

MAGNIFICATION-COMPENSATED RELAY FOR CONTROL OF AN IMAGE LOCATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Application Ser. No. 63/516,148 – entitled “Magnification-Compensated Relay for Control of an Image Location” filed on July 28, 2023, the contents of which are incorporated by reference herein.

TECHNICAL FIELD

[0002] Embodiments described herein relate generally to laser-processing apparatuses, optical relay systems, the components thereof, and to techniques for operating the same.

BACKGROUND

[0003] Laser-processing systems or apparatus are used in a wide variety of applications, including printed circuit board (PCB) machining, additive manufacturing, and the like. Many laser-processing systems include a scan lens for focusing a beam of laser energy onto a workpiece and a positioner for moving the focused beam of laser energy relative to some material to be processed. In some laser-processing systems, the scan lens can be moved while the positioner remains stationary, so the optical path length between the scan lens and the positioner can change depending on the movement of the scan lens. A change in the optical path length can result in the beam of laser energy rotating about a pivot point that is located outside the entrance pupil of the scan lens (also referred to herein as the “scan lens entrance pupil” or, more simply, the “SLEP”). Location of the pivot point outside the SLEP can introduce telecentric errors, create beam distortion at the workpiece, and result in undesirable beam clipping by the galvo mirrors and at the scan lens entrance pupil.

SUMMARY

[0004] One embodiment of the present invention can be characterized as a system that includes: a scan lens, a first positioner configured to move the scan lens, and an optical relay system configured to relay a beam of laser energy propagating along a beam path to an entrance pupil of the scan lens. The optical relay system includes an optical relay including a first lens and a second lens, a first retroreflector configured to direct the beam path of the beam of laser energy to the optical relay, a second retroreflector positioned on a first side of the scan lens, and a third retroreflector positioned on a second side of the scan lens. The second retroreflector and the third retroreflector may be positioned between the first lens and the second lens, wherein the first retroreflector is movable relative to the second retroreflector

and the third retroreflector, wherein the first positioner is configured to move the scan lens relative to the second retroreflector.

[0005] The system may further comprise a second positioner configured to deflect the beam path of the beam of laser energy about a pivot point. The optical relay system is arranged and configured to relay the pivot point to the entrance pupil of the scan lens. The second positioner may be either an AOD system or a galvanometer mirror system. In one embodiment, the optical relay system has a longitudinal magnification between 0.81 and 0.25. In another embodiment, the optical relay system has a longitudinal magnification between 0.64 and 0.36. In another embodiment, the optical relay system has a longitudinal magnification between 0.56 and 0.42. In another embodiment, the optical relay system has a longitudinal magnification between 0.51 and 0.47. In another embodiment, the optical relay system has a longitudinal magnification of 0.499. The first retroreflector may be mounted on a linear stage configured to move the first retroreflector relative to the optical relay. The first positioner may include a linear stage. The optical relay system may include a mirror configured to direct the beam path of the beam of laser energy from the third retroreflector to the scan lens. The system may further include a third positioner configured to deflect the beam path of the beam of laser energy, wherein the third positioner is coupled to the first positioner.

[0006] Another embodiment of the present invention can be characterized as a system that includes: a first lens and a second lens, a first retroreflector, a second retroreflector, and a third retroreflector. The first retroreflector is arranged to receive a beam of laser energy propagating along a beam path and is configured to direct the beam path to the first lens, the second retroreflector is arranged to receive the beam of laser energy from the first lens and direct the beam path to the third retroreflector, and the third retroreflector is arranged to receive the beam path from the second retroreflector and configured to direct the beam path to the second lens. The first retroreflector may be movable relative to the second retroreflector and the third retroreflector. The second retroreflector and the third retroreflector may also be positionally fixed relative to each other. The system may further include a structure, wherein the first lens and the second lens are positionally fixed to the structure and positionally fixed relative to each other.

[0007] The system may further include a structure and a positioner coupled to the structure, wherein the first retroreflector is coupled to and movable by the positioner. The system may further include a mirror coupled to the positioner and arranged and configured to direct the beam path.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. 1 schematically illustrates a laser-processing apparatus according to one embodiment.

[0009] FIGS. 2 and 3 show various positional states of the laser processing apparatus according to one embodiment.

DETAILED DESCRIPTION

[0010] Example embodiments are described herein with reference to the accompanying drawings. Unless otherwise expressly stated, in the drawings the sizes, positions, etc., of components, features, elements, etc., as well as any distances therebetween, are not necessarily to scale, but are exaggerated for clarity. In the drawings, like numbers refer to like elements throughout. Thus, the same or similar numbers may be described with reference to other drawings even if they are neither mentioned nor described in the corresponding drawing. Also, even elements that are not denoted by reference numbers may be described with reference to other drawings.

