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Optomechanical assemblies for temperature-robust laser beam combination and delivery

Abstract

An optomechanical assembly for temperature-robust laser beam processing includes a baseplate and an optics plate. The baseplate includes a source area for accommodating a source of the laser beam, and a light-processing area located away from the source area and including first and second anchor points. The optics plate is disposed in the light-processing area and includes first and second portions and a flexible coupling interconnecting the first and second portions. The first and second portions are fixed to the baseplate at the first and second anchor points, respectively. The flexible coupling allows for a thermally-induced change in distance between the first and second anchor points in the presence of dissimilar thermal expansion of the optics plate and the baseplate. The assembly further includes a series of optical elements for manipulating a laser beam from the laser source. Each of the optical elements is rigidly bonded to the first portion.

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Background/Summary

PRIORITY (1) This application claims priority to U.S. Provisional Application Ser. No. 63/143,670, filed Jan. 29, 2021, the disclosure of which is incorporated herein in its entirety.

TECHNICAL FIELD OF THE INVENTION
(1) The present invention relates in general to laser beam shaping and directing in the presence of temperature variation, in particular to optomechanical assemblies adapted to reduce temperature-induced changes in spatial properties of a laser beam.
DISCUSSION OF BACKGROUND ART

(2) Laser light may be generated with a high degree of spatial coherence. The high spatial coherence offers a level of spatial control that cannot be achieved using incoherent light sources such as incandescent light bulbs or even light-emitting diodes. For example, a laser beam can be focused tightly or form a well-collimated laser beam that maintains a relatively small beam diameter over great distances. It is therefore possible to deliver a laser beam very precisely to a target location and, furthermore, deliver the laser beam to the target location with well-defined transverse size and convergence/divergence. This spatial control may, however, be affected by changes in the temperature of the environment. As the temperature of the environment changes, or as internal parts of a laser system generate heat, optical elements used to manipulate the laser beam may expand or contract, and their locations may shift due to thermal expansion or contraction of structures supporting the optical elements. These temperature effects can cause a variety of issues, such as laser beam pointing error, loss of collimation, and changes in convergence/divergence resulting in a longitudinal focus shift. Herein, the terms “transverse” and “longitudinal” are defined with respect to the local propagation direction of the referenced laser beam.
(3) Many laser-based technologies rely on stable spatial properties of a laser beam. Such technologies may utilize a variety of schemes to stabilize the spatial laser beam properties in the presence of temperature changes. The temperature of the laser system, or one or more key subsystems thereof, may be actively controlled to maintain a constant temperature throughout a wide temperature range. The materials of optical elements and/or support structures may be limited to materials that have relatively low coefficients of thermal expansion. Another option is to actively control certain optical elements to correct for temperature-induced changes. For example, changes to laser beam pointing or a laser beam parameter (such as waist size, waist location, and Rayleigh range).
(4) Modern, laser-based flow cytometry is one example of a technology that requires stable spatial properties of a laser beam. In flow cytometry, the laser beam is focused on a flowing sample. Typically, as fluorescently-labeled cells within the flowing sample pass through the laser beam focus one by one, fluorescence, forward-scattered laser light, and side-scattered laser light are independently detected to identify the cells by their fluorescence properties and size. The transverse profile of the laser beam at its focus may be narrow in the dimension parallel to the sample flow path and elongated in the transverse dimension perpendicular to the sample flow path, with the narrow dimension being as small as about 10-15 microns. Reliable and accurate cell identification relies on the laser beam focus being stable. Most commercially available flow cytometers are equipped with multiple lasers, each having a different wavelength, for compatibility with many different fluorophores and for processing of samples labeled with a combination of different fluorophores. Until recently, the different laser beams intersected the sample flow path at different locations, and each laser channel had its own separate side-scattered fluorescence detection system. More recently, however, so called spectral flow cytometers have been developed. A spectral flow cytometer co-propagates and co-focuses all laser beams to the same plane of intersection with the sample flow path. As compared to a conventional flow cytometry, spectral flow cytometry uses a single side-scatter fluorescence detection system common to all laser channels. This fluorescence detection system uses a spectrograph to distinguish between different wavelengths.
SUMMARY OF THE INVENTION
(5) Disclosed herein are optomechanical assemblies for temperature-robust delivery of a laser beam. The present optomechanical assemblies are based on a two-prong approach to reducing the impact of temperature changes on a subassembly for manipulating the laser beam: (1) materials of the subassembly have relatively low coefficients of thermal expansion, and (2) mechanical decoupling between the subassembly and a supporting baseplate prevents thermal expansion or contraction of the baseplate from forcing expansion, contraction, or distortion of the subassembly. For the remainder of this disclosure, unless otherwise noted, the term expansion covers both positive expansion and negative expansion (i.e., contraction). The temperature of the

