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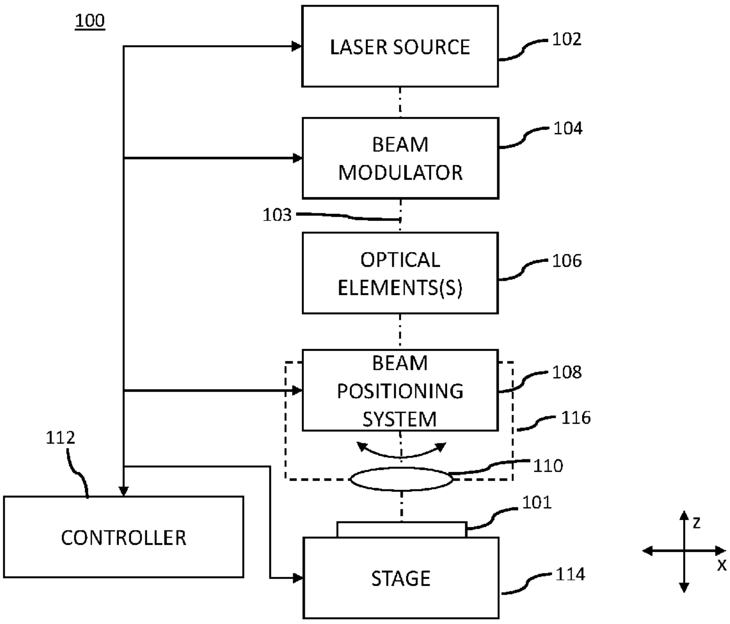

FIG. 1

(57) **Abstract:** A laser-processing system for processing a workpiece is adapted to estimate a thermal response of at least one of many beam path components to a beam of laser energy during a predetermined processing period while the workpiece is to be processed, generate one or more commands based at least in part on the estimated thermal response, and output the one or more commands to one or more components of the system and outputting commands to one or more components of the system to processes the workpiece during the processing period.

[Continued on next page]

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METHOD AND APPARATUS FOR COMPENSATING FOR THERMALLY-INDUCED BEAM POINTING ERRORS IN A LASER-PROCESSING SYSTEM

BACKGROUND

I. Technical Field

[0001] Embodiments of the present invention relate generally to systems and methods for positioning a beam of laser energy and, more particularly, positioning a beam of laser energy in a manner that compensates for thermally-induced beam pointing errors.

II. Discussion of the Related Art

[0002] Laser-processing systems generally employ lasers to process (e.g., cut, weld, drill, etc.) workpieces such as printed circuit boards, metal plates, and the like. Such systems typically include optical elements such as a beam positioning system (e.g., a pair of orthogonally-oriented galvanometer mirrors) for scanning or otherwise positioning the beam of laser energy relative to the workpiece and a scan lens for focusing the scanned beam of laser energy at or near the workpiece. Other optical elements (e.g., mirrors, lenses, beam expanders, waveplates, polarizers, acousto-optic devices, etc.) are typically arranged in a beam path between the laser source (which generates the beam of laser energy) and the beam positioning system. An optical element such as a scan lens is often arranged in the beam path optically downstream of the beam positioning system, e.g., to focus the beam of laser energy onto the workpiece such that the beam waist of the focused beam of laser energy is located at or near the workpiece.

[0003] Optical elements in the aforementioned laser-processing systems will typically absorb some fraction of optical power within the beam of laser energy, whereby the absorbed optical power is converted into heat within the optical elements. When the beam of laser energy is of sufficiently high power (e.g., in excess 100 W), the absorbed optical power absorbed can induce thermal lensing or aberrations within some of the optical elements themselves. If the thermal gradients within the optical elements are relatively stable during workpiece processing, then thermal lensing and other deformation or aberrations can usually be taken into account to ensure that the workpiece is satisfactorily processed. However, stability of the thermal gradients may be compromised depending upon one or more factors relating to the operation of the system, such as varying the optical power used to process the workpiece, temporarily halting delivery of laser energy through the scan lens (e.g., when swapping in new workpieces to be to processed), and the like. If the thermal gradients within the optical elements are not sufficiently stable (i.e., “unstable”), then a spatial deviation between a position where the beam waist of the beam of laser energy is intended to be delivered relative to the workpiece and the position where the beam waist was actually delivered to the workpiece (i.e., a “thermally-induced beam pointing error”) can be undesirably large. The absorbed optical power can also induce thermal deformation in mounting devices used to precisely position or orient the optical elements within the laser-processing systems, which can also lead to thermally-induced beam pointing errors.

[0004] One technique for avoiding thermally-induced beam pointing errors is to design and operate the laser-processing system so that the optical elements in the system are thermally stable while the workpiece is being processed. Generally, this solution requires that all optical elements in the system to be exposed to constant optical power from the beam of laser energy, which is not always practical. Other techniques for avoiding thermally-induced beam pointing errors typically involve measuring the temperature of optical elements (e.g., using a temperature sensor) in the beam path (e.g., galvanometer mirrors, the scan lens) and then adjusting the operation of the beam positioning system based on the measured temperature. However, such techniques cannot satisfactorily respond to gradual or rapid changes in measured temperature.

SUMMARY

[0005] One embodiment of the present invention can be broadly characterized as a laser-processing system for processing a workpiece. The system can include a laser source operative to output a beam of laser energy propagatable along a beam path and a plurality of beam path components arranged within the beam path. The plurality of beam path components can include a beam positioning system operative to deflect the beam path within a scan field in response to a position command and a scan lens arranged to focus the beam laser energy as deflected by the beam positioning system, thereby producing a focused beam of laser energy having a beam waist. The system can further include a controller communicatively coupled to the beam positioning system. The controller can be configured to generate the position command based, at least in part, on an estimated thermal response of at least one of the plurality of beam path components to the beam of laser energy during a predetermined processing period and output the generated position command to the beam positioning system to operate the beam positioning system during the processing period.

[0006] Another embodiment of the present invention can be broadly characterized as a laser-processing system for processing a workpiece. The system can include a laser source operative to output a beam of laser energy propagatable along a beam path and a plurality of beam path components arranged within the beam path, wherein the plurality of beam path components include a scan lens arranged to focus the beam laser energy as deflected by the beam positioning system, thereby producing a focused beam of laser energy having a beam waist. The system can further include at least one stage operative impart relative movement between the beam waist and the workpiece in response to a stage position command and a controller communicatively coupled to the at least one stage beam positioning system. The controller can be configured to generate the stage position command based, at least in part, on an estimated thermal response of at least one of the plurality of beam path components to the beam of laser energy during a predetermined processing period and output the generated stage position command to the at least one stage to operate the at least one stage during the processing period.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 schematically illustrates a laser-processing system according to various embodiments of the present invention.

[0008] FIG. 2 illustrates an embodiment of a beam modulator that may be incorporated into the laser-processing system shown in FIG. 1.

[0009] FIG. 3 illustrates a laser beam monitoring system that may be incorporated as part of the laser-processing system shown in FIG. 1, according to one embodiment of the present invention.

[0010] FIG. 4 schematically illustrates an application analysis module implemented by the controller shown in FIG. 1, according to one embodiment of the present invention.

[0011] FIG. 5 schematically illustrates the thermal compensation module shown in FIG. 4, according to one embodiment of the present invention.

DETAILED DESCRIPTION

[0012] Example embodiments are described herein with reference to the accompanying FIGS. 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.

[0013] The terminology used herein is for the purpose of describing particular example embodiments only and is not intended to be limiting. 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. The section headings used herein are for organizational purposes only and are not to be construed as limiting the subject matter described.

[0014] 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.

[0015] 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.

[0016] 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.

[0017] It will be appreciated that many different forms and embodiments 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. Embodiments Concerning Laser-Processing System and Associated Components, Generally

[0018] Referring to FIG. 1, a laser-processing system, such as system 100, for processing a workpiece 101 includes a laser source 102, a beam modulator 104, one or more optical elements 106, a beam positioning system 108, a scan lens 110 and a controller 112. The system 100 may also include a workpiece stage 114 for positioning or otherwise holding the workpiece 101.

[0019] As illustrated in FIG. 1, laser energy output by the laser source 102 propagates along a beam path (indicated by the dot-dash line) 103. The beam modulator 104, optical element(s) 106, beam positioning system 108 and scan lens 110 are arranged in the beam path 103. As used herein, the term “beam path” refers to the path along which the beam of laser energy actually travels as it propagates from the laser source 102 to (and through) the scan lens 110 (e.g., to the workpiece 101), and also refers to the path along which the beam of laser energy would travel upon being output by the laser source 102. The optical element(s) 106, beam positioning system 108 and scan lens 110 are generically referred to herein as “beam path components.”