[0011] The terminology used herein is for the purpose of describing particular example embodiments only and is not intended to be limiting. Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art. As used herein, the singular forms “a,” “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It should be recognized that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. Unless otherwise specified, a range of values, when recited, includes both the upper and lower limits of the range, as well as any sub-ranges therebetween. Unless indicated otherwise, terms such as “first,” “second,” etc., are only used to distinguish one element from another. For example, one node could be termed a “first node” and similarly, another node could be termed a “second node”, or vice versa.

[0012] Unless indicated otherwise, the term “about,” “thereabout,” etc., means that amounts, sizes, formulations, parameters, and other quantities and characteristics are not and need not be exact, but may be approximate and/or larger or smaller, as desired, reflecting tolerances, conversion factors, rounding off, measurement error and the like, and other factors known to those of skill in the art. Spatially relative terms, such as “below,” “beneath,” “lower,” “above,” and “upper,” and the like, may be used herein for ease of description to describe one

element or feature's relationship to another element or feature, as illustrated in the FIGS. It should be recognized that the spatially relative terms are intended to encompass different orientations in addition to the orientation depicted in the FIGS. For example, if an object in the FIGS. is turned over, elements described as “below” or “beneath” other elements or features would then be oriented “above” the other elements or features. Thus, the exemplary term “below” can encompass both an orientation of above and below. An object may be otherwise oriented (e.g., rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may be interpreted accordingly.

[0013] The section headings used herein are for organizational purposes only and, unless explicitly stated otherwise, are not to be construed as limiting the subject matter described. It will be appreciated that many different forms, embodiments and combinations are possible without deviating from the spirit and teachings of this disclosure and so this disclosure should not be construed as limited to the example embodiments set forth herein. Rather, these examples and embodiments are provided so that this disclosure will be thorough and complete, and will convey the scope of the disclosure to those skilled in the art.

I. Overview

[0014] FIG. 1 schematically illustrates a laser-processing apparatus in accordance with one embodiment of the present invention.

[0015] Referring to the embodiment shown in FIG. 1, a laser-processing apparatus 100 (also referred to herein simply as an “apparatus”) for processing a workpiece 102 can be characterized as including a laser source 104 for generating a beam of laser energy, one or more positioners (e.g., a first positioner 106, a second positioner 108, a third positioner 110, a fourth positioner 130, a fifth positioner 140, or any combination thereof) and a scan lens 112. The scan lens 112 and the second positioner 108 may be integrated into a scan head 120, described in further detail below.

[0016] Laser energy transmitted along a beam path 114, through the scan lens 112, propagates along a beam axis 118 so as to be delivered to the workpiece 102. Laser energy propagating along the beam axis 118 may be characterized as having a Gaussian-type spatial intensity profile or a non-Gaussian-type (i.e., “shaped”) spatial intensity profile (e.g., a “top-hat”, a Gauss-Bessel type, or a Bessel-type spatial intensity profile). Regardless of the type of spatial intensity profile, the spatial intensity profile can also be characterized as a shape (i.e., a cross-sectional shape, also referred to herein as a “spot shape”) of the beam of laser energy propagating along the beam axis 118 (or beam path 114), which may be circular, elliptical, square, rectangular, triangular, hexagonal, ring-shaped, etc., or arbitrarily shaped.

As used herein, the term “spot size” refers to the diameter or maximum spatial width of the beam of laser energy delivered at a location (also referred to as a “process spot,” “spot location” or, more simply, a “spot”) where the beam axis 118 intersects a region of the workpiece 102 that is to be, at least partially, processed by the delivered beam of laser energy. For purposes of discussion herein, spot size is measured as a radial or transverse distance from the beam axis 118 to where the optical intensity drops to, at least, $1/e^2$ of the optical intensity at the beam axis 118. Generally, the spot size of the beam of laser energy will be at a minimum at the beam waist. Once delivered to the workpiece 102, laser energy within the beam can be characterized as impinging the workpiece 102 at a spot size in a range from 2 μm to 200 μm . It will be appreciated, however, that the spot size can be made smaller than 2 μm or larger than 200 μm .

[0017] Generally, the aforementioned positioners (e.g., the first positioner 106, the second positioner 108, the third positioner 110, the fourth positioner 130, and the fifth positioner 140) are configured to change the relative position between the spot and the workpiece 102. In view of the description that follows, it should be recognized that inclusion of the second positioner 108 is optional, provided that the apparatus 100 includes the first positioner 106 and, optionally, the third positioner 110, the fourth positioner 130, and the fifth positioner 140. Likewise, it should be recognized that inclusion of the third positioner 110 is optional, provided that the apparatus 100 includes the first positioner 106 and, optionally, the second positioner 108, the fourth positioner 130, and the fifth positioner 140. Those skilled in the art will appreciate that inclusion of any of the positioners is optional, provided that the apparatus 100 includes a combination of the other positioners.