optomechanical assemblies may change in response to ambient temperature changes or as heat is generated from an internal source such as a laser. Flow cytometers may utilize the presently disclosed assemblies for temperature-robust laser beam delivery to maintain a stable laser beam focus at the intersection with the sample flow path.
(6) The same principles are applied to optomechanical assemblies for temperature-robust combination, and delivery, of a plurality of laser beams. In such beam-combining assemblies, multiple different subassemblies, made of materials with relatively low coefficients of thermal expansion are supported by a common baseplate. Each subassembly manipulates a different respective laser beam before this laser beam is combined with the other laser beams to form a composite laser beam. Mechanical decoupling between each subassembly and a supporting baseplate prevents thermal expansion of the baseplate from forcing expansion or distortion of the subassemblies. The presently disclosed beam-combination assemblies are suitable for incorporation in spectral flow cytometers, where they may maintain a stable focus of a composite multi-color laser beam at the intersection with the sample flow path.
(7) In one aspect, an optomechanical assembly for temperature-robust laser beam processing includes a baseplate. The baseplate includes a source area for accommodating a source of the laser beam and a light-processing area located away from the source area and including first and second anchor points. The assembly further includes an optics plate disposed in the light-processing area. The optics plate includes first and second portions and a flexible coupling that interconnects the first and second portions. The first and second portions are fixed to the baseplate at the first and second anchor points, respectively. The flexible coupling allows for a thermally induced change in distance between the first and second anchor points in the presence of dissimilar thermal expansion of the optics plate and the baseplate. In addition, the assembly includes a linearly arranged series of optical elements for manipulating a laser beam from the laser source. Each of the optical elements is rigidly bonded to the first portion of the optics plate and arranged along a propagation axis of the laser beam that is coincident with a line between the first and second anchor points. The coefficient of thermal expansion (CTE) of the optics plate is (a) matched to the CTEs of the optical elements to within 20% and (b) lower than the CTE of the baseplate.
(8) In another aspect, a temperature-robust optomechanical assembly for laser beam combination includes a baseplate that has orthogonal lengthwise and widthwise dimensions and includes a sequence of source areas. The source areas are distributed along the widthwise dimension and is each configured to accommodate a laser source for generating a respective laser beam. The assembly further includes a corresponding sequence of optical subassemblies offset from the sequence of source areas in the lengthwise dimension. Each optical subassembly includes an optics plate fixed to the baseplate. Each optics plate includes at least one flexure to accommodate dissimilar thermal expansion of the optics plate and the baseplate. At least one of the optical subassemblies includes a linearly arranged series of optical elements that is (a) rigidly bonded to the optics plate, (b) characterized by coefficients of thermal expansion (CTEs) that are matched with the CTE of the optics plate to within 20%, and (c) configured to manipulate the laser beam received from the corresponding source area. The assembly also includes a mirror rigidly bonded to the optics plate of a first one of the optical subassemblies. In addition, for each of the one or more subsequent optical subassemblies, the assembly includes a respective beam combiner rigidly bonded to the optics plate thereof. The mirror and the one or more beam combiners are cooperatively configured to serially combine the laser beams.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The accompanying drawings, which are incorporated in and constitute a part of the

