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(54) **EFFICIENT MICRO-MACHINING APPARATUS AND METHOD EMPLOYING MULTIPLE LASER BEAMS**

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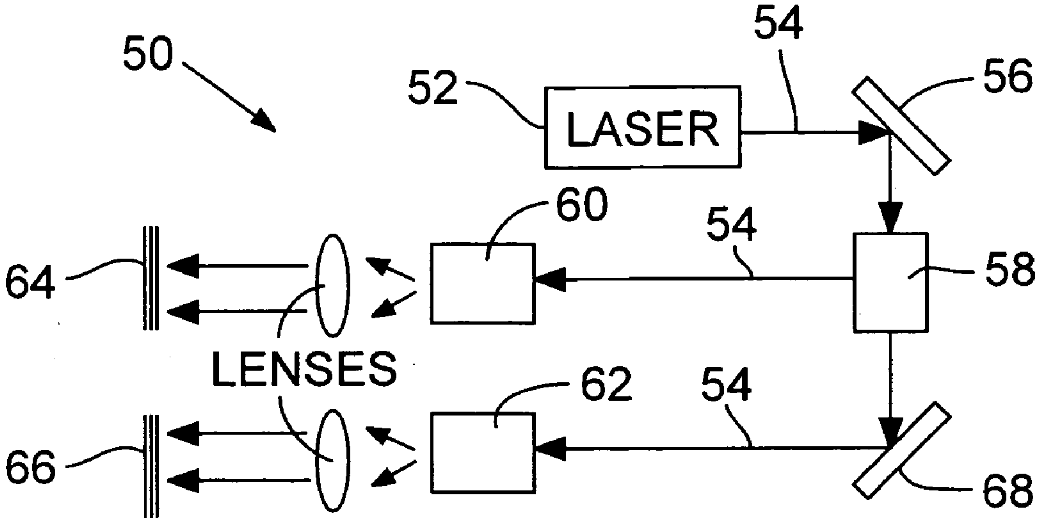
(52) **U.S. Cl.** **219/121.6**

(57) **ABSTRACT**

A laser beam switching system employs a laser coupled to a beam switching device that causes a laser beam to switch between first and second beam positioning heads such that while the first beam positioning head is directing the laser beam to process a workpiece target location, the second beam positioning head is moving to another target location and vice versa. A preferred beam switching device includes first and second AOMs positioned such that the laser beam passes through the AOMs without being deflected. When RF is applied to the first AOM, the laser beam is diffracted toward the first beam positioning head, and when RF is applied to the second AOM, the laser beam is diffracted toward the second beam positioning head.



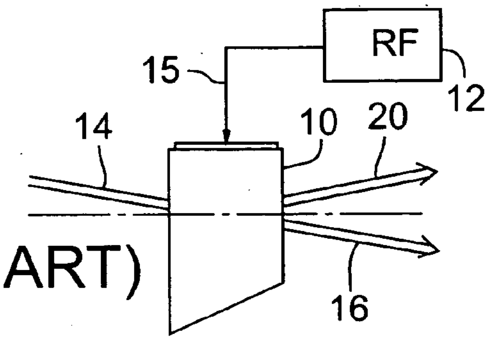


FIG. 1
(PRIOR ART)

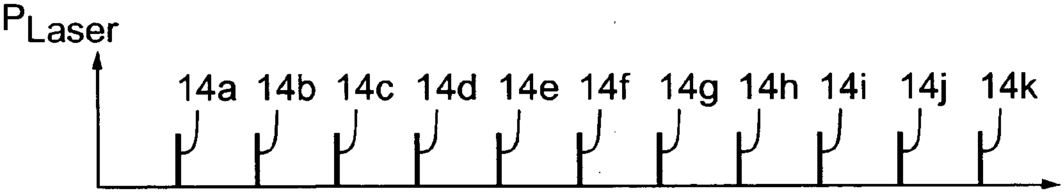


FIG. 2A(PRIOR ART)