[0018] The apparatus 100 may also include one or more other optical components (e.g., beam traps, beam expanders, beam shapers, beam splitters, apertures, filters, collimators, lenses, mirrors, prisms, polarizers, phase retarders, retroreflectors, diffractive optical elements (commonly known in the art as DOEs), refractive optical elements (commonly known in the art as ROEs), or the like or any combination thereof) to focus, expand, collimate, shape, polarize, filter, split, combine, crop, absorb, or otherwise modify, condition, direct, etc., the beam of laser energy as it propagates along the beam path 114. To the extent that optical components such as beam expanders, lenses, beam splitters, prisms, dichroic filters, windows, waveplates, DOEs, ROEs, etc., are formed of bulk transparent materials (which may, optionally, be coated one or more anti-reflection coatings, or the like) intended to transmit an incident beam of laser energy, such optical components are generically referred to herein as “transmissive optical components.” As used herein, the collection of positioners

and other optical components can, when assembled together into the laser-processing apparatus 100, be considered to constitute a “beam path assembly.”

A. Laser Source

[0019] In one embodiment, the laser source 104 is operative to generate laser pulses. As such, the laser source 104 may include a pulsed laser source, a CW laser source, a QCW laser source, a burst mode laser, or the like or any combination thereof. In the event that the laser source 104 includes a QCW or CW laser source, the laser source 104 may be operated in a pulsed mode, or may be operated in a non-pulsed mode but further include a pulse gating unit (e.g., an acousto-optic (AO) modulator (AOM), a beam chopper, etc.) to temporally modulate beam of laser radiation output from the QCW or CW laser source. Although not illustrated, the apparatus 100 may optionally include one or more harmonic generation crystals (also known as “wavelength conversion crystals”) configured to convert a wavelength of light output by the laser source 104 to a separate wavelength. In another embodiment, however, the laser source 104 may be provided as a QCW laser source or a CW laser source and not include a pulse gating unit. Thus, the laser source 104 can be broadly characterized as operative to generate a beam of laser energy, which may manifested as a series of laser pulses or as a continuous or quasi-continuous laser beam, which can thereafter be propagated along the beam path 114. Although many embodiments discussed herein make reference to laser pulses, it should be recognized that continuous or quasi-continuous beams may alternatively, or additionally, be employed whenever appropriate or desired.

B. First Positioner

[0020] The first positioner 106 is arranged, located or otherwise disposed in the beam path 114 and is operative to diffract, reflect, refract, or the like, or any combination thereof, laser pulses that are generated by the laser source 104 (i.e., to “deflect” the laser pulses) so as to deflect or impart movement of the beam path 114 (e.g., relative to the scan lens 112) and, consequently, deflect or impart movement of the beam axis 118 relative to the workpiece 102. Generally, the first positioner 106 is operative to impart movement of the beam axis 118 relative to the workpiece 102 along the X-axis (or direction), the Y-axis (or direction), or a combination thereof. Although not illustrated, the Y-axis (or Y-direction) will be understood to refer to an axis (or direction) that is orthogonal to the illustrated X- and Z-axes (or directions).

[0021] Generally, the first positioner 106 can be provided as a galvanometer mirror system, an AO deflector (AOD) system, an electro-optic (EO) deflector (EOD) system, a fast-steering mirror (FSM) system, or the like or any combination thereof. AODs of AOD systems

generally include an AO cell formed of a material such as crystalline germanium (Ge), gallium arsenide (GaAs), wulfenite (PbMoO₄), tellurium dioxide (TeO₂), crystalline quartz, glassy SiO₂, arsenic trisulfide (As₂S₃), lithium niobate (LiNbO₃), or the like or any combination thereof. EODs of EOD systems generally include an EO cell formed of lithium niobate, potassium tantalite niobate, etc. To the extent that AO cells and EO cells are configured to transmit an incident beam of laser energy, the AO and EO cells can be considered to be types of transmissive optical components.

C. Second Positioner

[0022] The second positioner 108 is disposed in the beam path 114 and is operative to diffract, reflect, refract, or the like or any combination thereof, laser pulses that are generated by the laser source 104 and passed by the first positioner 106 (i.e., to “deflect” the laser pulses) so as to deflect or impart movement to the beam path 114 (e.g., relative to the scan lens 112) and, consequently, deflect or impart movement of the beam axis 118 relative to the workpiece 102. Generally, the second positioner 108 is operative to impart movement of the beam axis 118 relative to the workpiece 102 along the X-axis (or direction), the Y-axis (or direction), or a combination thereof.

