hole is cut through the wafer. The oxide mask in the handle side is etched to expose the silicon surface and the photoresist on the device side is stripped away and wafer is
cleaned for silicon fusion bonding, step C. The remaining portion 1350 of Si on the
device side is etched to release the lens mount after layers 1326, 1324 and 1325 have
been joined into subassembly 134 by wafer fusion bonding, as indicated in steps D
and E.

5 The layers and subassemblies can be fusion-bonded and/or solder-bonded using a
solder having a melting/process temperature that is lower than the temperature used
to assemble the actuator subassembly and also less than the Curie temperature of the
piezoelectric actuator material, or an organic adhesive (e.g. an epoxy or cyanate
ester). Additionally, an anodic bonding process can be used to form the bond.

10 Alternatively, an ultraviolet cured epoxy may be used. The actuators should be
mechanically preloaded so as to prevent them from going into tension. This can be
accomplished by placing a small load (<0.5 N) on the fiber. As discussed below, an
organic adhesive, for example a UV curable adhesive, can be used to bond the fiber
under preload to the bottom of layer 1310 and seal the layer.

15 Instead of solder bonding the sub-assemblies or individual layers of the switch
fabric, these components can also be aligned and fixed in place mechanically by
clamping, optionally with additional guide pins to facilitate stacking the
components. Screws with compression springs can be used to hold the sub-
assemblies or layers together, as is known in the art. It will be understood that the
springs, being part of the load path of the actuators, have to be sized so as to hold the
components firmly in place under the maximum forces produced by the actuators.
The mechanical clamping method also allows testing of subassemblies before the
remaining components of the switch fabric are added and the reuse of sub-
assemblies or layers if other components of the switch fabric break after final
assembly.

Referring now to FIG. 13D, which shows an exploded view of the switch fabric 130
of FIG. 13A to better illustrate the assembly process. In addition to the layers
described above with reference to FIG. 13A, there is shown a printed wiring board
1303 having through-holes for the fiber 22 and solder bumps and electrically

30 conductive paths for interconnects. Also shown is a fiber bonding/clamping layer for
holding the fiber in the switch fabric 130 at the end distal from the fiber collet 72 (see FIG. 7) and for providing a preload to the fiber. This is illustrated in FIG. 13E.

As seen in FIG. 13E, the fiber bonding/clamping layer 1302 has a recess adapted to accommodate the coated fiber 22 (which includes the core, the cladding and the protective coating). The fiber, with the coating removed along approximately 30 mm near the tip which is beveled to reduce back-reflections, is then fed through the tube until reaching an approximate position. The fiber is thereby held in place straight over an extended length and prevented from sagging. With the lenses -- and optionally wedges for windage (see below) -- in place, the assembly is placed in a fixture (not shown) and each fiber is individually actively aligned relative to the corresponding lens in the z-axis until the light beam emitted from the free end (tip) of the fiber is collimated. Once the desired alignment is achieved, the fiber is moved by a small distance (for example 5 μm) towards the lens and fixed in place in the fiber holder 72, 82 by a UV-curable epoxy.

To keep the fiber straight in the switch fabric 130, the fiber is preloaded by retracting the fiber from the bottom layer 1302 in the direction away from the lens by the same small distance (e.g., 5 μm) that was added above. The preloaded fiber 22 is then locked in place in the fiber capillary tube 1301 by applying, for example, a UV-curable epoxy.

The assembly 130 can optionally be placed individually or in tiled array into a windowed hermetically sealed packagesuch that the individual windowed packages allow beams to traverse from one assembly 130 or array of assembly 130's through the windows and optically transparent medium or optical devices (such as lenses or mirrors) interspersed between these windows. Alternately both transmitting and receiving elements and switch fabrics can be place into a single hermetically sealed package, as illustrated in FIG. 13F. Temperature control can be provided using heaters or Peltier thermoelectric devices within the package if this is required for stabilization over the operating temperature range. A hermetic header with hermetic lead feedthroughs and seam-sealed lid made, for example, of Kovar can be used to
enclose the free-space optical path in an inert dry atmosphere. This excludes particles, prevents condensation on the optical surfaces, contributes to the reliability of the bare fibers bending within the package, and controls the atmosphere for the piezoelectric material as well.