specification, schematically illustrate preferred embodiments of the present invention, and together with the general description given above and the detailed description of the preferred embodiments given below, serve to explain principles of the present invention.
(2) FIGS. **1** and **2** illustrate an optomechanical assembly for temperature-robust delivery of a laser beam, according to an embodiment.
(3) FIG. **3** illustrates an optomechanical assembly for temperature-robust laser beam combination, according to an embodiment.
(4) FIG. **4** illustrates an optics plate configured to accommodate a series of optical elements and decouple these optical elements from thermal expansion of a baseplate supporting the optics plate, according to an embodiment.
(5) FIGS. **5** and **6** illustrate another optics plate including two flexures that serve to decouple a series of optical elements from thermal expansion of a supporting baseplate, according to an embodiment.
(6) FIG. **7** illustrates direct bonding of an optical element to an optics plate, according to an embodiment.
(7) FIG. **8** illustrates indirect bonding of an optical element to an optics plate via a mount, according to an embodiment.
(8) FIG. **9** illustrates indirect bonding of an optical element to an optics plate via two pillars that hold the optical element above the optics plate, according to an embodiment.
DETAILED DESCRIPTION OF THE INVENTION
(9) Referring now to the drawings, wherein like components are designated by like numerals, FIGS. **1** and **2** are top plan views of one optomechanical assembly **100** for temperature-robust delivery of a laser beam. Assembly **100** may, advantageously, be implemented in a flow cytometer to deliver a laser beam to a sample flow path in a temperature robust manner. Assembly **100** includes a baseplate **110** and a subassembly **120** mounted on baseplate **110**. Subassembly **120** is mounted to baseplate **110** in a light-processing area **114**. Subassembly **120** is configured to manipulate a laser beam **190** received from a laser source **160** that is mounted to baseplate **110** in a source area **112**. Assembly **100** may be provided with or without laser source **160**. FIGS. **1** and **2** show the state of assembly **100** at two different temperatures. The temperature associated with FIG. **2** is higher than the temperature associated with FIG. **1**.
(10) The shape of baseplate **110** may be different from that shown in FIGS. **1** and **2**, for example non-rectangular. Baseplate **110** may include a plurality of through-holes for mounting assembly **100** to a support. Four exemplary through-holes **111** are labeled in FIG. **1**.
(11) Subassembly **120** includes an optics plate **130** mounted to baseplate **110**, and a series of optical elements **140** and **142** mounted to a portion **132** of optics plate **130**. Optical elements **140** and **142** serve to manipulate laser beam **190** to produce a manipulated laser beam **192**. Optical elements **140** and **142** are arranged in series along laser beam **190**, and include a last optical element **140** as well as one or more preceding optical elements **142**. In the example depicted in FIGS. **1** and **2**, optical element **140** is a mirror and subassembly **120** includes three preceding optical elements **142**(*a-c*), wherein elements **142**(*a*) and **142**(*b*) are lenses and element **142**(*c*) may be a waveplate, polarizer, or filter. In this depicted example, lenses **142**(*a*) and **142**(*b*) may form a telescope configured to change the size of a collimated laser beam. Without departing from the scope hereof, subassembly **120** may instead be implemented with a different series of optical elements than depicted in FIGS. **1** and **2**.
(12) Optical elements **140** and **142** are rigidly bonded to portion **132** of optics plate **130**. Each one of optical elements **140** or **142** may be bonded to optics plate **130** either directly or indirectly via one or more mounting elements. When indirectly bonded to optics plate **130** via a mount, the optical element is rigidly bonded to the mount, the mount is rigidly bonded to optics plate **130**, and the mount itself is rigid. The coefficient of thermal expansion (CTE) of optics plate **130** is matched to the CTEs of optical elements **140** and **142**, to within 20%, to prevent significant differences

between thermal expansion of optics plate **130** and thermal expansion of optical elements **140** and **142** and, for example, to prevent the bonds from breaking during thermal expansion. For the same reasons, the CTEs of any mounts used to bond optical elements **140** and **142** to optics plate **130** are also matched to the CTEs of optical elements **140** and **142** to within 20%. Such mounts may be made of the same material as optical elements **140** and **142**.

(13) Furthermore, the CTEs of optics plate **130** and optical elements **140** and **142** are relatively low in order to limit changes in the relative locations of optical elements **140** and **142** caused by thermal expansion of optics plate **130** and/or optical elements **140** and **142** themselves. In one example, the CTEs of optics plate **130** and each optical element **140** and **142** are less than 10.sup.−5 K.sup.−1.

(14) In one embodiment, optics plate **130** is made of metal, and optical elements **140** and **142** are made of glass. In this embodiment, any mounts used to bond one or more of optical elements **140** and **142** to optics plate **130** may be made of metal or glass as well. Optics plate **130** may be made of titanium or a titanium alloy, for example an alpha-beta titanium alloy (e.g., Ti-6Al-4V). Optical elements **140** and **142** may be made of borosilicate glass, such as Schott N-BK7.

(15) In addition to portion **132**, optics plate **130** includes a portion **134** and a flexible coupling **136** that interconnects portions **132** and **134**. Portions **132** and **134** are fixed to baseplate **110** at respective anchor points **116** and **118** of baseplate **110**. Anchor points **116** and **118** are farther from and closer to, respectively, source area **112**. In one embodiment, portion **132** is fixed to anchor point **116** of baseplate **110** by a fastener **156** through a hole in portion **132**, and portion **134** is fixed to anchor point **118** of baseplate **110** by a fastener **158** through a hole in portion **134**. Flexible coupling may include or consist of one or more flexures, each interconnecting portions **132** and **134** while allowing for changes in distance between portions **132** and **134**.