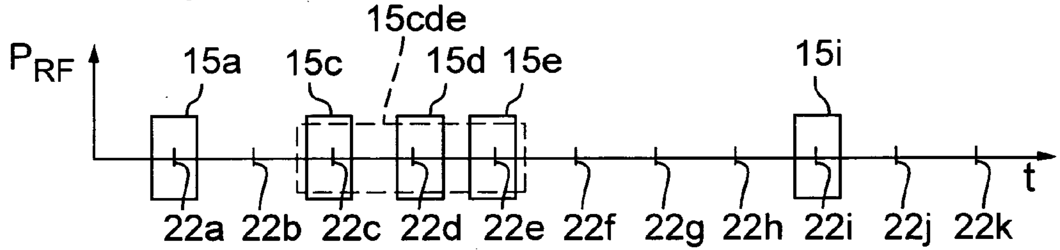


FIG. 2B(PRIOR ART)

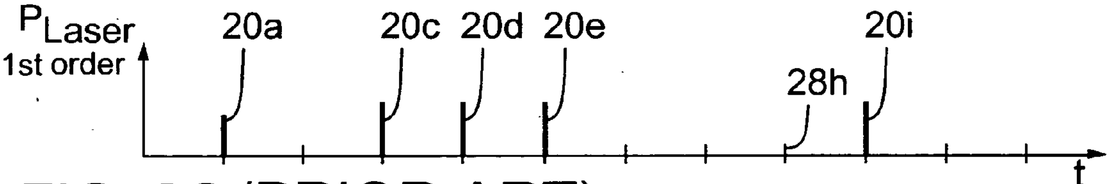


FIG. 2C (PRIOR ART)

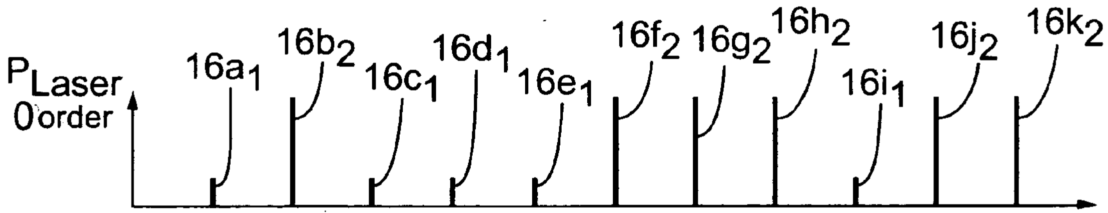


FIG. 2D (PRIOR ART)