FIG. 13B shows an individual unit-cell of the switch fabric depicted in FIG. 13A. It should be noted that in the embodiment depicted in FIG. 13B, the fiber 22 moves relative to the lens, whereas in FIG. 13A the fiber and lens form a unit. However, as stated above with reference to FIGS. 2 – 6, several the illustrated embodiments are exemplary only and several variants of moving the lens/fiber either separately or together can be implemented. These individual cells or subassemblies formed of multiple cells can be assembled into a larger switch fabric with a greater port count. The various layers and elements of the individual unit-cell that correspond to the layers/subassemblies of FIG. 13A are referenced with identical reference numerals.

The beam steering assemblies with the aforedescribed motion transformers can be assembled from individual units, such as the unit depicted in FIG. 13B, or from assemblies, such as the 9 unit assembly 130 depicted in FIG. 13A. Multiple sized assemblies of transmit of receive units can be arranged in various two-dimensional patterns, they can be “tiled” together to form larger assemblies. In this way, smaller defective subunits can be easily replaced in a larger unit of, for example, 64 elements, thereby reducing the overall cost of the optical switch.

Each fiber/lens assembly needs to be carefully collimated for optimizing the optical emitter-to-receiver coupling efficiency. This can be done by observing the wavefront of the device and locking the fiber in place in the tiltable fiber holder (e.g., 82 in FIG. 8) with solder or epoxy, for example, a UV-curable epoxy, when the beam collimation is optimized. This could be performed after assembly of the switch fabric in an external fixture either manually or with an additional actuator capable of displacing the fiber along the fiber axis (z-axis) and in the x- and y- translational directions to effect collimation of steering of the beam. For example z- axis positioning could be accomplished by means of a piezoelectric actuator acting between the elements 1301 and 1302 in Figure 13E.
Referring back to FIG. 1, after the optical switch 10 which incorporates the switch fabric 140 of FIG. 14, has been assembled, the beam trajectory from each emitter 12, 14 on the emitter fabric 11a should preferably point towards the center receiver 18 on the receiver fabric 11b. In this way, the maximum deflection angle of any fiber independent of its location in the emitter fabric 11a is at most half the solid angle $\gamma$ for the receiver fabric 11b.

Since all emitter elements are advantageously fabricated in an identical fashion regardless of their ultimate location in the array, the “optical” rest position of the elements, i.e., the pointing direction of the emitted beam, is preferably adjusted by placing additional optical elements, such as prisms, in front of the collimating lens of the emitters after assembly. Alternately the individual emitters can be mechanically aligned such that the passive (un-actuated) beam is oriented to the center of the receiver array. As illustrated in FIG. 14, a beam is emitted by the tiltable fiber holder 52 located on emitter fabric 11a behind stationary collimating lens 24. Without the prism 142 in the beam path, the collimated beam would impinge on the corresponding opposite lens 24 located on receiver fabric 11b and received by receiver 52. Prism 142, on the other hand, directs the same collimated beam towards the lens 24' located substantially at the center of receiver fabric 11b. The prisms can be selected based on the lateral spacing between the emitter/receiver on the corresponding fabric 11a, 11b from the center elements 24'. The prisms can be individual prism elements or a single element, similar to a Fresnel lens, applied to front of the collimator/lens assembly 136 (FIG. 13).

The overall size of switch 10 (FIG. 1) is determined by the packing density and the available solid scan angle from the beam-steering devices on switch fabric 11a, 11b. The physical length of the device can be shortened by folding the optical path with a fixed mirror. The input and output ports may be on the same array, or on different arrays. Additionally the fold mirror may be curved to introduce windage and to thereby obviate the need for the additional prisms 142, 144 shown in FIG. 14 and/or reduce the required tilt angle of the beam-steering elements located closer to the periphery of the switch fabric.
When the switch fabric 10, 140 is assembled, each beam-steering element can reasonably be expected to have initial pointing errors. Moreover, the beam trajectories – after correction of the initial pointing errors – may change over time and during operation. It is therefore desirable to incorporate a reliable and preferably simple calibration process in the switching system. This calibration process can be performed by an off-line set-up used just after assembly and at required intervals during operation, or by a permanent on-board set-up built into the system itself.

In addition to manufacturing tolerances, variations in performance of the piezoelectric actuators as well as hysteretic or nonlinear response of the actuators need to be accounted for. The actuators may be driven by a voltage or charge drive to improve repeatability.