(16) As illustrated by the differences between FIGS. **1** and **2**, flexible coupling **136** allows for a thermally induced change in the distance between anchor points **116** and **118** in the presence of dissimilar thermal expansion of baseplate **110** and subassembly **120**. Significantly dissimilar thermal expansion may arise when the CTEs of baseplate **110** and optics plate **130** differ by more than, e.g., 20%, for example when the CTE of baseplate **110** is at least twice the CTE of optics plate **130**. At the lower temperature of FIG. **1**, baseplate **110** has a length **110**L, portion **132** has a length **132**L, and portions **132** and **134** are a distance **136**L apart. Length **110**L, length **132**L, and distance **136**L are measured in the dimension parallel to the propagation axis of laser beam **190** between source area **112** and light-processing area **114**. (Baseplate **110** may or may not have sides that are parallel to length **110**L.) At the higher temperature of FIG. **2**, baseplate **110** has a length **110**L′, portion **132** has a length **132**L′, and portions **132** and **134** are a distance **136**L′ apart. Since the CTE of optics plate **130** is less than the CTE of baseplate **110**, the relative length increase of portion **132**, i.e., (**132**L′-**132**L)/**132**L, is less than the relative length increase of baseplate **110**, i.e., (**110**L′-**110**L)/**110**L. Anchor points **116** and **118** move with the thermal expansion of baseplate **110**, and the difference in relative length increase between portion **132** and baseplate **110** is accommodated by flexible coupling **136**. As seen in FIGS. **1** and **2**, the distance **136**L′ between portions **132** and **134** at the higher temperature of FIG. **2** exceeds the distance **136**L between portions **132** and **134** at the lower temperature of FIG. **1**.

(17) By virtue of flexible coupling **136**, the relative positions of optical elements **140** and **142** are unaffected by the thermal expansion of baseplate **110**, at least as long as the change in separation between anchor points **116** and **118** is within the dynamic range of flexible coupling **136**. The relative positions of optical elements **140** and **142** may still be affected by their intrinsic thermal expansion as well as thermal expansion of portion **132**. In the absence of flexible coupling **136**, baseplate **110** and optics plate **130** would, by virtue of being fixed to each other at anchor points **116** and **118**, act essentially as bimetallic strips. Therefore, without flexible coupling **136**, dissimilar thermal expansion of baseplate **110** and optics plate **130** would cause deformation that changes the relative locations of optical elements **140** and **142**, resulting in distortion and/or

misalignment of laser beam **190**.
(18) In one embodiment, the CTEs of optics plate **130** and optical elements **140** and **142** are lower than the CTE of baseplate **110**. For example, baseplate **110** may be made of aluminum or an aluminum alloy (e.g., 6061-T6), and optics plate **130** may be made of titanium or a titanium alloy, as discussed above. In this embodiment, the thermal expansions of optics plate **130** and baseplate **110** are dissimilar, but flexible coupling **136** accommodates the dissimilar thermal expansion and renders the relative locations of optical elements **140** and **142** robust to thermal expansion of baseplate **110**. Assembly **100** thereby reduces thermal expansion effects on the relative locations of optical elements **140** and **142**, as compared to an assembly where optical elements **140** and **142** are mounted directly to baseplate **110**. The dynamic range of flexible coupling **136** may allow for a change in separation between anchor points **116** and **118** of up to at least several microns, for example up to at least 5 microns.
(19) Without departing from the scope hereof, the CTE of baseplate **110** may be similar to or less than the CTEs of optics plate **130** and optical elements **140** and **142**.
(20) In the embodiment depicted in FIGS. **1** and **2**, anchor points **116** and **118** are located on a line that is coincident with a linear propagation axis of laser beam **190**. In another embodiment, one or both of anchor points **116** and **118** are offset from this axis. Additionally, without departing from the scope hereof, subassembly **120** may be configured such that the propagation path of laser beam **190**, between the optical elements mounted to portion **132** is folded, as opposed to linear as shown in FIGS. **1** and **2**.
(21) In the embodiment depicted in FIGS. **1** and **2**, each of portions **132** and **134** is fixed to baseplate **110** only at a single anchor point. Without departing from the scope hereof, since optical elements **140** and **142** are mounted to portion **132**, portion **134** may be fixed to baseplate **110** at two or more anchor points (and thus potentially be affected by thermal expansion of baseplate **110**). For example, portion **134** may be fixed to baseplate **110** at two anchor points **118** symmetrically offset from a linear propagation axis of laser beam.
(22) As baseplate **110** expands, the distance between portion **132** and source area **112** changes. As a result, the points where optical elements **140** and **142** intersect laser beam **190** shift along the propagation axis of laser beam **190** when baseplate **110** expands. In one scenario, laser beam **190** is collimated (or at least approximately collimated) at the input to subassembly **120** such that the properties of laser beam **192** are insensitive (or at least approximately insensitive) to such changes in the distance between portion **132** and source area **112**.
(23) Optical element **140** defines an origin **198**, from which subassembly **120** launches manipulated laser beam **192** for direct use or for further processing outside subassembly **120**. To stabilize the position of origin **198** relative to baseplate **110**, optical element **140** may be positioned close to anchor point **116** such that thermal expansion of portion **132** has minimal impact on the position of optical element **140**, and origin **198**, relative to anchor point **116**. In one embodiment, optical element **140** is positioned such that origin **198** is directly above anchor point **116**. Optical element **140** may be a mirror arranged to direct manipulated laser beam **192** out of subassembly **120** at a non-zero angle (e.g., approximately 90 degrees, as shown in FIGS. **1** and **2**) to the propagation axis of laser beam **190** between source area **112** and subassembly **120**. In this embodiment, positioning of optical element **140** close to anchor point **116** minimizes transverse translation of manipulated laser beam **192** caused by thermal expansion of portion **132**. In particular, positioning the point of incidence and reflection of laser beam **190** on optical element **140** directly above anchor point **116** is expected to eliminate such transverse translation. Furthermore, in this embodiment, baseplate **110** may have through-holes (for mounting assembly **100** to a support) that are approximately aligned with the propagation axis of manipulated laser beam **192** for added temperature robustness. For example, anchor point **116** and two through-holes **111** of baseplate **110** may be located on a line that is either coincident with, or parallel and close to, the propagation axis of manipulated laser beam.