[0023] In view of the above, it should be appreciated that the second positioner 108 can be provided as a micro-electro-mechanical-system (MEMS) mirror or mirror array, an AOD system, an electro-optic deflector (EOD) system, a fast-steering mirror (FSM) element (e.g., incorporating a piezoelectric actuator, electrostrictive actuator, voice-coil actuator, etc.), a galvanometer mirror system, a resonant scanning mirror system, rotating polygon scanner, or the like or any combination thereof.

[0024] In one embodiment, the second positioner 108 can be provided as a two-axis galvanometer mirror system including two galvanometer mirror components, i.e., a first galvanometer mirror component (e.g., an X-axis galvanometer mirror component) arranged to impart movement of the beam axis 118 relative to the workpiece 102 along the X-axis and a second galvanometer mirror component (e.g., a Y-axis galvanometer mirror component) arranged to impart movement of the beam axis 118 relative to the workpiece 102 along the Y-axis. In another embodiment, however, the second positioner 108 may be provided as a galvanometer mirror system including only a single galvanometer mirror component arranged to impart movement of the beam axis 118 relative to the workpiece 102 along the X- and Y-axes. In yet other embodiments, the second positioner 108 may be provided as a rotating polygon mirror system, etc.

D. Third Positioner

[0025] In the illustrated embodiment, the third positioner 110 includes one or more linear stages (e.g., each capable of imparting translational movement to the workpiece 102 along the X-, Y- and/or Z-directions), one or more rotational stages (e.g., each capable of imparting rotational movement to the workpiece 102 about an axis parallel to the X-, Y- and/or Z-directions), or the like or any combination thereof arranged and configured to impart relative movement between a workpiece 102 and the scan lens 112, and, consequently, to impart relative movement between the workpiece 102 and the beam axis 118.

[0026] In view of the configuration described herein, it should be recognized that movement of the process spot relative to the workpiece 102 (e.g., as imparted by the first positioner 106 and/or the second positioner 108) can be superimposed by any movement of the workpiece 102 or scan lens 112 as imparted by the third positioner 110.

E. Fourth Positioner

[0027] FIG. 2 schematically illustrates the apparatus 100 and the fourth positioner 130 accordance with one embodiment of the present invention. In the illustrated embodiment, the fourth positioner 130 includes one or more linear stages configured to impart translational movement of the scan head 120 in the Z-direction (e.g., to move the beam waist of the beam of laser energy relative to the workpiece 102). The fourth positioner 130 includes a carriage 134 mounted on a linear guide rail 132 that is mounted on the carriage 144 of the fifth positioner 140 (as described below).

[0028] In view of the configuration described herein, it should be recognized that movement of the process spot relative to the workpiece 102 (e.g., as imparted by the first positioner 106 and/or the second positioner 108) can be superimposed by any movement of the scan head 120 as imparted by the fourth positioner 130.

F. Fifth Positioner

[0029] FIG. 2 schematically illustrates the apparatus 100 and the fifth positioner 140 in accordance with one embodiment of the present invention. In the illustrated embodiment, the fifth positioner 140 includes one or more linear stages configured to impart relative movement between the fourth positioner 130 (including the scan head 120) and the workpiece 102 in the X-direction (e.g., to move the process spot relative to the workpiece 102). The fifth positioner 140 includes a carriage 144 mounted on a linear guide rail 142 that is fixed on a structure 300 (e.g., such as a frame or gantry) of the apparatus 100.

[0030] In view of the configuration described herein, it should be recognized that movement of the process spot relative to the workpiece 102 (e.g., as imparted by the first positioner 106,

the second positioner 108, and/or the fourth positioner 130) can be superimposed by any movement of the scan lens 112 as imparted by the fifth positioner 140.

G. Scan Lens

[0031] The scan lens 112 (e.g., provided as either a simple lens, or a compound lens) is generally configured to focus the beam of laser energy directed along the beam path 114, typically so as to produce a beam waist that can be positioned at or near the desired process spot. The scan lens 112 may be provided as a non-telecentric f-theta lens (as shown), a telecentric f-theta lens, an axicon lens (in which case, a series of beam waists are produced, yielding a plurality of process spots displaced from one another along the beam axis 118), or the like or any combination thereof. As described above, in one embodiment, the scan lens 112 and the second positioner 108 are integrated into a common scan head 120.