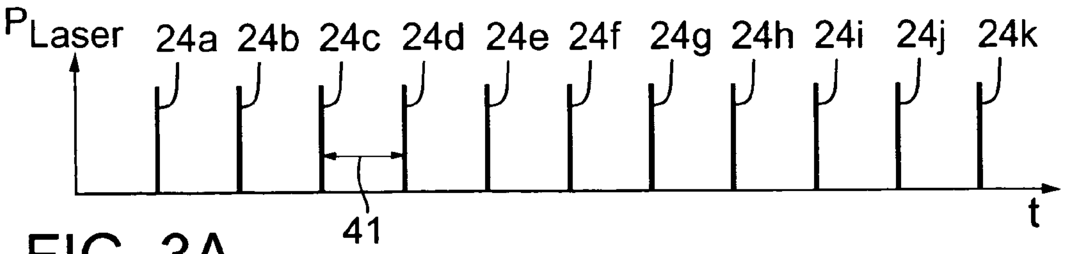


FIG. 3A

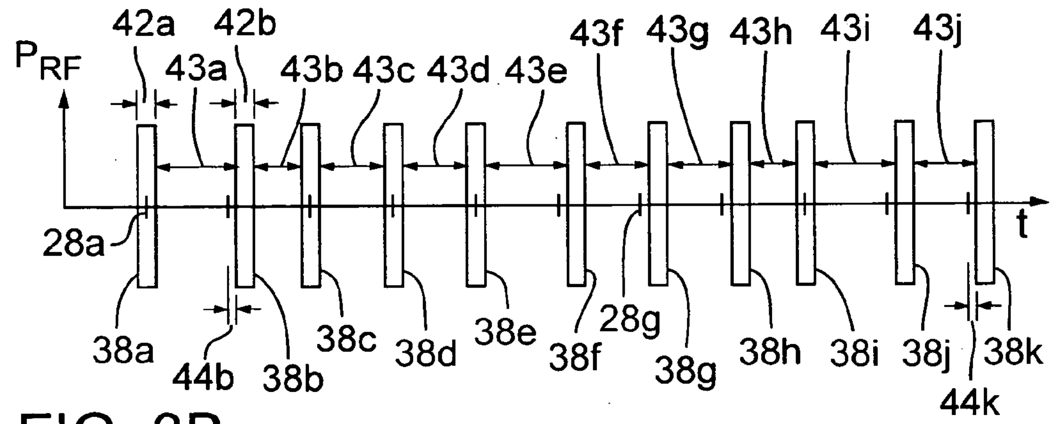


FIG. 3B

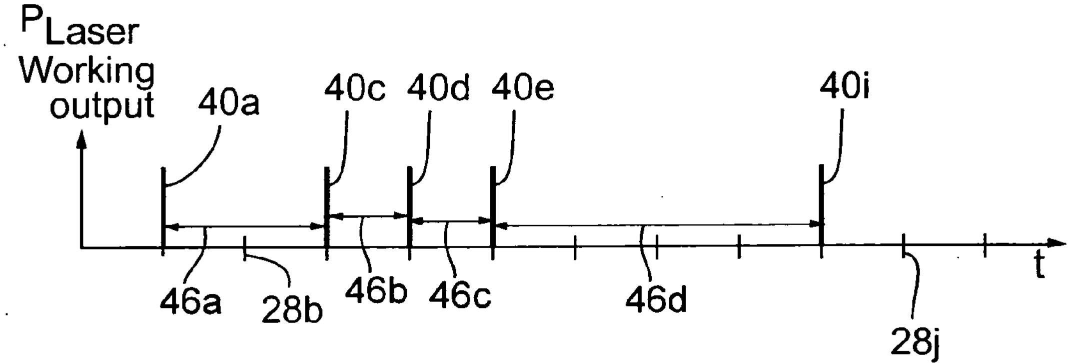


FIG. 3C

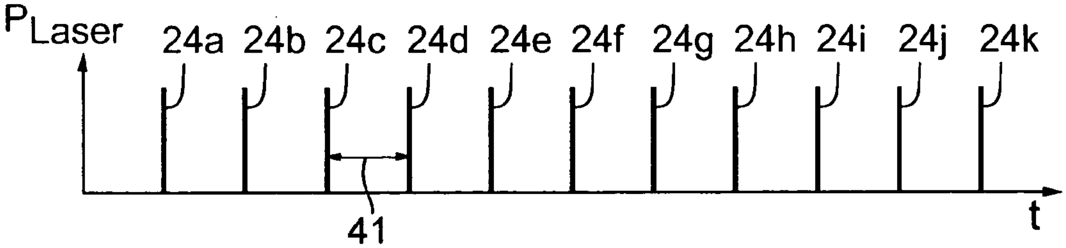


FIG. 4A

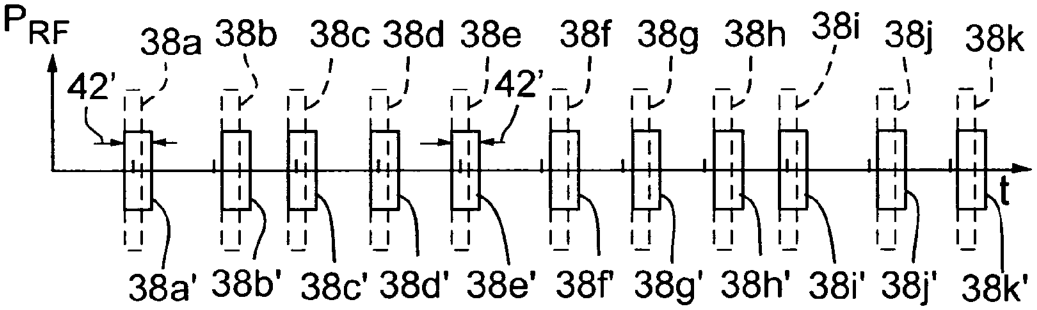


FIG. 4B

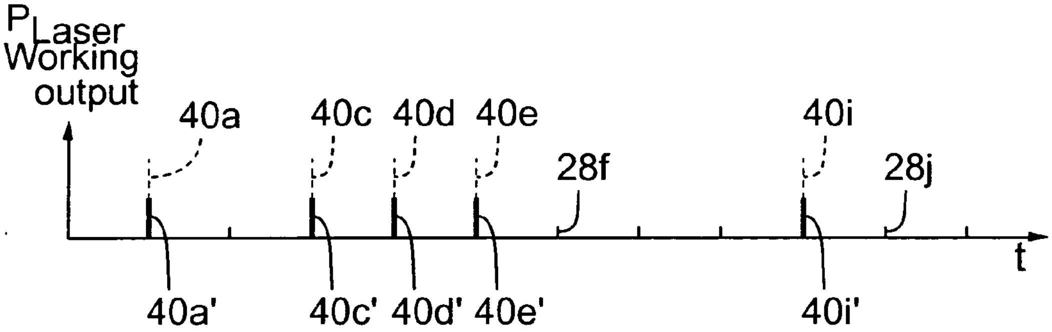