(24) Optics plate **130** may be integrally formed. In one such implementation, flexible coupling **136** is in the form of one or more relatively thin and bendable connectors between portions **132** and **134**. In another such implementation, flexible coupling **136** is in the form of one or more connectors between portions **132** and **134**, wherein the contact area between each connector and each of portions **132** and **134** has a small cross-sectional area to allow flexure in the region proximate to the contact areas.
(25) In one use scenario, a flow cytometer incorporates assembly **100** to generate and shape manipulated laser beam **192** for interrogation of samples. In this scenario, the flow cytometer further includes a focusing lens that focuses manipulated laser beam **192** at the sample flow path. This focusing lens may be mounted on baseplate **110**, or externally to assembly **100**.
(26) FIG. **3** is a top plan view of one optomechanical assembly **300** for temperature-robust laser beam combination. Assembly **300** is an extension of assembly **100** wherein the baseplate supports a plurality of subassemblies **120** configured to manipulate different respective laser beams **190** and serially combine the manipulated laser beams. Assembly **300** may, advantageously, be implemented in a spectral flow cytometer to combine multiple laser beams of different colors and deliver the resulting composite laser beam to a sample flow path in a temperature robust manner.
(27) Assembly **300** includes a baseplate **310**. Baseplate **310** is an extension of baseplate **110** that includes a plurality of source areas **112** and a corresponding plurality of light-processing areas **114**. Each source area **112** is configured to accommodate a respective laser source **160**. Assembly **300** may be provided with or without laser sources **160**. Assembly **300** includes a plurality of subassemblies **120**, each mounted in a different respective light-processing area **114** to manipulate laser beam **190** received from laser source **160** of the corresponding source area **112**. Each subassembly **120** of assembly **300** is configured within the corresponding light-processing area **114** of baseplate **310** in the same manner as subassembly **120** of assembly **100** is configured within light-processing area **114** of baseplate **110**.
(28) In the example depicted in FIG. **3**, assembly **300** includes three source areas **112(1-3)** and three light-processing areas **114(1-3)**. Each light-processing area **114**(*i*), i∈{1, 2, 3}, contains a subassembly **120**(*i*) configured to manipulate a laser beam **190**(*i*) received from laser source **160**(*i*) located in source area **112**(*i*). Last optical element **140** of subassembly **120(1)** is implemented as a mirror **340**M that directs manipulated laser beam **192(1)**, produced by optical elements **142** of subassembly **120(1)**, toward last optical element **140** of subassembly **120(2)**. Last optical element **140** of subassembly **120(2)** is implemented as a beam combiner **340**C that combines manipulated laser beam **192(1)** with manipulated laser beam **192(2)**, produced by optical elements **142** of subassembly **120(2)**, to form a composite laser beam **394(2)**. Beam combiner **340**C of subassembly **120(2)** directs composite laser beam **394(2)** toward last optical element **140** of subassembly **120(3)**. Last optical element **140** of subassembly **120(3)** is implemented as a beam combiner **340**C that combines composite laser beam **394(2)** with manipulated laser beam **192(3)**, produced by optical elements **142** of subassembly **120(3)**, to form a composite laser beam **394(3)**. Mirror **340**M and each beam combiner **340**C of assembly **300** thus cooperate to serially combine manipulated laser beams **192(1)**, **192(2)**, and **192(3)** into a single composite laser beam **394(3)**.
(29) In another embodiment, not shown in FIG. **3**, assembly **300** omits the middle subassembly **120(2)** and includes only the first subassembly **120(1)** and the last subassembly **120(3)** for combination of two laser beams. Similarly, the sequence of subassemblies **120** in assembly **300** may include more than one subassembly **120** between the first and last subassemblies **120** for serial combination of more than three laser beams. In such embodiments, the beam combiner **340** of each non-first subassembly **120** combines the manipulated laser beam **192**, produced by this subassembly **120**, with a manipulated or composite laser beam received from the preceding subassembly **120** in the sequence. Furthermore, one or more subassemblies **120** of assembly **300** may omit optical elements **142** and only function as a beam combiner, or, in the case of the first subassembly **120(1)**, serve to direct laser beam **190(1)** to a second subassembly **120** in the