H. Controller

[0032] Generally, the apparatus 100 includes one or more controllers, such as controller 122, to control, or facilitate control of, the operation of the apparatus 100. In one embodiment, the controller 122 is communicatively coupled (e.g., over one or more wired or wireless, serial or parallel, communications links, such as USB, RS-232, Ethernet, Firewire, Wi-Fi, RFID, NFC, Bluetooth, Li-Fi, SERCOS, MARCO, EtherCAT, or the like or any combination thereof) to one or more components of the apparatus 100, such as the laser source 104, the first positioner 106, the second positioner 108, the third positioner 110, the fourth positioner 130, the fifth positioner 140, the scan lens 112 (when provided as a variable-focal length lens), etc., which are thus operative in response to one or more control signals output by the controller 122.

[0033] For example, the controller 122 may control an operation of the first positioner 106, the second positioner 108, the third positioner 110, the fourth positioner 130, the fifth positioner 140, or any combination thereof, to impart relative movement between the beam axis 118 and the workpiece 102 so as to cause relative movement between the process spot and the workpiece 102 along a path or trajectory (also referred to herein as a “process trajectory”) within the workpiece 102. It will be appreciated that any two, three or four of the five positioners, or all five of the positioners, may be controlled such that the positioners simultaneously impart relative movement between the process spot and the workpiece 102 (thereby imparting a “compound relative movement” between the beam axis and the workpiece). Of course, at any time, it is possible to control only one positioner (e.g., the first positioner 106, the second positioner 108, the third positioner 110, the fourth positioner 130, or the fifth positioner 140) to impart relative movement between the process spot and the

workpiece 102 (thereby imparting a “non-compound relative movement” between the beam axis and the workpiece).

[0034] Generally, the controller 122 includes one or more processors operative to generate the aforementioned control signals upon executing instructions. A processor can be provided as a programmable processor (e.g., including one or more general purpose computer processors, microprocessors, digital signal processors, or the like or any combination thereof) operative to execute the instructions. Instructions executable by the processor(s) may be implemented software, firmware, etc., or in any suitable form of circuitry including programmable logic devices (PLDs), field-programmable gate arrays (FPGAs), field-programmable object arrays (FPOAs), application-specific integrated circuits (ASICs) – including digital, analog and mixed analog/digital circuitry – or the like, or any combination thereof. Execution of instructions can be performed on one processor, distributed among processors, made parallel across processors within a device or across a network of devices, or the like or any combination thereof.

[0035] In one embodiment, the controller 122 includes tangible media such as computer memory, which is accessible (e.g., via one or more wired or wireless communications links) by the processor. As used herein, “computer memory” includes magnetic media (e.g., magnetic tape, hard disk drive, etc.), optical discs, volatile or non-volatile semiconductor memory (e.g., RAM, ROM, NAND-type flash memory, NOR-type flash memory, SONOS memory, etc.), etc., and may be accessed locally, remotely (e.g., across a network), or a combination thereof. Generally, the instructions may be stored as computer software (e.g., executable code, files, instructions, etc., library files, etc.), which can be readily authored by artisans, from the descriptions provided herein, e.g., written in C, C++, Visual Basic, Java, Python, Tel, Perl, Scheme, Ruby, assembly language, hardware description language (e.g., VHDL, VERILOG, etc.), etc. Computer software is commonly stored in one or more data structures conveyed by computer memory.

[0036] Although not shown, one or more drivers (e.g., RF drivers, servo drivers, line drivers, power sources, etc.) can be communicatively coupled to an input of one or more components such as the laser source 104, the first positioner 106, the second positioner 108, the third positioner 110, the fourth positioner 130, the fifth positioner 140, and the scan lens 112 (when provided as a variable-focal length lens), etc., for controlling such components. Accordingly, one or more components such as the laser source 104, the first positioner 106, the second positioner 108, the third positioner 110, the fourth positioner 130, the fifth positioner 140, and the scan lens 112 (when provided as a variable-focal length lens), etc.,

can be considered to also include any suitable driver, as is known in the art. Each of such drivers would typically include an input communicatively coupled to the controller 122, and the controller 122 is operative to generate one or more control signals (e.g., trigger signals, etc.), which can be transmitted to the input(s) of one or more drivers associated with one or more components of the apparatus 100. Components such as the laser source 104, the first positioner 106, the second positioner 108, the third positioner 110, the fourth positioner 130, the fifth positioner 140, and the scan lens 112 (when provided as a variable-focal length lens), etc., are thus responsive to control signals generated by the controller 122.