[0020] Generally, the laser source 102 is configured to generate a high-power beam of laser energy, and may be provided as a CO_2 laser source, CO laser source, a high-power fiber laser, a high-power disk laser, etc., which outputs a beam of laser energy manifested as a series of laser pulses, or as a continuous wave (CW) or quasi-CW (QCW) beam of laser energy. As used herein, characterizing a beam of laser energy as being “high-power” indicates that the optical power in the beam of laser energy is sufficient to induce beam pointing errors in one or more of the aforementioned beam path components. In some embodiments, a high-power beam of laser energy manifested as a series of laser pulses, can be characterized as having a peak power greater than or equal to 1 kW (e.g., greater than or equal to 1.5 kW, 2 kW, 3 kW, etc., or between any of these values). In other embodiments, a high-power beam of laser energy manifested as a CW or QCW beam of laser energy can have an average power greater than or equal to 100 W (e.g., greater than or equal to 150 W, 200 W, 300 W, 400 W, 500 W, etc., or between any of these values). It will be appreciated that these power values can vary, e.g., depending on the wavelength of the beam of laser energy or other factors such as pulse duration, pulse repetition rate, beam diameter, the optical absorption characteristics of the beam path components, or the like or any combination thereof.

[0021] The beam modulator 104 is operative to selectively, and variably, attenuate (e.g., in response to one or more control signals output by the controller 112) the beam of laser energy output by the laser source 102. Upon being output from the beam modulator 104, the beam of laser energy propagates from the beam modulator 104 further along beam path 103 to the other components of the system 100 and, ultimately, to the workpiece 101. Examples of the beam modulator 104 can include one or more systems such as a variable neutral density filter, an acousto-optical (AO) modulator (AOM), an AO deflector (AOD), an electro-optical (EO) modulator (EOM), an EO deflector (EOD), liquid crystal variable attenuator (LCVA), a micro-electro-mechanical system (MEMS)-based VOA, an optical attenuator wheel, a polarizer/waveplate filter, or the like or any combination thereof. The degree of attenuation that can be imparted to the beam of laser energy by the beam modulator 104 can range from 0% to 100%, depending on the configuration of the beam modulator 104. Thus, the beam modulator 104 can be selectively, and variably operated to transmit some or all of the beam of laser energy incident thereto to the remaining beam path components, or to prevent transmission to the beam path components completely. In some embodiments, the beam modulator 104 can be operated as a “pulse picker” (e.g., to selectively transmit only certain pulses within a train of laser pulses in the beam of laser energy) or as a “pulse slicer” (e.g., to selectively transmit only one or more certain portions of one or more laser pulses in the beam of laser energy, or to divide a CW or QCW beam of laser energy into a plurality of pulses).

[0022] In one embodiment, and with reference to FIG. 2, the beam modulator 104 may be provided as an AO device 200, such as an AOM or AOD, and driving circuitry 202 electrically coupled to the AO device 200.

[0023] The AO device 200 includes an AO cell and at least one ultrasonic transducer attached to the AO cell, as is known in the art. Generally, the material from which the AO cell is formed will depend upon the wavelength of the beam of laser energy that is to be attenuated. For example, if the beam of laser energy has a wavelength in a range from 2 μm (or thereabout) to 20 μm (or thereabout), then the AO cell can be formed of a material including crystalline germanium, as is known in the art.

[0024] The driving circuitry 202 can include one or more RF synthesizers and one or more amplifiers coupled to an output of one or more RF synthesizers. Each RF synthesizer is configured to generate an RF signal having any desired or otherwise suitable waveform, and each amplifier is configured to amplify the RF signal output by an RF synthesizer and output the amplified RF signal. Amplified RF signals can be output, as drive signals, to the at least one transducer of the AO device 200.

[0025] As will be recognized by those of ordinary skill in the art, AO devices such as AO device 200 modulate a beam of laser energy incident to, and propagating through the AO cell, using diffraction events caused by one or more acoustic waves contemporaneously propagating through the AO cell. In this case, an acoustic wave can be launched into the AO cell by applying a drive signal to the at least one transducer of the AO device 200, as is known in the art. Upon diffracting an incident beam of laser energy, a diffraction pattern is produced that typically includes zeroth- and first-order diffraction peaks, and may also include other higher-order diffraction peaks (e.g., second-order, third-order, etc.). The amount of optical power diffracted into the first-order diffraction peak (e.g., as compared to the zeroth-order diffraction peak) can be affected by one or more factors, the amplitude of the drive signal applied to the at least one transducer of the AO device 200, the frequency of the drive signal applied to the at least one transducer of the AO device 200 and, when multiple transducers are provided, the phase relationship between drive signals contemporaneously applied to the transducer of the AO device 200. As is known in the art, the portion of the diffracted beam of laser energy in the zeroth-order diffraction peak is referred to as a "zeroth-order" beam, the portion of the diffracted beam of laser energy in the first-order diffraction peak is referred to as a "first-order" beam, and so on.

[0026] Generally, the zeroth-order beam and other orders of diffracted beams (e.g., the first-order beam) propagate along different beam paths upon exiting the AO cell (e.g., through an optical output side of the AO cell). For example, the zeroth-order beam propagates along a zeroth-order beam path, the first-order beam propagates along a first-order beam path, and so on. In FIG. 2, the zeroth-order beam path is identified at 204, and the first-order beam path is identified at 206. As is known in the art, the angle Θ (also referred to herein as the "deflection angle") between the zeroth-order beam path 204 and the first-order beam path 103 can depend upon one or more factors such as the frequency of the drive signal applied to the at least one transducer of the AO device 200. Although not illustrated, one or more beam traps may be provided to absorb or otherwise intercept laser energy propagating along the zeroth-order beam path 204 (and any other, higher-order, beam paths) while allowing laser energy propagating along the first-order beam path 206 to proceed to the various other components system 100 and, ultimately, to the workpiece 101. Thus, the first-order beam path 206 corresponds to the beam path 103 shown in FIG. 1 at all locations optically downstream of the beam modulator 104.

[0027] In one embodiment, the beam modulator 104 may be provided as a series of AO devices, such as AO device 200, arranged optically in series to deflect the beam of laser energy propagating along beam path 103 (e.g., relative to the beam positioning system 108) within a two-dimensional scan field. For example, the beam modulator 104 can be provided as a first AO device and a second AO device arranged optically "downstream" of the first AO device. Like AO device 200, each of the first AO device and second AO device may be electrically coupled to driving circuitry such as driving circuitry 202. The first AO device can be arranged and operative to deflect the beam path 103 (e.g., relative to the beam positioning system 108) within a first one-dimensional scan field of the two-dimensional scan field (e.g., within a one-dimensional scan field extending along a first axis, such as the X-axis) and the second AO device can be arranged and operative to deflect the beam path 103 (e.g., relative to the beam positioning system 108) within a second scan field of the two-dimensional scan field (e.g., within a one-dimensional scan field along a second axis, such as the Y-axis). In this case, the first AO device diffracts the incident beam of laser energy propagating from the laser source 102 and the second AO device diffracts the first-order beam produced by the first AO device. Although not illustrated, one or more beam traps would be provided to absorb or otherwise intercept laser energy propagating along all beam paths other than the first-order beam paths, from each of the first AO device and the second AO device.

[0028] Referring back to FIG. 1, the optical element(s) 106 may include one or more components such as a beam expander, beam shaper, beam splitter, aperture, filter, collimator, lens, mirror, prism, polarizer, phase retarder, diffractive optical element, refractive optical element, or the like or any combination thereof, to focus, expand, collimate, shape, polarize, filter, split, combine, crop, or otherwise modify, condition, absorb, reflect, diffract, refract, etc., the beam of laser energy as it propagates along beam path 103 from the beam modulator 104 to the beam positioning system 108. Although not illustrated, one or more optical elements 106 may also be disposed in the beam path 103 between the laser source 102 and the beam modulator 104. The optical element(s) 106 may be positioned in the beam path 103 using one or more associated devices such as a housing, bracket, mount, frame, stage, etc., (each generically referred to as a “mounting device”) as is known in the art. Such mounting devices may, in turn, be attached to a frame (not shown) of the system 100 in any manner suitable or otherwise known in the art. For purposes of discussion, a mounting device will be considered to be a part of its associated optical element 106.

[0029] The beam positioning system 108 is operative to reflect, diffract and/or refract the incident beam of laser energy propagating along beam path 103 (e.g., in response to one or more control signals output by the controller 112) to thereby deflect the beam path 103 (e.g., relative to the scan lens 110) within a scan field extending along one or more axes (e.g., along the X-axis shown in FIG. 1, along a Y-axis orthogonal to the X- and Z-axes shown in FIG. 1, or the like or any combination thereof). In one embodiment, the beam positioning system 108 is provided as pair of galvanometer mirrors arranged optically in series. In some embodiments, the beam positioning system 108 can include one or more components such as a galvanometer mirror, a fast steering mirror, an AOD, an EOD, a MEMS-based scanning system, or the like or any combination thereof. For example, the beam positioning system 108 can include as a first galvanometer mirror arranged and operative to deflect the beam path 103 within a first scan field extending along the X-axis and a second galvanometer mirror arranged and operative to deflect the beam path 103, which was previously deflected within the first scan field by the first galvanometer mirror, within a second scan field extending along the Y-axis. Thus the beam positioning system 108 having the first galvanometer mirror and second galvanometer mirror is configured to deflect the beam path 103 within a two-dimensional scan field. As should be appreciated, when the beam path 103 is deflected within the scan field of the beam positioning system 108, the beam waist of the focused beam of laser energy (as it is ultimately delivered to the workpiece 101) will necessarily be located or positioned within the scan field of the beam positioning system 108. It should further be appreciated that, in embodiments in which the beam modulator 104 is configured and operative to deflect the beam path 103 (e.g., as described above), the scan field associated with the beam modulator 104 will be superimposed onto the scan field of the beam positioning system 108 (e.g., so that the beam positioning system 108 deflects the scan field of the beam modulator 104).