sequence for combination with another laser beam.
(30) In one scenario, each laser beam **190** processed by assembly **300** is a collimated laser beam at the input to the corresponding subassembly **120**, and manipulation performed by subassemblies **120**(**1-3**) may serve, at least in part, to change the size of these collimated laser beams. For example, the manipulation performed by subassemblies **120**(**1-3**) may set the beam diameter of all the collimated laser beams to the same value. In this scenario, each subassembly **120** may include a telescope. In certain embodiments, assembly **300** matches the size of one or more collimated laser beams **190** to the size of one or more other collimated laser beams **190**. For example, in implementations with three subassemblies **120** that process three respective collimated laser beams **190**, subassembly **120**(**1**) may omit optical elements **142**, while optical elements **142** of subassemblies **120**(**2**) and **120**(**3**) generate manipulated laser beams **192** that have the same size as laser beam **190**(**1**).
(31) Although it is possible to configure assembly **300** to operate with at least some of laser beams **190** being non-parallel, the parallel configuration depicted in FIG. **3** likely is a more compact and simpler design to build and operate. In the embodiment depicted in FIG. **3**, source areas **112** are distributed along a widthwise dimension parallel to the y-axis of coordinate system **302**, and each light-processing area **114** is offset from the corresponding source area **112** in a lengthwise dimension parallel to the x-axis of coordinate system **302**. In this embodiment, the propagation paths of the manipulated and composite laser beams, between subassemblies **120** and out of the last subassembly **120**, may conveniently be substantially along the widthwise dimension. Furthermore, the propagation paths of laser beams **190** between source areas **112** and the corresponding light-processing areas **114** may be substantially along the lengthwise dimension, such that the beam combiner **140** of each non-first subassembly **120** combines two laser beams incident on the beam combiner from mutually orthogonal directions. For added temperature robustness, two screw holes of baseplate **110** may be collinear with anchor points **116**.
(32) FIG. **4** is a top plan view of one optics plate **400** configured to accommodate a series of optical elements and decouple these optical elements from thermal expansion of a baseplate supporting the optics plate. Optics plate **400** is an embodiment of optics plate **130** and may be implemented in assemblies **100** and **300** on baseplates **110** and **310**, respectively. Optics plate **400** includes portions **432** and **434** and two flexures **436**. Each flexure **436** connects between portions **432** and **434**. Portion **432** is configured to accommodate optical elements **140** and **142**. Portion **432** defines a through-hole **466** configured to accommodate a fastener for fixing portion **432** to the baseplate, and portion **434** defines a through-hole **468** configured to accommodate a fastener for fixing portion **434** to the baseplate. In operation, as the baseplate expands, the distance **460**D between through-holes **466** and **468** changes. Flexures **436** absorb this change, such that the length **432**L of portion **432** remains unaffected by the thermal expansion of the baseplate.
(33) Optics plate **400** may be integrally formed, for example machined from one solid piece of metal such as titanium or a titanium alloy. One or more of portion **432**, portion **434**, and flexures **436** may have a different shape than depicted in FIG. **4**, without departing from the scope hereof.
(34) In one use scenario, a flow cytometer incorporates assembly **300** to generate a composite laser beam **394** for interrogation of samples. In this scenario, the flow cytometer further includes a focusing lens that focuses composite laser beam **394**(**3**) after being launched from beam combiner **340**C of the laser subassembly **120**(**3**). This focusing lens may be mounted on baseplate **310**, or externally to assembly **300**. In one preferred embodiment, the optical axis of the focusing lens is aligned with the propagation axis of the composite laser beam **294**(**3**).
(35) FIGS. **5** and **6** are top plan views of another optics plate **500** including two flexures that serve to decouple a series of optical elements from thermal expansion of a supporting baseplate. FIGS. **5** and **6** show optics plate **500** at two different temperatures, with configuration changes being exaggerated for clarity. The temperature associated with FIG. **6** is higher than the temperature associated with FIG. **5**. Optics plate **500** is an embodiment of optics plate **400** that defines a slit