[0037] Although not shown, one or more additional controllers (e.g., component-specific controllers) may, optionally, be communicatively coupled to an input of a driver communicatively coupled to a component (and thus associated with the component) such as the laser source 104, the first positioner 106, the second positioner 108, the third positioner 110, the fourth positioner 130, the fifth positioner 140, and the scan lens 112 (when provided as a variable-focal length lens), etc. In this embodiment, each component-specific controller can be communicatively coupled to the controller 122 and be operative to generate, in response to one or more control signals received from the controller 122, one or more control signals (e.g., trigger signals, etc.), which can then be transmitted to the input(s) of the driver(s) to which it is communicatively coupled. In this embodiment, a component-specific controller may be operative as similarly described with respect to the controller 122.

[0038] In another embodiment in which one or more component-specific controllers are provided, the component-specific controller associated with one component (e.g., the laser source 104) can be communicatively coupled to the component-specific controller associated with one component (e.g., the first positioner 106, etc.). In this embodiment, one or more of the component-specific controllers can be operative to generate one or more control signals (e.g., trigger signals, etc.) in response to one or more control signals received from one or more other component-specific controllers.

II. Embodiments Addressing Mislocation of Pivot Point Relative to the SLEP

[0039] In some embodiments of the apparatus 100, when the scan lens 112 is moved while the first positioner 106 remains stationary, the optical path length between the first positioner 106 and the entrance pupil of the scan lens 112 can change depending on the movement of the scan lens 112.

[0040] In embodiments where the scan lens is mounted to an X-stage (e.g., the fifth positioner 140) that moves the scan head 120 along the X-axis, the pivot point may be displaced relative to the entrance pupil, resulting in telecentric errors of the beam path 114

that cause errors in the location of the process spot on the workpiece 102. In addition, in some embodiments, the first positioner 106 may be provided as a pair of AODs capable of a increased range of deflection of the beam path 114 relative to prior art AODs. For example, in such embodiments where the second positioner 108 is provided as a pair of galvanometer mirrors, when the pivot point is displaced from the entrance pupil (due to the X-direction motion of the scan lens 112 changing the optical path length), the increased range of deflection of the beam path 114 can cause the beam path 114 to miss the galvanometer mirrors at or near their furthest extent of beam path deflection. One solution to this problem is to increase the size of the galvanometer mirrors. However, because the galvanometer mirrors undergo very high accelerations during operation, the additional mass of larger mirrors can contribute to wobble of the mirrors that can deleteriously affect positioning accuracy of the process spot at the workpiece 102.

[0041] What follows below is a discussion of exemplary embodiments of an optical relay system operative to compensate for the increase in optical path length caused by movement of the scan lens 112 relative to the first positioner 106, to ensure that the beam of laser energy 116 propagating along the beam path 114 rotates about a pivot point that is located at, or at least close to, the entrance pupil of the scan lens 112, so the beam path 114 does not miss the galvanometer mirrors.

[0042] Generally, optical relays with a fixed magnification of $M=1$ are used to image an object (e.g., the AOD pivot point of deflection) to a new plane (e.g., an image plane located at the scan lens entrance pupil), for example, to ensure proper telecentricity of the beam path 114 at the workpiece 102. Such relays are generally fixed with respect to both the first positioner 106 and the scan lens 112. However, if the scan lens 112 moves with respect the first positioner 106 and with respect to a fixed relay having a magnification of 1, the pivot point will move relative to the scan lens 112, resulting in displacement of the pivot point relative to the scan lens entrance pupil.

[0043] FIG. 2 shows a schematic view of an embodiment of the apparatus 100 in a first positional state. In this embodiment, the apparatus 100 includes an optical relay system 200 operative to automatically position a pivot point 124 at a scan lens entrance pupil 126 during movement of the scan head 120 along the X-axis relative to the first positioner 106. The apparatus 100 includes the first positioner 106, the second positioner 108, the fourth positioner 130, the fifth positioner 140, and the optical relay system 200. The first positioner 106 directs the beam of laser energy 116 (e.g., schematically illustrated as an arrow) along the beam path 114. The apparatus 100 further includes a structure 300 (e.g., such as a frame

or gantry) that includes two structure portions 302 (e.g., part of the frame or gantry, or another structure such as an optics wall). The fifth positioner 140 includes a guide rail 142 mounted to the structure 300, and a carriage 144 configured to move along the guide rail 142 along the X-axis. A fold mirror 212 configured to direct the beam path 114 from the optical relay system 200 to the scan head 120 is also mounted on the carriage 144. The fourth positioner 130 is mounted to the carriage 144 and is operative to move the scan head 120 (including the second positioner 108 with the scan lens 112 having the entrance pupil 126) along the Z-axis as necessary to locate the beam waist relative to the workpiece 102. In this embodiment, for the purposes of illustration of the invention, in the positional state shown in FIG. 2, the fifth positioner 140 is positioned so that the beam path 114 of the beam of laser energy 116 intersecting the workpiece 102 is an arbitrary distance $X_1 = 110$ mm from the first positioner 106.