[0030] Generally, the scan lens 110 is configured to focus the beam of laser energy propagating along the beam path 103 (e.g., such that the beam waist of the focused beam of laser energy is located at or near the workpiece 101). Thus, the scan lens 110 can be considered as being configured to project, onto the workpiece 101, the scan field of the beam positioning system 108. The scan lens 110 can be provided as an f-theta scan lens, a telecentric f-theta scan lens, or the like. In an alternative embodiment, the scan lens 110 may be replaced with a concave mirror arranged to reflect the beam of laser energy onto the workpiece 101 while also focusing the reflected beam of laser energy.

[0031] Although not shown, the system 100 can optionally include at least one optical stage arranged and operative to move the scan lens 110 (e.g., in response to one or more control signals output by the controller 112). For example, the at least one optical stage may be operative to translate the scan lens 110 along one or more of the X-, Y-, or Z-axes, rotate the scan lens 110 about one or more of the X-, Y-, or Z-axes, the like or any combination thereof. In this case, the scan lens 110 may be incorporated within a housing such as scan head 116 that houses the beam positioning system 108, and the at least one optical stage may be mechanically coupled to the scan head 116.

[0032] The workpiece stage 114 may include a chuck (e.g., a vacuum chuck, an electrostatic chuck, a mechanical etc.) operative to prevent or minimize movement of the workpiece 101 when the workpiece 101 is supported on the workpiece stage 114. Further, the workpiece stage 114 may be provided as one or more motion stages arranged and operative to move the workpiece 101 (e.g., in response to one or more control signals output by the controller 112). For example, the workpiece stage 114 may be operative to translate the workpiece 101 along one or more of the X-, Y-, or Z-axes, rotate the workpiece about one or more of the X-, Y-, or Z-axes, the like or any combination thereof.

[0033] The controller 112 is operative to generate and output one or more control signals to one or more components of the system 100, such as the laser source 102, beam modulator 104, beam positioning system 108, workpiece stage 114, optical stage, or the like or any combination thereof, to control the operation(s) of such components in any manner suitable or otherwise known in the art.

[0034] According to embodiments of the present invention, a control signal output by the controller 112 will convey a command that has been produced by an application analysis module of the controller 112. The application analysis module (not shown) is operative to access a computer file containing a set of application data representing (e.g., in terms of size, shape, location, orientation, etc.) one or more features (e.g., slots, trenches, vias, holes, openings, scribe lines, etc.) to be formed within the workpiece 101 during processing of the workpiece 101. In one embodiment, computer file may also contain workpiece data representing certain characteristics of the workpiece 101 to be processed (e.g., in terms of type, material construction, dimensions, etc.). In another embodiment, the workpiece data can be appended to or otherwise associated with the set of application data via user interaction with a user interface (not shown) of the system 100. The application analysis module is operative to process or analyze the application data and workpiece data in any suitable manner known in the art to obtain, derive or otherwise produce (by any technique suitable or otherwise known in the art) a series of commands intended to coordinate and control the operations of one or more components of the system 100 (e.g., the laser source 102, beam modulator 104, beam positioning system 108, optical stage, workpiece stage 114, or the like or any combination thereof) so that the workpiece 101 will be processed to form the feature(s) therein (e.g., as described in the computer file).

[0035] For example, the application analysis module may generate one or more commands which, when output to the laser source 102, cause the laser source 102 to output a beam of laser energy having a particular average power, peak power, temporal power profile, pulse duration, duty ratio, etc. Commands output to the laser source 102 are generically referred to as “laser commands.” A laser command intended to control an average, instantaneous or peak power of the output beam of laser energy is referred to herein generally as a “laser power command.”

[0036] In another example, the application analysis module may output one or more commands which, when output to the beam modulator 104, cause the beam modulator 104 to attenuate the optical power in the beam of laser energy incident thereto. Optionally, the degree to which the beam of laser energy is to be attenuated may take into account on or more factors such as the average power, peak power, temporal power profile, pulse duration, etc., of the beam of laser energy output by the laser source 102, predetermined known optical absorption characteristics of the beam path components, or the like or any combination thereof. Such commands to be output to the beam modulator 104 are referred to as “transmission commands.”

[0037] In an embodiment in which the beam modulator 104 is provided as the aforementioned AO device 200 and driving circuitry 202 discussed relative to FIG. 2, and to the extent that the deflection angle Θ can be varied by frequency of the drive signal applied to the at least one transducer of the AO device 200, the application analysis module is operative to generate and output one or more commands to the driving circuitry 202 to cause the frequency of one or more drive signals applied to the at least one transducer of the AO device 200 to be varied at least once (e.g., to deflect the beam path 103 to a desired position). Such commands would be output to the driving circuitry 202 contemporaneously with one or more corresponding transmission commands (e.g., as discussed above) and are referred to as “frequency-modulated position commands.” In an embodiment in which the beam modulator 104 is provided as one or more of the aforementioned AO devices (and associated driving circuitry), and to the extent that the deflection angle Θ can be varied by varying the frequency of the drive signal applied to at least one transducer of an AO device, the application analysis module may output a first frequency-modulated position command to driving circuitry associated with the first AO device and output a second frequency-modulated position command to driving circuitry associated with the second AO device.

[0038] In another example, the application analysis module may output one or more commands which, when output to the beam positioning system 108, cause the beam positioning system 108 to deflect the beam path 103 (e.g., at a desired velocity, to a desired position, etc.) within the scan field thereof. Such commands to be output to the beam positioning system are generically referred to as “beam position commands.” In an embodiment in which the beam positioning system 108 is provided as the aforementioned pair of galvanometer mirrors, the application analysis module may output a first beam position command to the first galvanometer mirror and output a second beam position command to the second galvanometer mirror. Because the beam position commands and the aforementioned frequency-modulated position commands can affect the relative position between workpiece 101 and the beam waist of the focused beam of laser energy propagating from the scan lens 110, the beam position commands and the aforementioned frequency-modulated position commands may be considered to be different embodiments of a “position command.”

[0039] In another example, the application analysis module may output one or more commands to the optical stage to cause the optical stage to move the scan lens 110 or scan head 116 (e.g., at a desired velocity, to a desired position, etc.), and such commands to be output to the optical stage system are referred to as “optical stage position commands.” In yet another example, the application analysis module may output one or more commands to the workpiece stage 114 to cause the workpiece stage 114 to move the workpiece 101 (e.g., at a desired velocity, to a desired position, etc.), and such commands are referred to as “workpiece stage position commands.” Optical stage position commands and workpiece stage position commands may be generically referred to herein as “stage position commands.” Because stage position commands can affect the relative position between workpiece 101 and the beam waist of the focused beam of laser energy propagating from the scan lens 110, the stage position commands may be considered to be different embodiments of a “position command.”

[0040] Control signals conveying the aforementioned commands may be sequentially output in a coordinated manner (e.g., by any technique suitable or otherwise known in the art) so that the workpiece 101 will be processed to form feature(s) therein as desired. As the workpiece 101 is processed, the beam of laser energy is delivered to a multitude of positions at the workpiece 101 (e.g., as a series of laser pulses and/or as a CW or QCW beam of laser energy). The total amount of time during which the workpiece 101 is processed can be divided, at least conceptually, into a sequence of processing periods of arbitrary or predetermined duration, and may optionally take into account the update rates of one or more of the aforementioned components of the system 100. In some embodiments, a processing period may be in a range from 0.5 μs (or thereabout) to 150 μs (or thereabout), such as 0.5 μs, 1 μs, 5 μs, 10 μs, 25 μs, 50 μs, 75 μs, 100 μs, 150 μs, etc., or between any of these values.

[0041] Generally, the controller 112 includes one or more processors operative to generate the aforementioned commands and control signals (e.g., upon executing one or more 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 any other suitable form of circuitry including programmable logic devices (PLDs), central processing units (CPUs), graphics processing units (GPUs), accelerated processing units (APUs), real-time processing units (RPUs), 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) operative to execute the instructions. Execution of instructions can be performed on one processor, distributed among multiple processors, made parallel across processors within a device or across a network of devices, or the like or any combination thereof.

[0042] Generally, the instructions may be embodied as software (e.g., an executable code, file, library file, or the like or any combination thereof), hardware configuration (e.g., in the case of FPGAs, ASICs, etc.), or the like or any combination thereof, which can be readily specified 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 such as LUCID, VHDL or VERILOG, etc.). Software is commonly stored in one or more data structures conveyed by tangible media such as computer memory, which is accessible (e.g., via one or more wired or wireless communications links) by a processor. Examples of tangible media include 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.), or the like or any combination thereof, and may be accessed locally, remotely (e.g., across a network), or any combination thereof.