Referring now to FIG. 15, the system 150 can be calibrated during the initial post manufacturing configuration using, for example, a position sensor array or camera 152. A laser beam is injected into the optical fiber, resulting in a collimated beam being launched from fabric 11a. A fraction of the beam is reflected by a partially reflecting mirror, cube beam splitter, or pellicle 154 and is received by the camera or sensor array 152. The beam-steering device moves the collimated beam in a search pattern while monitoring the optical power in the target fiber attached to switch fabric 11b. The beam position on the camera or sensor array 152 which corresponds to maximum power received by each target fiber is recorded in a lookup table. The process is repeated for every combination of transmit and receive fiber. Each beam-steering device can then be moved to direct the beam to any desired target port by feeding back readings from the position sensor array 152. The charge required to complete a transition can also be recorded in a lookup table for every combination of transmit and receive ports. After completion of the calibration process, the beam splitter 154 and position sensor 152 may be removed. The charge data stored in the lookup table is then used during operation to move any beam-steering element to a new target.
Referring now to FIG. 16, the pointing and alignment of beam 15 can be actively controlled both upon switching between ports and during operation by monitoring the power transmitted from the emitter 14 to the receiver 16. For this purpose, optical tap couplers 168 are installed in the optical fiber lines. on the receiver side, or the transmitter side, or both. Through these taps, the optical power at the receiver or differential optical power across the switch can be monitored by sensors 166 and a corrective signal can be applied to the actuators to optimize power. Alternatively, rather than measuring the communication signal, a reference laser or LED light 162, possibly at a different wavelength from the communication signal to reduce interference, can be coupled into the fibers through tap couplers 164 and again measured by sensors 166. When a different wavelength is coupled into the input side of the device, the output couplers (tap couplers) 168 can be wavelength-selective. The proposed method for actively aligning and optimizing the switch does not require or rely on additional components, such as optical quadrant detectors or capacitance sensors installed on the moving elements themselves, although this can additionally be done using capacitive or piezoresistive sensors.

With optical quadrant detectors, capacitance or piezoresistive sensors, it is fairly straightforward to implement a control loop that guides each beam to its target. However, special techniques are needed for designing a control loop based on the optical power signal alone, since the optical power signal does not contain any directional information for adjusting the signal to the actuators and thus the pointing direction of transmit or receive elements (lens and/or fibers). The control system must hence be able to ascertain the direction to move both transmit and receive elements so as to achieve maximal optical power coupling through the optical link for typical M x N configurations. For 1 x N configurations only the emitter needs be actively controlled while the receivers can optionally be passively aligned.

FIG. 17 is a 3-dimensional plot of the intensity of the light from emitter 14 as received by detector 16 as a function of the tilt angles of the emitter and/or receiver beam-steering element. As seen in FIG. 17, the intensity has a maximum when the fiber is optimally positioned, and falls off for misalignment of the fiber tip in the x- and y-coordinate directions. When a small high-frequency modulation signal
(dither) is superimposed on one or both of the x and y signals and the modulation signals going to each of the actuators are appropriately phased, the beam trajectory associated with the articulating emitter and/or detector element (lens and/or fiber) traces out a small orbit 172 about a nominal position, which causes a small modulation of the received optical power signal. The optimum position corresponds to an orbit 174 that is substantially symmetric about the maximum power point. More complex orbits can be produced by using dither waveforms with different phase relationships between the voltage signals applied to the various actuators. Different phase signals can hence be used to separate the x- and y- directions.

Appropriate convolution and filtering of the optical power and input modulation signals can be used to obtain the optical power gradient information (power changes associated with small perturbations of each of the actuators in the transmit and receive elements). The gradient information is then used to close the loop on the actuators and achieve the desired optical power level. The transmit and receive elements can be modulated at two different frequencies or with different dither waveforms and the power signal can be appropriately filtered to simultaneously extract gradient information for both the transmit and receive beam-steering elements.

Intentional detuning of the beam pointing (caused by slight controlled misalignment of the transmit and receive ports) within a switch can be used to introduce controllable amounts of optical insertion loss for a variable optical attenuator (VOA) function. This feature can be used to implement stand-alone single VOAs or compact multichannel parallel arrays of VOAs. The attenuator feature can also be used in conjunction with the switching operation to balance powers in optical networks without requiring separate VOAs in addition to the switching matrix. This functionality can be achieved by increasing the amplitude of the modulation on the actuators. The beam will then trace an orbit with larger diameter about the optimum position. As the diameter of the orbit is increased, the optical insertion loss of the system is increased, thus providing VOA functionality.