FIG. 4C

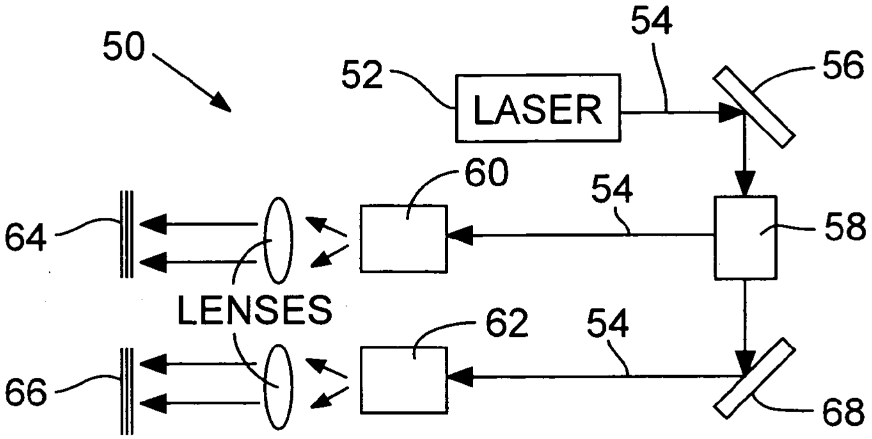

50
52
LASER
54
56
60
54
58
64
LENSES
62
54
66
68

FIG. 5

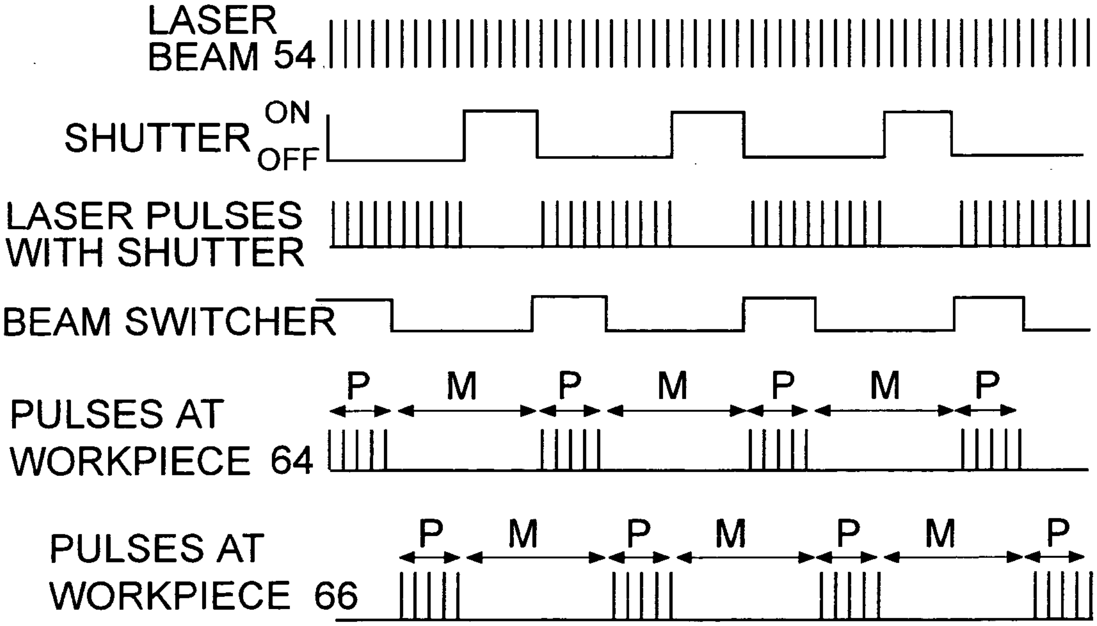

LASER BEAM 54
SHUTTER
ON
OFF
LASER PULSES WITH SHUTTER
BEAM SWITCHER
PULSES AT WORKPIECE 64
P
M
P
M
P
M
P
PULSES AT WORKPIECE 66
P
M
P
M
P
M
P