[0043] It should be noted that various functions performed by the controller 112 are described as being performed by certain modules. This division of modules is for illustration only. In an alternate aspect, a function performed by a particular module may be divided amongst multiple modules. Moreover, in an alternate aspect, two or more modules described herein may be integrated into a single module. Each module described herein may be implemented using hardware (e.g., an FPGA device, an ASIC, etc.), software (e.g., instructions executable by a processor), or any combination thereof.

[0044] Although the system 100 has been described above as including a single beam positioning system 108 and scan lens 110 (e.g., incorporated within a single, common scan head 116), it will be appreciated that the system 100 may, in other embodiments, be provided with multiple scan heads 116, with each scan head 116 including a beam positioning system 108 and scan lens 110 (and, optionally, independently movable by a separate optical stage). In such other embodiments, an optical switch may be arranged and operable to selectively deflect the beam path 103 (e.g., from the beam positioning system 108 of one scan head 116 to the beam positioning system 108 of another scan head 116, and vice-versa). In this case, the optical switch would be arranged in the beam path 103 either optically upstream or downstream of the beam modulator 104 and be communicatively coupled to the controller 112 (e.g., so as to be operable to deflect the beam path 103 in response to one or more commands output by the application analysis module). Alternatively, in embodiments in which the beam modulator 104 is provided as a device capable of deflecting the beam path 103 (e.g., an AOM, AOD, as described above, an EOM, EOD, etc.), the beam modulator 104 may be operated (e.g., in response to one or more frequency-modulated position commands output by the application analysis module) to selectively deflect the beam path 103 from the beam positioning system 108 of one scan head 116 to the beam positioning system 108 of another scan head 116 and vice-versa.

[0045] Although not shown in FIG. 1, the system 100 may optionally include a laser beam monitoring system operative to measure the optical power or energy in the beam of laser energy propagating along the beam path 103. In one embodiment, the laser beam monitoring system can be provided as laser beam monitoring system 300 shown in FIG. 3.

[0046] Referring to FIG. 3, the laser beam monitoring system 300 includes a mirror 302 and a laser sensor 304. The mirror 302 is arranged within beam path 103 and is provided as a partially-transmissive mirror configured to reflect a majority of light in the incident beam of laser energy propagating along beam path 103 (i.e., into beam path 103r) and transmit a small amount of the light (e.g., 2% or thereabout) into beam path 103t. In FIG. 3, the mirror 302 can be arranged within beam path 103 at any location optically “upstream” or “downstream” of the beam modulator 104. In this case, beam path 103r corresponds to beam path 103 shown and described above with respect to FIG. 1. The laser sensor 304 is arranged to receive laser energy transmitted through the mirror 302 (e.g., propagating along beam path 103t).

[0047] In one embodiment, the laser sensor 304 is configured to measure the instantaneous optical power in the beam of laser energy incident thereon and generate sensor data based on the sensing or measurement. The sensor data can be output to the controller 112 by any suitable means (e.g., via wired or wireless communication, as is known in the art). The controller 112 causes the sensor data to be stored (e.g., locally within the controller 112, on some computer memory within the system 100 accessible to the controller 112, on some computer memory located remote from the system 100 but communicatively connected to the system 100 via one or more networks). In another embodiment, the sensor data output to the controller 112 can be further processed (e.g., time-integrated) at the controller 112 to derive the energy content of the beam of laser energy incident upon the laser sensor 304 (e.g., over a predetermined time duration, etc.), and the sensor data thus processed can be stored (e.g., as described above).

[0048] In another embodiment, the laser sensor 304 is provided as an integrating detector (e.g., configured to measure the instantaneous optical power in the beam of laser energy incident thereon and integrate the measured optical power to derive the energy content of the beam) and generate sensor data. The sensor data can be output to the controller 112 by any suitable means (e.g., via wired or wireless communication, as is known in the art) and is stored (e.g., as described above).

[0049] In some embodiments, sensor data obtained or otherwise processed or derived and stored or accessible at the controller 112 can be monitored (e.g., on a periodic basis, during preventative maintenance periods, or the like or any combination thereof) in order to determine whether the laser source 102 is operating properly. If it is determined that the laser source 102 is not operating properly, then the controller 112 may control an operation of the beam modulator 104 to compensate for the operation of the laser source 104. For example, if the sensor data indicates that the measured or derived power or energy is below a target threshold, then the controller 112 may adjust the manner in which the beam modulator 104 is operated to reduce the extent by which it attenuates the incident beam of laser energy. Likewise, if the sensor data indicates that the measured or derived power or energy is above a target threshold, then the controller 112 may adjust the manner in which the beam modulator 104 is operated to increase the extent by which it attenuates the incident beam of laser energy.

[0050] In an embodiment in which the mirror 302 is located optically downstream of the beam modulator 104 and in which the beam modulator 104 is provided as described above with respect to FIG. 2, the mirror 302 is arranged within the first order beam path 206. In another embodiment, however, the mirror 302 can be arranged within the zeroth-order beam path 204.

II. Embodiments Concerning Compensation of Thermally-Induced Beam Pointing Errors

[0051] According to embodiments described herein, one or more of the aforementioned beam path components will absorb at least some fraction of energy within the high-power beam of laser energy propagating along the beam path 103 from the beam modulator 104. Thus, the stability of the thermal gradients within the beam path components may be compromised (e.g., depending upon one or more factors relating to the operation of the system, as described above), leading to the generation of thermally-induced beam pointing errors which can deleteriously affect the accuracy and/or quality with which the workpiece 101 is processed.

[0052] The inventors have discovered that the aforementioned thermally-induced beam pointing errors can be generally categorized as errors associated with “drift,” “shift” or “scaling.” As described in greater detail below, embodiments of the present invention provide for thermal compensation techniques which can compensate for (i.e., prevent or otherwise reduce the effects of) one or more of these thermally-induced beam pointing errors much more rapidly than conventional techniques described above.

[0053] As used herein, “drift” refers to movement of the beam waist of the focused beam of laser energy along one or more axes (e.g., the aforementioned X- and/or Y-axes) of a scan field projected onto the workpiece 101 by the scan lens 110. Drift in one axis can be different from drift in another axis. Similarly, drift in either axis can vary from one system 100 to another and between different scan heads 116 of the same system 100 (e.g., depending on the manner in which the components in the beam path 103 of any system 100 are mounted and aligned). In some cases, thermal accumulation within an optical component 106 (e.g., a mirror) or mounting device associated with an optical component 106 can result in undesirable drift.

[0054] As used herein, “shift” refers to movement of the beam waist of the focused beam of laser energy along the beam path 103 as it propagates from the scan lens 110. Generally, thermal accumulation within a transmissive optical component 106 (e.g., a lens, prism, etc.), or the scan lens 110 can cause the beam waist to move away from the workpiece 110 (e.g., in a direction toward to the scan lens 110), thereby changing (typically, increasing) the size of the spot of the beam of laser energy at the workpiece 101. Likewise, loss of thermal energy within a transmissive optical component 106 or scan lens 110 can cause the beam waist to move away from the scan lens 110 (e.g., in a direction toward the workpiece 101), thereby changing (typically, decreasing) the size of the spot of the beam of laser energy at the workpiece 101.

[0055] As used herein, “scaling” refers to the degree to which the intended size of the scan field projected by the scan lens 110 decreases or increases (e.g., due to a corresponding shortening or lengthening of the focal length of the scan lens 110, as described above). Generally, thermal accumulation within the scan lens 110 can shrink a scan field (e.g., of the beam positioning system 108, etc.) projected therethrough onto the workpiece 101. Likewise, loss of thermal energy within the scan lens 110 can expand the scan field (e.g., of the beam positioning system 108, etc.) projected therethrough onto the workpiece 101.

[0056] To the extent that the aforementioned thermally-induced beam pointing errors can be undesirably large, embodiments of the present invention compensate for their effects, e.g., by counteracting or otherwise minimizing or reducing thermally-induced drift, shift and/or scaling.

A. Embodiments Concerning Thermal Compensation Module, Generally

[0057] According to embodiments of the present invention, and referring to FIG. 4, the application analysis module includes a thermal compensation module 400 operative to implement one or more thermal compensation techniques. As will be described in greater detail below, the thermal compensation module 400 processes laser power data 402 (and, optionally, beam position data 404) to estimate a thermal response (e.g., of one or more beam path components or of the system 100 in general, or any combination thereof) during a given processing period. As used herein, a "thermal response" is a measure of how quickly a thermal gradient may grow, dissipate or otherwise change (e.g., in one or more beam path components or of the system 100 in general, or any combination thereof) during a given processing period (e.g., in the presence or absence of optical power in the beam of laser energy) to generate one or more of the aforementioned thermally-induced beam pointing errors.