The orientation at which the power is maximized may vary slightly depending on the wavelength of the optical signal. This variation is caused by dependence of
properties of optical elements on wavelength. Therefore, additional compensation is needed in the case where an optional reference laser or LED source 162 of differing wavelength from the communication signal is used to close the loop. Additionally, servoing the modulation signal to a given intensity amplitude can be done using a variety of control techniques.

FIG. 18 shows optical power contours 180 at two different wavelengths as a function of orientation of beam pointing angle. Solid lines 182 correspond to a wavelength $\lambda_1$, for example, the wavelength of a reference signal emitted by laser or LED source 172. Dotted lines 184 correspond to wavelength $\lambda_2$ corresponding to the wavelength of the optical communication signal whose power is to be maximized (or optionally attenuated). During the calibration process, the optical power of both $\lambda_1$ and $\lambda_2$ beams is measured, which may require separate power sensors. At a typical point A neither wavelength is at peak power. At point B, the optical communication signal $\lambda_2$ is at peak power, while at point C the reference signal $\lambda_1$ is at peak power. Thus, using the modulation technique described above, the gradient of the power signal with respect to position can be found for either wavelength. The control loop is then closed based on the gradient of $\lambda_2$ power until the device settles at point B. The insertion loss of the $\lambda_1$ signal as well as its gradient vector is then recorded in a calibration table. This calibration process is repeated for each of the beam-steering devices in the switch. During operation, the orientation of the optical elements may then be controlled by servoing the strength and gradient of the reference signal $\lambda_1$ to the values stored in the calibration table.

It should be noted that the actuators described in detail permit several modes of operation and directions of motion. In general, the actuators can be operated in concert or in opposition. Moved together in synchronism, the actuators will effect a pure translation along the actuator motion axis (fiber axis and optical in the example discussed above). For example, external cavity lasers, vertical cavity surface-emitting lasers (VCSEL's) and/or Fabry-Perot tunable filters implemented either in free space or as waveguides can be wavelength-tuned using these types of amplified piezoelectric actuators. The ability to adjust tilt as well as axial position could allow

- 35 -
for fine control of cavity alignment for such filters or lasers to optimize transmission or laser cavity alignment. This same linear motion can be used when bonded to optical fibers to stretch the fibers for length, delay, or phase control, or for fibers containing fiber Bragg gratings to stretch them to tune their optical wavelength passband and/or dispersion properties. Birefringent fibers could also be manipulated for polarization mode control.

A possible actuation mechanism for changing the length of a fiber or otherwise deforming the fiber — and thereby the controlling optical transmission characteristic such as filter wavelength tuning in the case of a fiber having an applied Bragg grating — is shown in FIGS. 19A and 19B. FIG. 19A shows a particular embodiment in which a piezoelectric actuator 1910 elongating/contracting along an axis acts on a movable silicon micro-machined ferrule 1920 to which a fiber 1930 is attached. The movable ferrule consist of a thicker section of the wafer in which a fiber hole is formed, said thicker section flexibly attached via an impermeable membrane designed to be compliment to ferrule translation but stiff to internal pressure loads. Both the fiber and the actuator are attached at the base such that deformation/actuation of the piezoelectric actuator results in deformation of the fiber for instance stretching between the fixed end and the movable end. In alternate embodiments (not shown), the motion transformation subassemblies depicted previously can be interspersed between the piezoelectric actuator and the movable silicon ferrule (and attached fiber) such that the piezoelectric elongation causes greater (amplified) elongation of the fiber. Fig. 19B shows another embodiment which uses a hydraulic motion amplifier wherein the stroke of the piezo actuator is amplified by a ratio of the surface area of two pistons communicating via a hydraulic fluid reservoir. The fiber is clamped at the top to the movable piston/ferrule and at the bottom surfaces of the structure of FIG. 19B, with the grating on the fiber disposed therebetween. As the piezoelectric actuator compresses the fluid reservoir pressurizing the hydraulic chamber the hydraulic pressure acts on the movable fiber piston to effect elongation of the fiber. By varying the areas of the piezoelectric drive piston and the fiber piston, amplified elongation can be attained. This structure can also be micromachined using MEMS technology. These types of elements can also be employed as variable path length elements, as wavelength
tunable filters or in more complicated subsystems, such as wavelength add/drop multiplexers.