570. Slit **570** defines (a) a portion **532** defining a through-hole **466** and configured to accommodate optical elements **140** and **142** and, (b) a portion **534** defining a through-hole **468**, and (c) two flexures **536**(**1**) and **536**(**2**), each connecting between portions **532** and **534**.
(36) More specifically, slit **570** partially surrounds through-hole **468**, with a rim-shaped segment of portion **534** between slit **570** and through-hole **468**. Slit **570** extends in two opposite directions away from through-hole **468** to two respective termini **572**(**1**) and **572**(**2**). Slit **570** thereby separates portions **532** and **534** from each other. Each flexure **536** extends from portion **534** to portion **532** at a respective one of the two termini **572**. Slit **570** may be formed by wire erosion.
(37) In operation, as the baseplate expands, the distance **460** between through-holes **466** and **468** changes from distance **460**L in FIG. **5** to distance **460**L′ in FIG. **6**. Flexures **536** absorb this change, as seen in FIG. **6**, such that the length **532**L of portion **532** remains unaffected by the thermal expansion of the baseplate (although length **532**L may increase from length **532**L in FIG. **5** to a length **532**L′ in FIG. **6** due to thermal expansion of optics plate **500** itself). Each flexure **536** may flex primarily at the corresponding terminus **572** and/or at its connection to portion **536** near the rim around through-hole **468**. Alternatively, a substantial portion of the flex may be distributed along the length of each flexure **536** between portions **532** and **534**.
(38) In one implementation, width **532**W of optics plate **500** is in the range between 5 and 100 millimeters, and the dynamic range of flexures **536** can accommodate a change in distance **460**L of at least several microns, for example at least 5 microns.
(39) FIG. **7** illustrates, in side-view, a configuration **700** wherein an optical element **740** is bonded directly to a top surface **750** of portion **132** of optics plate **130**. Any one of optical elements **140** and **142** may be bonded directly to portion **132** according to configuration **700**.
(40) FIG. **8** illustrates, in side-view, a configuration **800** wherein optical element **740** is only indirectly bonded to top surface **750** of portion **132** of optics plate **130** via a mount **860**. In configuration **800**, optical element **740** is directly bonded to a surface **852** of mount **860**, and mount **860** is directly bonded to top surface **750** of portion **132**. Mount **860** may be made of the same material as optical element **740**, or a similar material. For example, optical element **740** and mount **860** may both be made of a low-CTE glass, such as borosilicate glass. Alternatively, mount **860** may be made of the same material or a similar material to portion **132**. Mount **860** may even be an integral feature of portion **132**. Any one of optical elements **140** and **142** may be bonded to portion **132** according to configuration **800**.
(41) FIG. **9** illustrates, in side-view, a configuration **900** wherein optical element **740** is only indirectly bonded to top surface **750** of portion **132** of optics plate **130** via two pillars **960** that hold optical element **740** above top surface **750**. In configuration **900**, optical element **740** is clamped between pillars **960**, with optical element **740** being directly bonded to a side surface **952** of each pillar **960**. Each pillar **960** is directly bonded to top surface **750**. Any one of optical elements **140** and **142** may be bonded to portion **132** according to configuration **900**.
(42) Each direct bond in configurations **700**, **800**, and **900** may include an adhesive or be adhesive-free (e.g., formed by contact bonding). Optical elements **140** and **142** may be indirectly bonded to top surface **750** of portion **132** according to different and more elaborate bonding configurations than those shown in FIGS. **7-9**, as long as the bonds are rigid.
(43) The present invention is described above in terms of a preferred embodiment and other embodiments. The invention is not limited, however, to the embodiments described and depicted herein. Rather, the invention is limited only by the claims appended hereto.

Claims

1. An optomechanical assembly for temperature-robust laser beam processing, comprising: a baseplate including: a source area for accommodating a source of the laser beam, and a light-processing area located away from the source area and including first and second anchor points; an