[0058] The thermal compensation module 400 may thereafter apply one or more correction functions (also discussed in greater detail below) to the estimated thermal response(s) and, optionally, any input preliminary position commands 406, to produce one or more position command corrections 408. For example, and in one embodiment shown in FIG. 5, the thermal compensation module 400 may include one or more thermal response modules 500 operative to estimate the thermal response of the system 100 and a correction function module 502 operative to apply correction function(s) to the estimated thermal response(s).

[0059] Since the thermal compensation techniques do not involve temperature measurements of any of the beam path components, the system 100 does not include any temperature sensor (e.g., thermocouple, thermistor, resistance temperature detector, pyrometer, infrared thermometer, etc.) for measuring (directly or indirectly) the temperature of any of the aforementioned beam path components of the system 100, and thermally-induced beam pointing errors can be quickly and accurately compensated for during processing of the workpiece 101.

[0060] Laser power data 402 represents, or is otherwise associated or correlated with, the amount of optical power or energy that will be at one or more of the beam path components during a particular processing period. Laser power data 402 can be derived from (e.g., by the application analysis module), or otherwise correspond to, the laser power command, the transmission command, sensor data, or the like or any combination thereof.

[0061] Beam position data 404 represents or is otherwise associated or correlated with the position of the beam path 103 at one or more of the beam path components during a particular processing period. Beam position data 404 can be derived from (e.g., by the application analysis module), or otherwise correspond to, a position command such as a beam position command, a frequency-modulated position command, or the like or any combination thereof.

[0062] Optionally, any of the aforementioned position commands (e.g., any of the beam position commands, frequency-modulated position commands, optical stage position commands, workpiece stage position commands, or any combination thereof) can also be input to the thermal compensation module 400 to facilitate estimating the thermal response of the system 100 during a given processing period. Such position commands, as input to the thermal compensation module 400, are also herein referred to as "preliminary position commands" 406.

[0063] Generally, a position command correction 408 output by the thermal compensation module 400 will correspond to a preliminary position command associated with one or more of the aforementioned beam path components, the beam modulator 104, or any combination thereof. Accordingly, the application analysis module is operative to apply (e.g., to add, as indicated at 410) each position command correction 408 produced by the thermal compensation module 400 to a corresponding preliminary position command 406 to thereby produce a corrected position command 412. Upon applying a position command correction 408 to a corresponding preliminary position command 406, the preliminary position command 406 is adjusted based on the estimated thermal response of one or more of the beam path components during the given processing period, and the adjustment compensates for one or more of the aforementioned thermally-induced beam pointing errors.

[0064] For example, one or more preliminary position commands 406 (e.g., a first beam position command and/or first frequency-modulated position command) may be adjusted at 410 to compensate for drift estimated to occur in a positive direction along the X-axis (i.e., in a rightward direction as illustrated in FIG. 1) during a given processing period, and the adjustment compensates for the estimated drift by generating one or more corrected position commands 412 that, when operated upon by the beam positioning system 108 or beam modulator 104, offsets the estimated drift in a negative direction along the X-axis (i.e., in a leftward direction as illustrated in FIG. 1) during the given processing period. Although the example provided above discusses compensation of estimated drift in the positive X-axis direction, it should be appreciated that drift estimated to occur in the negative X-axis direction may be compensated for in a similar manner. Further, although the example provided above discusses compensation of estimated drift along the positive X-axis, it should be appreciated that compensation of estimated drift along the Y-axis may be performed in a similar manner.

[0065] In another example, one or more preliminary position commands 406 (e.g., a first beam position command and/or first frequency-modulated position command) may be adjusted at 410 to compensate for scaling estimated to cause a reduction in scan field size along the X-axis during a given positioning period, and the adjustment compensates for the estimated scaling by generating one or more corrected position commands 412 that, when operated upon by the beam positioning system 108 or beam modulator 104, offsets the estimated scaling by increasing the deflection of the beam path 103 along the X-axis during the given period. Although the example provided above discusses compensation of estimated scaling (i.e., reduction) in scan field size along the X-axis, it should be appreciated that expansion of the scan field size estimated to occur along the X-axis may be compensated for in a similar manner. Further, although the example provided above discusses compensation of estimated scaling along the X-axis, it should be appreciated that compensation of estimated scaling (i.e., reduction or expansion of scan field size along the Y-axis) may be performed in a similar manner.

[0066] In another example, one or more preliminary position commands 406 (e.g., an optical stage position command and/or workpiece stage position command) may be adjusted at 410 to compensate for shift estimated to cause the beam waist to move toward the scan lens 110 during a given positioning period, and the adjustment compensates for the estimated shift by generating one or more corrected position commands 412 that, when operated upon by the optical stage and/or workpiece stage 114, offsets the estimated shift by moving the scan lens 110 toward the workpiece 101 and/or moving the workpiece 101 toward the scan lens 110 during the given period. Although the example provided above discusses compensation of estimated shift toward the scan lens 110 (i.e., in the positive Z-axis direction, or upwards, as illustrated in FIG. 1), it should be appreciated that shift estimated to occur in the negative Z-axis direction may be compensated for in a similar manner.

[0067] Although the examples described above have described example processes by which corrected position commands 412 can be produced and output to compensate for thermally-induced drift, shift and scaling individually, it will be appreciated that these embodiments may be combined as desired or otherwise suitable in order to produce a corrected beam position command adapted to compensate for one or more of thermally-induced drift, shift and scaling along one or more axes. The application analysis module is operative to output, the corrected position command(s) 412 (e.g., as position commands conveyed by one or more control signals) to one or more of the beam modulator 104, beam positioning system 108, optical stage, workpiece stage 114 or any combination thereof (e.g., in a coordinated manner, as described above) to ensure that the workpiece 101 is processed during the given processing period in a manner that compensates for one or more of the aforementioned thermally-induced beam pointing errors.

B. Embodiments Concerning Estimation of Thermal Responses

[0068] As mentioned above, the thermal compensation module 400 processes the laser power data 402 (and, optionally, the beam position data 404) to estimate one or more thermal responses of the system 100 during a given processing period, insofar as the thermal response is associated with one or more of the aforementioned thermally-induced beam pointing errors.

[0069] In one embodiment, the thermal response of the system 100 can be estimated by estimating the thermal response of one or more of the beam path components of the system 100. Accordingly, the thermal response of the system 100 during, for example, an nth processing period, can be described as the sum of all estimated thermal responses of beam path components in the system 100, e.g., given by the following function (1):

$$\sum_{i=1}^{m} TR(n)_i = (P(n)_i * \alpha_i) + \left(P(n-1)_i * (1-\alpha_i)\right), \quad (1)$$

where i represents a beam path component of the system 100 containing m number of beam path components. Thus, $TR(n)_i$ represents the estimated thermal response of an ith beam path component during the n^{th} processing period, $P(n)_i$ represents laser power data for the ith beam path component during the nth processing period, $P(n\text{-}1)_i$ represents laser power data for the

i^{th} beam path component during the previous processing period (i.e., during the n-1^{th} processing period), and α_i is a time constant associated with the i^{th} beam path component. Generally, the time constant α_i is a parameter which characterizes a general response of the i^{th} beam path component to a heat input. According to the various embodiments described herein, the value for α_i can be set empirically, modelled, or otherwise determined (e.g., via system calibrations) using any technique suitable or known in the art.

[0070] In one embodiment, and to the extent that a thermally-induced beam pointing error generated by a beam path component is a response of the beam path component to heat, the time constant α_i may be regarded as a parameter which characterizes how quickly a thermally-induced beam pointing error is generated in response to the heat input. However, depending on the beam path component and/or the thermally-induced beam pointing error, the inventors have discovered a thermally-induced beam pointing error may be generated due to multiple responses of the beam path component to the heat input, wherein the multiple responses are associated with different time scales. Accordingly, the time constant α_i may be a single value or, if the thermally-induced beam pointing error is generated due to multiple responses, the time constant α_i may be represented as a combination (e.g., linear or otherwise) of multiple values (e.g., each associated with a respective one of the different time scales).

[0071] In another embodiment, and to the extent that different thermally-induced beam pointing errors generated by a beam path component may be generated over different time scales, the time constant α_i may be represented as a combination (e.g., linear or otherwise) of multiple values (e.g., each associated with a respective one of the different time scales). In another embodiment, however, different time constants α_i (whether represented as a single value or as a combination of values, as described above) may be used in different instances of function (1) to estimate different thermal responses of the system 100 during a given processing period. For example a first instance of function (1) may be used to estimate a thermal response of the system 100 (i.e., the sum of thermal responses of all beam path components) responsible for generating drift, second instance of function (1) may be used to estimate a thermal response of the system 100 (i.e., the sum of thermal responses of all beam path components) responsible for generating shift, and a third instance of function (1) may be used to estimate a thermal response of the system 100 (i.e., the sum of thermal responses of all beam path components) responsible for generating scaling. If a beam path component does not contribute to a particular thermally-induced beam pointing error, then the time constant α_i for that beam path component would be zero. The first instance of function (1) is also referred to herein as a “drift-estimating function,” the second instance of function (1) is also referred to herein as a “shift-estimating function,” and the third instance of function (1) is also referred to herein as a “scaling-estimating function.”