The rapid tuning is also advantageous for use with scanning-type optical performance monitors in which optical power and other signal characteristics are sampled sequentially at several wavelengths, or with wavelength locker schemes used to stabilize the wavelength of tunable lasers.

As shown in FIG. 20A and 20B, these actuators lend themselves to integration with planar waveguide circuits, which are themselves layered and potentially fabricated via microfabrication techniques. For example, actuators 2010 could be used to apply stress or deformation to optical waveguides or otherwise deform them to induce stress birefringence, change the optical path length or optical propagation characteristics through refractive index modulation caused by the photoelastic effect. This type of index/length modulation can be used with the Mach-Zehnder interferometer configuration depicted in FIG. 20A to create optical phase shifts that can switch the optical output between ports, or tune, attenuate or modulate optical signals. In the particular embodiment depicted in Figure 20A, the piezoelectric actuator acts to pressurize a sealed filled hydraulic chamber formed via microfabrication processes. It acts via a forced movement of a sealed movable piston. The pressurized fluid then acts to deform a thinned section of the substrate upon which a planar waveguide element has been fabricated. In this case this is one leg of a mach Zehnder interferometer. As the membrane stretches and bows outward, the waveguide stretches as well and causes a path length change in the leg of the interferometer sufficient to cause a controllable phase delay on the order of 180° to cause selective interference with the signal in the un-deformed leg of the interferometer. In one particular embodiment the silicon substrate for the planar wave guide is thinned (etched) to the order of <10 μm thickness over a circular area of 0.5 - 1 mm diameter along the wave guide. Pressure in the chamber on order of 0.5 to 2 MPa causes bowing of the membrane and waveguide with resulting stresses in the silicon on order < 1 GPA and optical path length changes in the deformed wave guide on order 500-1000 nm.
In an alternate embodiment depicted in Figure 20B, the necessary deformation of the wave guide can be cased by a mechanical motion transformation layer 2050 of the types previously described, arranged such that the actuation of the piezoelectric actuator acts through the motion transformer to cause deformation of the thinned substrate (membrane) and affixed planar wave guide element 2070.

Finally, beam-steering and tunable beam offset can be adjusted by tilting a transmissive parallel plate and/or a mirror. In another beam-steering approach, lenses can be translated perpendicular to the optical axis either with respect to the input beam or to other lenses. Such a translation in the plane of the actuator layers might be achieved through linkages that couple multiple actuators in an array of the type described here. These linkages might be fabricated in additional micro-machined layers that are bonded to the layers discussed earlier.

While the invention has been disclosed in connection with the preferred embodiments shown and described in detail, various modifications and improvements thereon will become readily apparent to those skilled in the art. For example, the emitters and receivers described herein are not limited to optical fibers, but can include other optical waveguides and other emitters, such as lasers and LEDs, as well as conventional detectors. The materials described in connection with the actuation mechanism and the optical system are merely examples, and those skilled in the art will be able to identify and use other materials suitable for the application, such as shape-memory alloys, electrically active polymers or any other material that may be electrically or magnetically activated. Accordingly, the spirit and scope of the present invention is to be limited only by the following claims.

We claim:
CLAIMS:

1. Apparatus for positioning an optical device, comprising
   a motion transformer having a compliant member for coupling with an
   optical device and for coupling to an actuator capable of generating a mechanical
   movement, for generating relative mechanical movement between the actuator
   and the optical device.

2. Apparatus according to claim 1, wherein the motion transformer comprises a
   unitary body.

3. Apparatus according to claim 1, wherein the motion transformer comprises a
   layered sub-assembly.

4. Apparatus according to claim 1, wherein the motion transformer comprises an
   assembly of micro-machined layers.

5. Apparatus according to claim 1, wherein the motion transformer comprises an
   assembly of micro-machined silicon wafers.

6. Apparatus according to claim 1, wherein the motion transformer comprises
   a compliant member including a lever arm.

7. Apparatus according to claim 1, wherein the motion transformer comprises
   a compliant member having
   a lever arm, and
   a flexible joint the lever arm to a housing.