[0044] The optical relay system 200 includes an optical relay 201 arranged in optical communication with the first positioner 106. In this embodiment, the optical relay 201 includes a first lens 202 and a second lens 204 mounted on the structure portions 302. The optical relay system 200 further includes a first retroreflector 206, a second retroreflector 208 and a third retroreflector 210. The first retroreflector 206 includes a first mirror 206a and a second mirror 206b. The second retroreflector 208 is mounted on one of the structure portions 302 and includes a first fold mirror 208a and a second fold mirror 208b. The third retroreflector 208 is mounted on another of the structure portions 302 and includes a first fold mirror 210a and a second fold mirror 210b. The first retroreflector 206 and the fold mirror 212 are mounted on the carriage 144, which, in turn, is movable by the fifth positioner 140 (e.g., in response to one or more commands output by the controller 122) along the X-axis relative to the first positioner 106, the second retroreflector 208, the third retroreflector 210, and the optical relay 201). In another embodiment, the first retroreflector 206 and the fold mirror 212 may be mounted to an auxiliary stage (not shown) instead of the fifth positioner 140.

[0045] As described above, optical relays are used to image an object (e.g., the AOD pivot point of deflection) to a new plane (an image plane located at the scan lens entrance pupil 126) at a certain lateral magnification M . If the object distance in Z (the direction of light propagation) changes, the image distance in Z also changes, but by the square of the lateral magnification M times the change in object distance. Typically, the beam axis 114 is aligned to a stage such that the beam propagation is parallel to the stage travel, and the optical path length changes, but the beam doesn't nominally move on the optics mounted on the stage.

This means in the reference frame of the stage, the main thing that changes as the stage moves throughout the travel range is that the image location (the pivot point of deflection) moves in the direction that the beam of laser energy 116 propagates (and the direction the stage travels since they are parallel).

[0046] The optical relay system 200 works by directing the beam path 114 to the first retroreflector 206 that then directs the beam path 114 back in the opposite direction to the optical relay 201. Because the beam path is folded, the change in the object distance (from the AOD to the optical relay 201) is twice that of the motion of the scan head 120 on the fifth positioner 140. In this embodiment, the optical relay 201 is designed with a lateral magnification set at $M = \sqrt{2}/2 = 0.707$. This lateral magnification results in a longitudinal magnification of $M^2 = 0.5$, thereby changing the image distance (the distance from the optical relay 201 to the pivot point 124) by exactly the amount of movement of beam path 114 relative to the workpiece 102 (e.g., as the fifth positioner 140 moves the scan head 120 along the X-axis), thereby maintaining the location of the pivot point 124 at the scan lens entrance pupil 126.

[0047] FIG. 3 shows a schematic view of the embodiment of the apparatus 100 shown in FIG. 2 in a second positional state, wherein the fifth positioner 140 has moved the scan head 120 (and the optical path 114 incident on the workpiece 102) to a distance of $X_2 = 160$ mm from the first positioner 106, a change in the X-direction of 50 mm. Because the first retroreflector 206 is mounted on the carriage 144 and directs the beam of laser energy 116 propagating along the beam path 114 back toward the optical relay 201 after receiving the beam of laser energy 116 from the first positioner 106, the object distance ΔO (the distance between the first positioner 106 and the optical relay 201) increases by 100 mm. In this embodiment, because the optical relay 201 has a lateral magnification set at $M = 0.707$ (resulting in a longitudinal magnification of $M^2 = 0.5$). The change in the image distance ΔI (the change of the distance between the optical relay 201 and the entrance pupil 126), is half of the change in the object distance ($M^2 \cdot \Delta O$). In this embodiment, this results in the image distance moving in the X-direction by $0.5 \cdot 100 = 50$ mm, the same amount as the change in position of the scan head 120 mounted on the fifth positioner 140, thereby maintaining the location of the pivot point 124 at the entrance pupil 126.