[0072] In another embodiment, and to the extent that different thermally-induced beam pointing errors generated by a beam path component may be generated over the same time scale, a common time constant α_i (whether represented as a single value or as a combination of values, as described above) may be used in a common instance of function (1) to estimate a thermal response of the system 100 during a given processing period which is responsible for different thermally-induced beam pointing errors. For example, a common instance of function (1) may be used to estimate a common thermal response of the system 100 (i.e., the sum of thermal responses of all beam path components) that is responsible for generating shift and scaling. The common instance of function (1) in this embodiment may also be referred to herein as a “shift/scaling-estimating function.” Again, if a beam path component does not contribute to the either of the different thermally-induced beam pointing errors, then the time constant α_i for that beam path component would be zero.

[0073] As mentioned above, if a beam path component does not contribute to a particular thermally-induced beam pointing error, then the time constant α_i for that beam path component would be zero. In an alternative embodiment, if a beam path component contributes less than a predetermined threshold amount to a particular thermally-induced beam pointing error, then contribution of the estimated thermal response for the beam path component is not included in the respective of function (1). For example, the beam positioning system 108 may not contribute (or contribute less than a predetermined threshold amount) to shift and scaling; accordingly the estimated thermal response of the beam positioning system 108 need not be included in the shift- and/or scaling-estimating function. In another example, the scan lens 110 may not contribute (or contribute less than a predetermined threshold amount) to drift; accordingly the estimated thermal response of the scan lens need not be included in the drift-estimating function.

[0074] Generally, each beam path optical component absorbs some fraction of the optical power in the beam of laser energy propagating along beam path 103. Accordingly, the laser power data P(n) for one beam path component during a given processing period may be different than the power data for a different beam path component during the same processing period. Further depending on the configuration of the system, the difference in laser power data for at least two of the m beam path components may be relatively small or otherwise insignificant and so, in another embodiment, the same laser power data associated with a given processing period may be used for the at least two of the m beam path components.

[0075] In another embodiment, the thermal response of the system 100 as a whole can be estimated without explicit account of the individual thermal responses of each beam path component of the system 100. In this sense, the thermal response of the system 100 would simply be associated with one or more thermally-induced beam pointing errors detected (e.g., through direct or indirect observation, measurement, etc.) at an output location relative to the scan lens 110 (e.g., at the workpiece 101). Accordingly, the thermal response of the system 100 during the n^{th} processing period can be given by the following function (2):

$$TR(n) = (P(n) * \alpha) + (P(n-1) * (1-\alpha)), \quad (2)$$

where $TR(n)$ represents the estimated thermal response of the system 100 during the n^{th} processing period, $P(n)$ represents the laser power data for the scan lens 110 during the n^{th} processing period, $P(n-1)$ represents the laser power data for the scan lens 110 during the previous ($n-1^{th}$) processing period, and the time constant α indicates how quickly the temperature of the system 100 changes in response to the presence or absence of laser energy propagating along beam path 103. The value for α can be set empirically or otherwise set using any technique suitable or known in the art. As with function (1), the different instances of function (2) may be used to estimate thermal responses associated with different thermally-induced beam pointing errors. For example, a first instance of function (2) may be provided as the aforementioned “drift-estimating function,” a second instance of function (2) may be provided as the aforementioned “shift-estimating function,” and the third instance of function (2) may be provided as the aforementioned “scaling-estimating function.” In another example, a common instance of function (2) may be provided as the aforementioned “shift/scaling-estimating function.”

[0076] As will be appreciated, the aforementioned functions (1) and (2) are examples of a first-order infinite impulse (IIR) filter. This filter may be provided as a digital filter, an analog filter, or the like or any combination thereof. Nevertheless, embodiments of the present invention are not limited to the use of IIR filters to estimate thermal responses associated with the system 100. For example, other filters (whether implemented digitally or in analog) that can be used include a biquad filter, a Butterworth filter, or the like or any combination thereof. Coefficients of any filter implement in each thermal response module 500, and the respective order(s) thereof, can be selected or set empirically or by any other technique suitable or known in the art.

C. Embodiments Concerning Correction Functions

[0077] As mentioned above, the thermal compensation module 400 is operative to apply one or more correction functions to the estimated thermal response(s) and, optionally, any input preliminary position commands 406, to produce one or more position command correction 408. Generally, a correction function may be provided as any suitable function or combination of basis functions suitable for modelling thermally-induced beam pointing errors attributable to drift, shift or scaling. Examples of suitable functions include 1st order linear regression functions, nth-order polynomial functions (where n is two or greater), or the like.

[0078] Correction functions used to produce a position command correction 408 can vary depending on the estimated thermal response to which it is applied, depending on the type of thermally-induced beam pointing error to be compensated for, depending on the preliminary position command it is intended to adjust, or the like or any combination thereof. Examples of correction functions that may be applied to compensate for drift in the X- and Y-axes during a given processing period, *n*, can be described by the following correction functions (3) and (4):

$$Xdrift\_pcc(n) = (Adx * TR(n)^2) + \big(Bdx * TR(n)\big), \quad (3)$$

$$Ydrift\_pcc(n) = (Ady * TR(n)^2) + \big(Bdy * TR(n)\big), \quad (4)$$

where the values of coefficients *Adx*, *Bdx*, *Ady* and *Bdy* can be set empirically or otherwise set using any technique suitable or known in the art, *Adx* and *Ady* may be the same or different, and *Bdx* and *Bdy* may be the same or different. In this example, *TR(n)* represents the estimated thermal response output by, for example, the drift-estimating function associated with either function (1) or (2).

[0079] An example of a correction function that may be applied to compensate for shift (e.g., in the Z-axis) during a given processing period, *n*, can be described by the following correction function (5):

$$Zshift\_pcc(n) = (Asz * TR(n)^2) + \big(Bsz * TR(n)\big), \quad (5)$$

where the values of coefficients *Asz* and *Bsz* can be set empirically or otherwise set using any technique suitable or known in the art, and *Asz*, *Adx* and *Ady* may be the same or different, and *Bsz*, *Bdx* and *Bdy* may be the same or different. In this example, *TR(n)* represents the estimated thermal response output by the aforementioned shift-estimating function or the shift/scaling-estimating estimating function associated with either function (1) or (2).

[0080] Examples of correction functions that may be applied to compensate for scaling in the X- and Y-axes during a given processing period can be described by the following correction functions (6) and (7):

$$Xscale\_pcc(n) = (Xsx * TR(n)^2) + \big(Bsx * TR(n)\big) * Xprelim\_pos\_command(n), \quad (6)$$

$$Yscale\_pcc(n) = (Asy * TR(n)^2) + \big(Bsy * TR(n)\big) * Yprelim\_pos\_command(n) \quad (7)$$

where the values of coefficients *Asz* and *Bsz* can be set empirically or otherwise set using any technique suitable or known in the art, and *Asz*, *Adx* and *Ady* may be the same or different, and *Bsz*, *Bdx* and *Bdy* may be the same or different. *Xprelim_pos_command(n)* represents a first beam position command and/or a first frequency-modulated position command preliminary to be adjusted by a corresponding position command correction 408 and thereafter applied to the first galvanometer mirror and/or the first AO device, respectively, to cause the beam path 103 to be deflected in a desired manner along the X-axis (e.g., as described above) during the n^{th} processing period. *Yprelim_pos_command(n)* represents a second beam position command and/or a second frequency-modulated position command preliminary to be adjusted by a corresponding position command correction 408 and thereafter applied to the second galvanometer mirror and/or the second AO device, respectively, to cause the beam path 103 to be deflected in a desired manner along the Y-axis (e.g., as described above) during the n^{th} processing period. In this example, *TR(n)* represents the estimated thermal response output by the aforementioned scaling-estimating function associated with either function (1) or (2).

[0081] The coefficients of correction functions (3) to (7) may be set empirically, modelled, or otherwise determined (e.g., via system calibrations) using any technique suitable or known in the art. Further, the coefficients of correction functions (3) to (7) may change depending upon the size, number and density of features to be formed within the workpiece 101, depending on the placement of the workpiece 101 on the workpiece stage 114, depending on the utilization of the scan field(s) projected by the scan lens 110, depending on the location of the scan field (or location of the centroid of the scan field) within the scan lens during a processing period, or the like or any combination thereof.

III. Conclusion

[0082] 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.

[0083] For example, embodiments described above provide a system and technique for real-time compensation of thermally-induced beam pointing errors. It will be appreciated that these embodiments may be adapted for non-real-time compensation of thermally-induced beam pointing errors. For example, the application analysis module may generate a set of preliminary position commands (e.g., as described above) necessary to form features as desired in the workpiece 101 and input those preliminary position commands to the thermal compensation module 400. The thermal compensation module 400 may process the preliminary position commands (e.g., as described above) in the set to generate a set of position command corrections 408. The application analysis module may then apply each position command correction 408 to a corresponding preliminary position command (e.g., at 410, as discussed above) to generate a set of corrected position commands 412. After the set of corrected position commands 412 are generated, the corrected position commands 412 may be sequentially output (e.g., to the beam modulator 104, beam positioning system 108, optical stage and/or workpiece stage 114) as described above and in a coordinated manner with commands output to any other component of the system 100 (e.g., the laser source 102) so that the workpiece 101 will be processed to form feature(s) therein as desired.