8. Apparatus according to claim 1, wherein the motion transformer comprises
   a compliant member having
a lever arm, and
a flexible joint for coupling the lever arm to an optical device.

9. Apparatus according to claim 1, wherein the motion transformer comprises
a compliant member having a plurality of lever arms.

10. Apparatus according to claim 1, wherein the motion transformer comprises
a compliant member having
a plurality of lever arms, and
a plurality of flexures joining the plurality of lever arms to a housing.

11. Apparatus according to claim 1, wherein the motion transformer comprises
a compliant member including a membrane.

12. Apparatus according to claim 11, wherein the compliant member further
comprises
a flexible joint coupling the membrane to a housing.

13. Apparatus according to claim 1, wherein the motion transformer comprises
a compliant member having
an upper membrane, and
a lower membrane.

14. Apparatus according to claim 1, further comprising
a mechanical coupling for coupling the compliant member to an actuator.

15. Apparatus according to claim 1, further comprising
a stroke amplifier for amplifying movement of the optical device relative
to mechanical movement of the actuator.
16. Apparatus according to claim 1, further comprising
   a holding element coupled to the motion transformer and adapted for
   holding an optical device.

17. Apparatus according to claim 16, wherein
   the holding element is adapted for holding an optical device selected from
   the group consisting of a fiber, a lensed fiber, a lens, a mirror, a grating, a
   collimator, a prism, holographic grating and a filter.

18. Apparatus according to claim 1, further comprising
   a plurality of said motion transformers formed on a substrate.

19. Apparatus according to claim 18, wherein
   the plurality of motion transformers form a linear array on the substrate.

20. Apparatus according to claim 18, wherein
   the plurality of motion transformers form a two-dimensional array on the
   substrate.

21. Apparatus according to claim 1, wherein
   the motion transformer has a contact adapted to couple to a cylindrical actuator.

22. Apparatus according to claim 1, wherein
   the motion transformer has a contact adapted to couple to a plurality of actuators.

23. Apparatus according to claim 1, wherein
   the motion transformer has a contact adapted to couple to an actuator formed of a
   plurality of discrete actuators operating under independent control.

24. Apparatus for positioning an optical device, comprising
   an actuator for generating a mechanical movement, and
   a motion transformer having a compliant member for coupling with an optical
device and for coupling to the actuator for generating relative mechanical movement between the actuator and the optical device.

25. Apparatus according to claim 24, wherein
the actuator is selected from the group consisting of piezoelectric actuator, an electrostrictive actuator, a magnetostrictive actuator, an electrostatic actuator, a thermal actuator, an electromagnetic actuator, a shape memory alloy, and an electroactive polymer.

26. Apparatus according to claim 24, wherein
the actuator mechanically couples to the compliant member for causing the compliant member to flex in response to a generated mechanical movement.

27. Apparatus according to claim 26, wherein
the compliant member includes a lever arm, and
the actuator mechanically couples to the lever arm for pivoting the arm between a first and second position thereby causing the optical device to move to a selected position.

28. Apparatus according to claim 26, wherein
the compliant member includes a membrane, and
the actuator mechanically couples to the membrane for causing the membrane to flex thereby causing the optical device to move to a selected position.

29. Apparatus for steering a beam, comprising
an optical device capable of directing light, and
a motion transformer having a compliant member coupled with the optical device and coupled to an actuator capable of generating a mechanical movement, for causing relative mechanical movement between the actuator and the optical device.

new claim change of focus by further adjust axial position to adjust focus or
collimation of beam.

30. Apparatus according to claim 29, further including
    a light source.

31. Apparatus according to claim 30, wherein
    the light source is selected from the group consisting of an optical fiber, a
    laser, a semi-conductor laser, and a waveguide.

32. Apparatus according to claim 29, wherein
    the optical device comprises a waveguide for steering a beam by moving a
    waveguide relative to a light directing element.

33. Apparatus according to claim 29, wherein
    the optical device comprises a light directing element for steering a beam
    by moving a light directing element relative to a waveguide.

34. A method for positioning an optical device, comprising
    attaching an optical device to a motion transformer having a compliant member,
    contacting the compliant member with an actuator capable of generating a mechanical
    movement, and
    operating the actuator to generate relative mechanical motion between the actuator and
    the optical device.
Fig. 7G
Fig. 11D
Fig. 13D
Fig. 17