FIG. 6

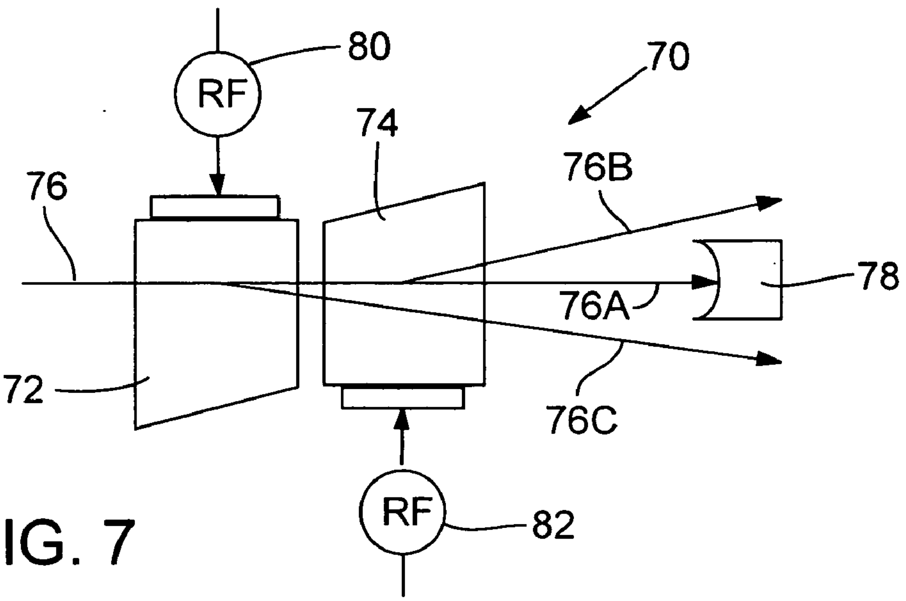

80
RF
70
74
76B
76
78
76A
72
76C
RF
82

FIG. 7

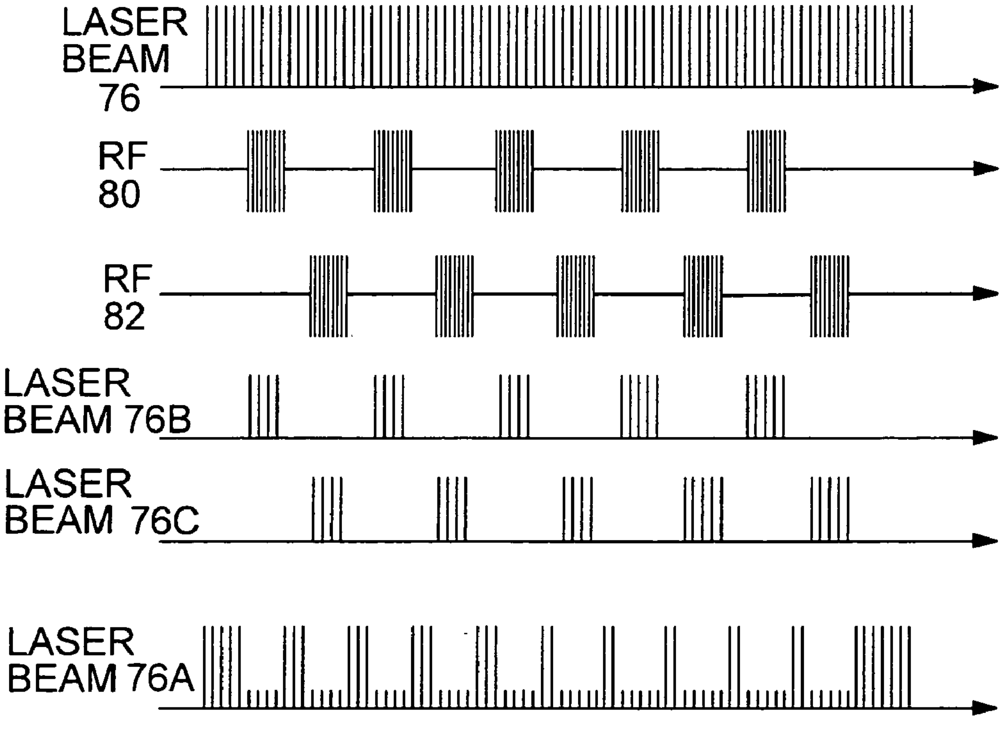

LASER BEAM 76
RF 80
RF 82
LASER BEAM 76B
LASER BEAM 76C
LASER BEAM 76A

FIG. 8

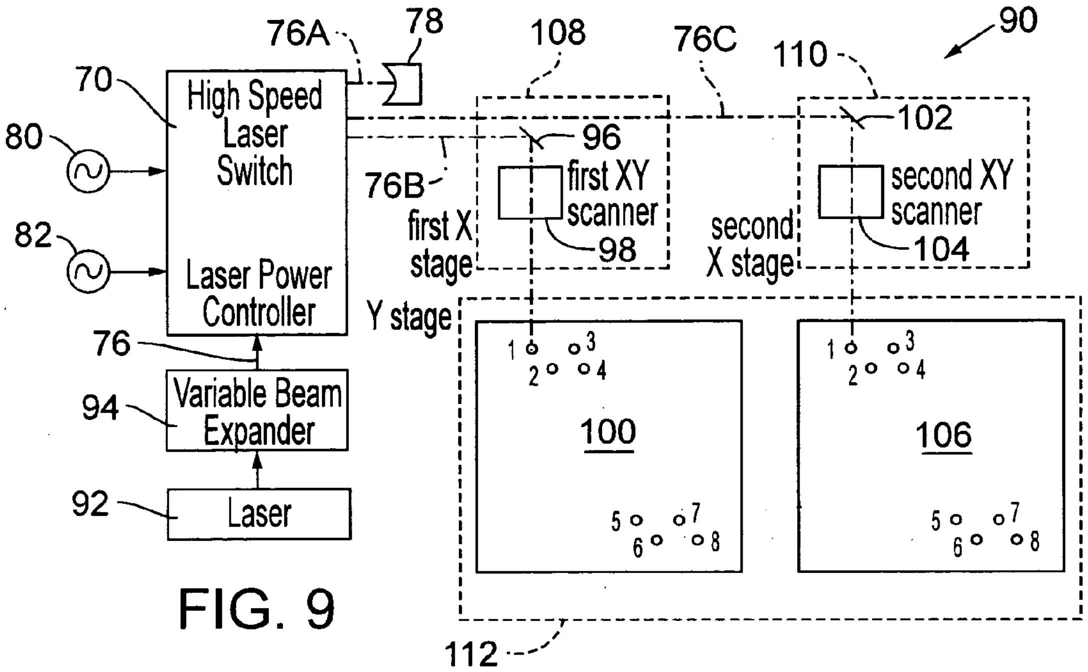

90
70
High Speed Laser Switch
Laser Power Controller
80
82
76
76A