[0084] In another example, although compensation for estimated shift has been discussed above as being effected by adjusting the position of the optical stage and/or workpiece stage 114, it will be appreciated that shift may be compensated for in other ways. For example, and in an embodiment in which the beam modulator 104 includes the aforementioned first AO device and second AO device (and associated driving circuitry), the beam modulator 104 may be operated to rapidly move the beam waist toward or away from the scan lens 110 by “chirping” the frequency of the drive signals applied to the first AO device and second AO device, in any manner suitable or otherwise known in the art.

[0085] 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 laser-processing system for processing a workpiece, the system comprising:

a laser source operative to output a beam of laser energy, wherein the beam of laser energy is propagatable along a beam path;

a plurality of beam path components arranged within the beam path, the plurality of beam path components including:

a beam positioning system operative to deflect the beam path within a scan field in response to a position command; and

a scan lens arranged to focus the beam laser energy as deflected by the beam positioning system, thereby producing a focused beam of laser energy having a beam waist; and

a controller communicatively coupled to the beam positioning system, the controller configured to generate the position command based, at least in part, on an estimated thermal response of at least one of the plurality of beam path components to the beam of laser energy during a predetermined processing period and output the generated position command to the beam positioning system to operate the beam positioning system during the processing period.

2. The system of claim 1, wherein the at least one of the plurality of beam path components includes the scan lens.

3. The system of claim 1, wherein the at least one of the plurality of beam path components includes the beam positioning system.

4. The system of claim 1, wherein the controller is further configured to estimate the thermal response of the at least one of the plurality of beam path components.

5. The system of claim 4, wherein the controller is configured to estimate the thermal response of the at least one of the plurality of beam path components based, at least in part, on laser power data corresponding to an amount of optical power or energy present at the at least one of the plurality of beam path components during the processing period.

6. The system of claim 5, wherein the controller is configured to estimate the thermal response of the at least one of the plurality of beam path components based, at least in part, on beam position data corresponding to a position of the beam path at the at least one of the plurality of beam path components during the processing period.

7. The system of claim 5, wherein the controller is configured to estimate the thermal response of the at least one of the plurality of beam path components based, at least in part, on a preliminary position command beam position data corresponding to a position of the beam path at the at least one of the plurality of beam path components during the processing period.

8. The system of claim 1, further comprising a beam modulator operative to attenuate the laser energy .

9. The system of claim 1, further comprising a laser beam monitoring system operative to measure an optical quality of the beam of laser energy and generate sensor data representing the measured optical quality.

10. The system of claim 9, wherein the controller is configured to estimate the thermal response of the at least one of the plurality of beam path components based, at least in part, on the sensor data.

11. The system of claim 1, wherein the system does not include a temperature sensor configured to sense a temperature of the beam positioning system or the scan lens.

12. The system of claim 1, further comprising at least one stage operative impart relative movement between the beam waist and the workpiece in response to a stage position command.

13. The system of claim 12, wherein the at least one stage is operative to move the workpiece.

14. The system of claim 12, wherein the at least one stage is operative to move the scan lens.

15. The system of claim 12, wherein the controller is communicatively coupled to the at least one stage beam positioning system, the controller configured to generate the stage position command based, at least in part, on the estimated thermal response of at least one of the plurality of beam path components to the beam of laser energy during the predetermined processing period and output the generated stage position command to the at least one stage to operate the at least one stage during the processing period.

16. A laser-processing system for processing a workpiece, the system comprising:

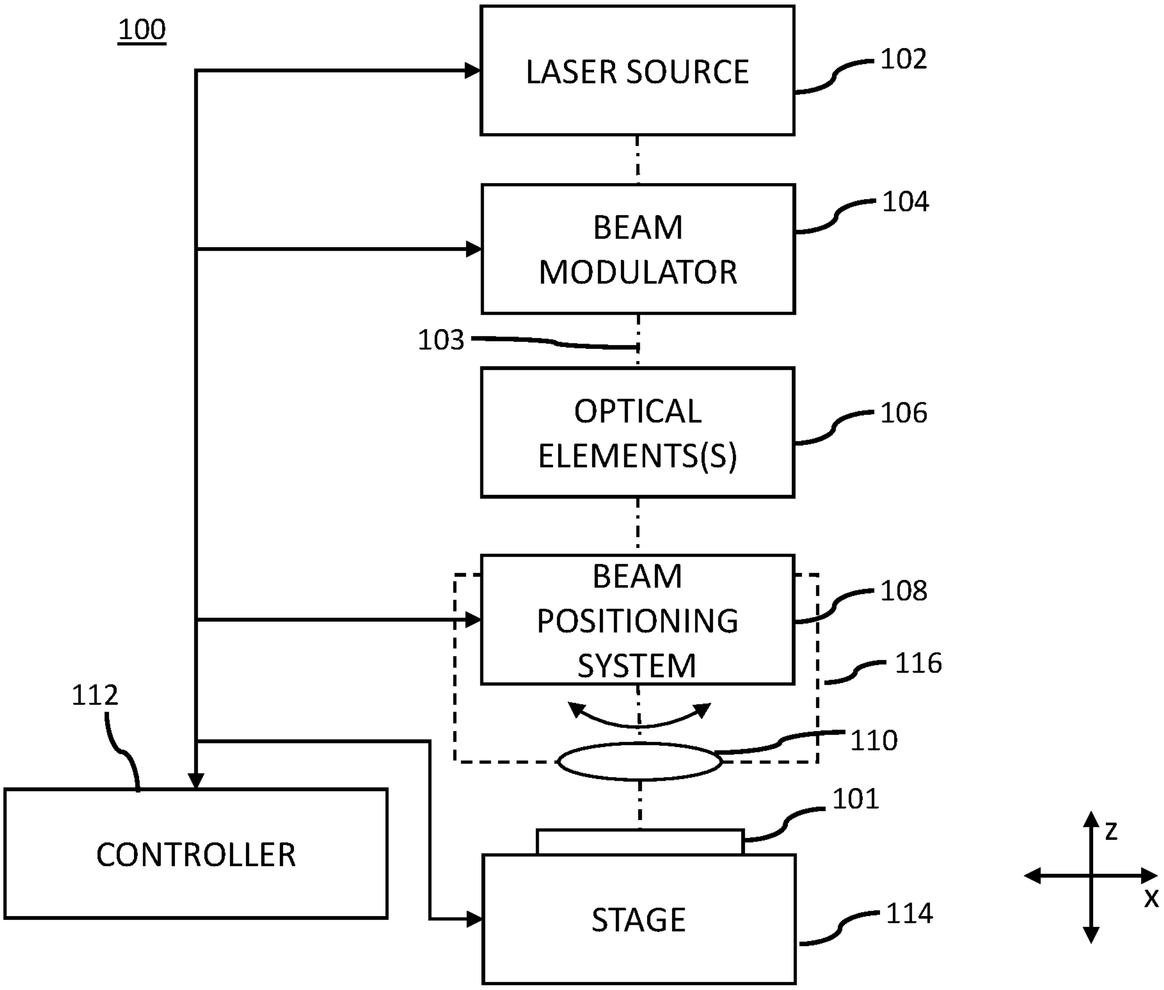
a laser source operative to output a beam of laser energy, wherein the beam of laser energy is propagatable along a beam path;

a plurality of beam path components arranged within the beam path, the plurality of beam path components including:

a scan lens arranged to focus the beam laser energy as deflected by the beam positioning system, thereby producing a focused beam of laser energy having a beam waist; and

at least one stage operative impart relative movement between the beam waist and the workpiece in response to a stage position command; and

a controller communicatively coupled to the at least one stage beam positioning system, the controller configured to generate the stage position command based, at least in part, on an estimated thermal response of at least one of the plurality of beam path components to the beam of laser energy during a predetermined processing period and output the generated stage position command to the at least one stage to operate the at least one stage during the processing period.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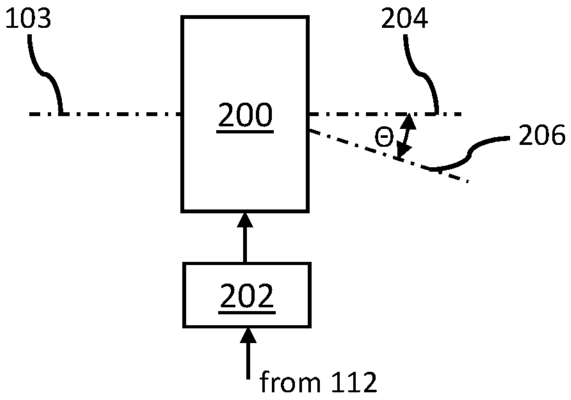
LASER SOURCE
102
BEAM MODULATOR
104
103
OPTICAL ELEMENTS(S)
106
BEAM POSITIONING SYSTEM
108
116
112
110
101
CONTROLLER
STAGE
114
z
x