[0048] Though a lateral magnification of $M = \sqrt{2}/2$ (resulting in a longitudinal magnification $M^2 = 0.5$) combined with folding the beam path to double the change in the object distance when the scan head 120 moves in the X-direction results in locating the pivot point 124 at the entrance pupil 126, in other embodiments, the optical relay 201 may be

designed with a longitudinal magnification M^2 that does not equal 0.5. While these settings of the lateral magnification may not be optimal for maintaining the position of the pivot point 124 at the entrance pupil 126, such magnification settings may be selected for other reasons (e.g., to achieve a particular beam diameter at the process spot). So, in various embodiments, the optical relay 201 may be provided with a lateral magnification M such that the longitudinal magnification M^2 of the optical relay 201 may be between about 0.81 and about 0.25, between 0.64 and about 0.36, between about 0.56 and about 0.42, or between about 0.51 and about 0.47. In another embodiment, the longitudinal magnification of the optical relay 201 is about 0.499. In other embodiments, the optical relay 201 may have a variable focus that may be set by manually by an operator, or by the controller 122.

III. Conclusion

[0049] The foregoing is illustrative of embodiments and examples of the invention, and is not to be construed as limiting thereof. Although a few specific embodiments and examples have been described with reference to the drawings, those skilled in the art will readily appreciate that many modifications to the disclosed embodiments and examples, as well as other embodiments, are possible without materially departing from the novel teachings and advantages of the invention. Accordingly, all such modifications are intended to be included within the scope of the invention as defined in the claims. For example, skilled persons will appreciate that the subject matter of any sentence, paragraph, example or embodiment can be combined with subject matter of some or all of the other sentences, paragraphs, examples or embodiments, except where such combinations are mutually exclusive. The scope of the present invention should, therefore, be determined by the following claims, with equivalents of the claims to be included therein.

WHAT IS CLAIMED IS:

1. A system, comprising:
 - a scan lens;
 - a first positioner configured to move the scan lens; and
 - an optical relay system configured to relay a beam of laser energy propagating along a beam path to an entrance pupil of the scan lens, wherein the optical relay system includes:
 - an optical relay including a first lens and a second lens;
 - a first retroreflector configured to direct the beam path of the beam of laser energy to the optical relay; and
 - a second retroreflector positioned on a first side of the scan lens; and
 - a third retroreflector positioned on a second side of the scan lens, wherein the second retroreflector and the third retroreflector are positioned between the first lens and the second lens,
 - wherein the first retroreflector is movable relative to at least one selected from the group consisting of the second retroreflector and the third retroreflector,
 - wherein the first positioner is configured to move the scan lens relative to the second retroreflector and the third retroreflector.
2. The system of claim 1, further comprising a second positioner configured to deflect the beam path of the beam of laser energy about a pivot point.
3. The system of claim 2, wherein the optical relay system is arranged and configured to relay the pivot point to the entrance pupil of the scan lens.
4. The system of claim 2, wherein the second positioner is at least one selected from the group consisting of an AOD system and a galvanometer mirror system.
5. The system of claim 1, wherein the optical relay has a longitudinal magnification between 0.81 and 0.25.
6. The system of claim 5, wherein the optical relay has a longitudinal magnification between 0.64 and 0.36.

7. The system of claim 6, wherein the optical relay has a longitudinal magnification between 0.56 and 0.42.
8. The system of claim 7, wherein the optical relay has a longitudinal magnification between 0.51 and 0.47.
9. The system of claim 8, wherein the optical relay has a longitudinal magnification of 0.499.
10. The system of claim 1, wherein the first retroreflector is mounted on a linear stage configured to move the first retroreflector relative to the optical relay.
11. The system of claim 10, wherein the first positioner includes the linear stage.
12. The system of claim 1, wherein the optical relay system includes a mirror configured to direct the beam path of the beam of laser energy from the third retroreflector to the scan lens.
13. The system of claim 1, further comprising a third positioner configured to deflect the beam path of the beam of laser energy, wherein the third positioner is coupled to the first positioner.
14. A system, comprising:
 - a first lens and a second lens; and
 - a first retroreflector, a second retroreflector and a third retroreflector,wherein:
 - the first retroreflector is arranged to receive a beam of laser energy propagating along a beam path and is configured to direct the beam path to the first lens,
 - the second retroreflector is arranged to receive the beam of laser energy from the first lens and configured to direct the beam path to the third retroreflector, and
 - the third retroreflector is arranged to receive the beam path from the second retroreflector and configured to direct the beam path to the second lens,

wherein the first retroreflector is movable relative to at least one selected from the group consisting of the second retroreflector and the third retroreflector.

15. The system of claim 14, wherein the second retroreflector and the third retroreflector are positionally fixed relative to each other.

16. The system of claim 14, further comprising a structure, wherein the first lens and the second lens are positionally fixed relative to each other.

17. The system of claim 14, further comprising:
a structure; and
a positioner coupled to the structure,
wherein the first retroreflector is coupled to and movable by the positioner.

18. The system of claim 17, further comprising a mirror coupled to the positioner and arranged and configured to direct the beam path.