optics plate disposed in the light-processing area and including first and second portions and a flexible coupling interconnecting the first and second portions, the first and second portions being fixed to the baseplate at the first and second anchor points, respectively, with the flexible coupling allowing for a thermally induced change in distance between the first and second anchor points in the presence of dissimilar thermal expansion of the optics plate and the baseplate; and a linearly arranged series of optical elements for manipulating a laser beam from the laser source, each of the optical elements being rigidly bonded to the first portion of the optics plate and arranged along a propagation axis of the laser beam that is coincident with a line between the first and second anchor points; wherein the coefficient of thermal expansion (CTE) of the optics plate is (a) matched to the CTEs of the optical elements to within 20% and (b) lower than the CTE of the baseplate.
2. The assembly of claim 1, wherein each of at least one of the optical elements is rigidly bonded to the optics plate via one or more rigid mounts having a CTE matched to the CTE of the corresponding optical element to within 20%.
3. The assembly of claim 1, wherein each of the baseplate and the optics plate is made of metal, and the optical elements are made of glass.
4. The assembly of claim 3, wherein each optical element is rigidly bonded to the optics plate either directly or via two glass pillars.
5. The assembly of claim 4, wherein the one or more glass pillars and the optical elements are made of the same material.
6. The assembly of claim 3, wherein the optics plate and the optical elements have CTEs less than 10^{-5} K^{-1}.
7. The assembly of claim 3, wherein the optics plate is made of titanium or a titanium alloy, and the optical elements are made of borosilicate glass.
8. The assembly of claim 1, wherein the flexible coupling includes a pair of flexures, each interconnecting the first and second portions.
9. The assembly of claim 1, wherein the optics plate defines: a first through-hole at the first anchor point; a second through-hole at the second anchor point; and a slit that (a) partially surrounds the second through-hole with a segment of the second portion between the slit and the second through-hole and (b) extends in two opposite directions away from the second through-hole to two respective termini, such that the slit separates the first and second portions from each other and defines two flexures forming the flexible coupling, each flexure extending from the second portion to the first portion at a respective one of the two termini, respectively.
10. The assembly of claim 1, wherein the optical elements include a telescope.
11. A temperature-robust optomechanical assembly for laser beam combination, comprising: the assembly of claim 1, wherein the baseplate forms several instances of the source area and the assembly includes several corresponding instances of both the optics plate and the series of optical elements bonded thereto, the several instances of the series of optical elements being configured to manipulate several corresponding instances of the laser beam received from the respective source areas; and a mirror rigidly bonded to a first instance of the optics plate, and, for the one or more subsequent instances of the optics plate, one or more respective beam combiners rigidly bonded thereto to serially combine the laser beams as manipulated.
12. A temperature-robust optomechanical assembly for laser beam combination, comprising: a baseplate having orthogonal lengthwise and widthwise dimensions, and including a sequence of source areas distributed along the widthwise dimension and each configured to accommodate a laser source for generating a respective laser beam; a corresponding sequence of optical subassemblies offset from the sequence of source areas in the lengthwise dimension, each optical subassembly including an optics plate fixed to the baseplate, each optics plate including at least one flexure to accommodate dissimilar thermal expansion of the optics plate and the baseplate, at least one of the optical subassemblies including a linearly arranged series of optical elements that is (a) rigidly bonded to the optics plate, (b) characterized by coefficients of thermal expansion (CTEs)

that are matched with the CTE of the optics plate to within 20%, and (c) configured to manipulate the laser beam received from the corresponding source area; and a mirror rigidly bonded to the optics plate of a first one of the optical subassemblies, and, for each of the one or more subsequent optical subassemblies, a respective beam combiner rigidly bonded to the optics plate thereof, the mirror and the one or more beam combiners being cooperatively configured to serially combine the laser beams.

13. The assembly of claim 12, wherein the mirror and the one or more beam combiners are aligned to a substantially widthwise propagation path of the laser beams.

14. The assembly of claim 13, wherein each laser beam has a lengthwise propagation path from the respective source area to the series of optical elements of the corresponding optical subassembly.

15. The assembly of claim 12, wherein the baseplate includes at least two source areas, and the sequence of optical subassemblies includes at least two optical subassemblies having a corresponding linearly arranged series of optical elements for manipulation of the respective laser beam.

16. The assembly of claim 12, wherein, for each optical subassembly, (a) the optics plate includes first and second portions connected to each other via the at least one flexure, each of the first and second portions being fixed to the baseplate at a respective single anchoring point, and (b) the optical elements are rigidly bonded to the first portion.

17. The assembly of claim 16, wherein the mirror and the one or more beam combiners are bonded to the respective optics plate at the anchoring point of the first portion, to minimize thermal-expansion-induced displacement of the mirror and the one or more beam combiners in the lengthwise dimension.

18. The assembly of claim 12, wherein the optics plate has a lower CTE than the baseplate.

19. The assembly of claim 12, wherein each series of optical elements includes a plurality of lenses for changing at least one of size and divergence of the laser beam.

20. The assembly of claim 19, wherein each of the lenses is rigidly bonded to the optics plate, either directly or via one or more rigid mounts, each rigid mount having a CTE matched to the CTEs of the optical elements to within 20%.

21. The assembly of claim 12, further comprising the laser source associated with each source area, wherein each laser source is configured to deliver the respective laser beam to the corresponding optical subassembly as a collimated input laser beam, and wherein at least one series of optical elements includes a telescope for changing diameter of the laser beam while maintaining collimation.

22. A flow-cytometer, comprising: the assembly of claim 12, further including the laser source associated with each source area, for generating a composite laser beam consisting of the laser beams as serially combined; and a focusing element for focusing the composite laser beam to a sample flow path.