FIG. 1


103
204
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202
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FIG. 2

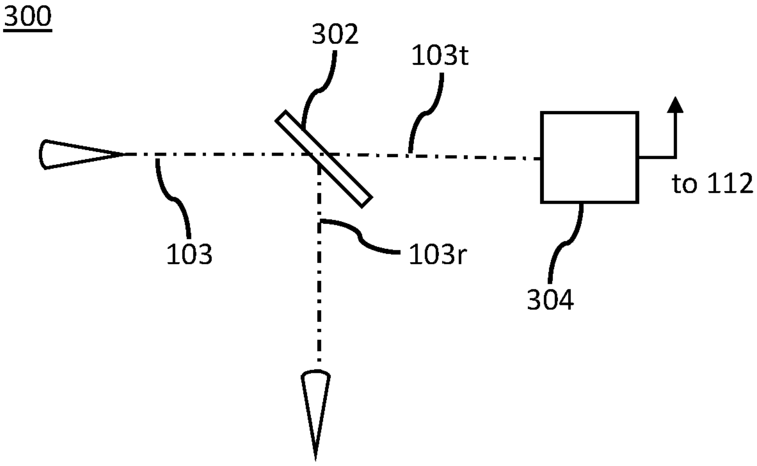

FIG. 3

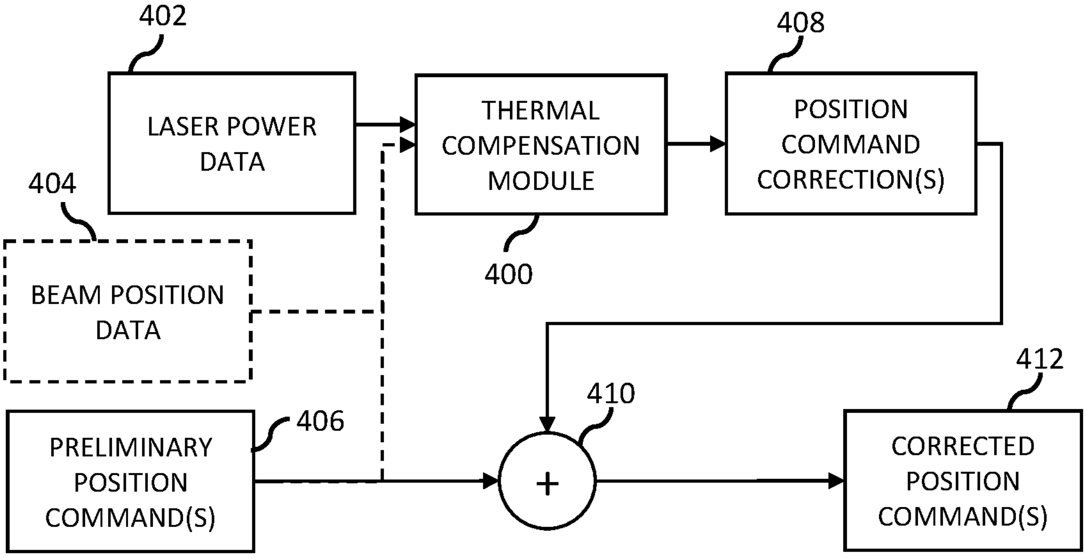

FIG. 4

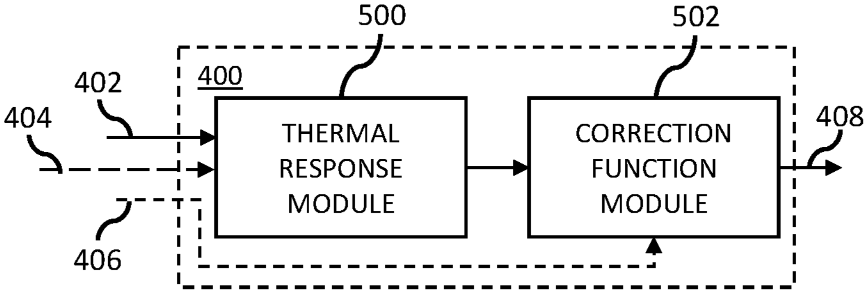

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2024/013324

A. CLASSIFICATION OF SUBJECT MATTER

B23K 26/082(2014.01)i; **B23K 26/06**(2006.01)i; **B23K 26/08**(2006.01)i; **B23K 26/03**(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

B23K 26/082(2014.01); B23K 26/042(2014.01); B23K 26/382(2014.01); G02B 27/30(2006.01); H01J 3/14(2006.01); H01J 40/14(2006.01); H01L 31/042(2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: laser-processing system, laser source, beam path components, controller, estimated thermal response

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y A	US 2016-0368089 A1 (IPG PHOTONICS CORPORATION) 22 December 2016 (2016-12-22) paragraphs [0002]-[0067]; and figure 1	1-5,8-10,12-16 6-7,11
Y	US 2019-0001442 A1 (ELECTRO SCIENTIFIC INDUSTRIES, INC.) 03 January 2019 (2019-01-03) paragraphs [0045]-[0074]; and figure 1	1-5,8-10,12-16
A	US 2006-0202115 A1 (LIZOTTE et al.) 14 September 2006 (2006-09-14) paragraphs [0064]-[0069]; and figures 1, 19-22	1-16
A	US 5315111 A (BURNS et al.) 24 May 1994 (1994-05-24) claims 1-25; and figures 1-6	1-16
A	KR 10-1709711 B1 (ELECTRO SCIENTIFIC INDUSTRIES, INC.) 24 February 2017 (2017-02-24) claims 1-2, 4-17; and figures 1-4	1-16

☐ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"D" document cited by the applicant in the international application	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"E" earlier application or patent but published on or after the international filing date	"&" document member of the same patent family
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search **31 May 2024**	Date of mailing of the international search report **31 May 2024**
Name and mailing address of the ISA/KR **Korean Intellectual Property Office** **189 Cheongsa-ro, Seo-gu, Daejeon** **35208, Republic of Korea** Facsimile No. **+82-42-481-8578**	Authorized officer **PARK, Tae Wook** Telephone No. **+82-42-481-3405**

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2024/013324

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
US 2016-0368089 A1	22 December 2016	CA 2989860 A1	22 December 2016
		CA 2989860 C	26 September 2023
		CA 3208157 A1	22 December 2016
		CN 107708914 A	16 February 2018
		CN 107708914 B	28 May 2021
		CN 113210854 A	06 August 2021
		EP 3310518 A1	25 April 2018
		EP 3310518 B1	16 June 2021
		EP 3932608 A1	05 January 2022
		JP 2018-520007 A	26 July 2018
		JP 7113621 B2	05 August 2022
		KR 10-2018-0018769 A	21 February 2018
		KR 10-2536222 B1	23 May 2023
		MX 2017016364 A	11 April 2018
		US 10751835 B2	25 August 2020
		US 2020-0376594 A1	03 December 2020
		WO 2016-205805 A1	22 December 2016
US 2019-0001442 A1	03 January 2019	CN 108025396 A	11 May 2018
		CN 108025396 B	11 September 2020
		CN 112091421 A	18 December 2020
		CN 112091421 B	23 December 2022
		CN 116213918 A	06 June 2023
		JP 2018-532595 A	08 November 2018
		JP 2021-181121 A	25 November 2021
		JP 2023-175958 A	12 December 2023
		JP 6921057 B2	18 August 2021
		JP 7404316 B2	25 December 2023
		KR 10-2018-0039747 A	18 April 2018
		KR 10-2024-0010086 A	23 January 2024
		KR 10-2623538 B1	11 January 2024
		TW 201718158 A	01 June 2017
		TW 202132034 A	01 September 2021
		TW 202304626 A	01 February 2023
		TW I726909 B	11 May 2021
		TW I780684 B	11 October 2022
		TW I819817 B	21 October 2023
		US 11077526 B2	03 August 2021
		US 2021-0316400 A1	14 October 2021
		WO 2017-044646 A1	16 March 2017
US 2006-0202115 A1	14 September 2006	CN 1841172 A	04 October 2006
		JP 2006-253671 A	21 September 2006
		KR 10-2006-0097668 A	14 September 2006
		TW 200643671 A	16 December 2006
		US 7321114 B2	22 January 2008
US 5315111 A	24 May 1994	None	
KR 10-1709711 B1	24 February 2017	CN 102245341 A	16 November 2011
		CN 102245341 B	27 August 2014
		JP 2012-510901 A	17 May 2012
		JP 5555250 B2	23 July 2014

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2024/013324

Patent document cited in search report	Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
		KR 10-2011-0102319 A	16 September 2011
		SG 171442 A1	28 July 2011
		US 2010-0140237 A1	10 June 2010
		US 8680430 B2	25 March 2014
		WO 2010-077506 A2	08 July 2010
		WO 2010-077506 A3	16 September 2010