78
108
76C
110
96
102
76B
first XY scanner
98
second XY scanner
104
first X stage
second X stage
Y stage
1
2
3
4
5
6
7
8
100
106
94
Variable Beam Expander
92
Laser
112

FIG. 9

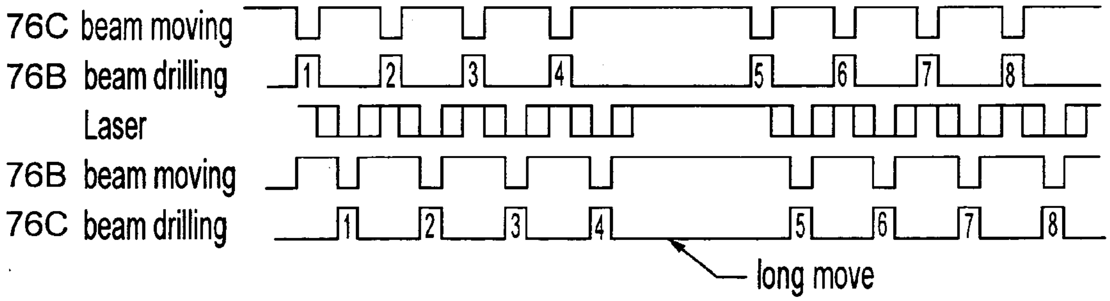

76C beam moving
76B beam drilling
Laser
76B beam moving
76C beam drilling
1
2
3
4
5
6
7
8
long move

FIG. 10

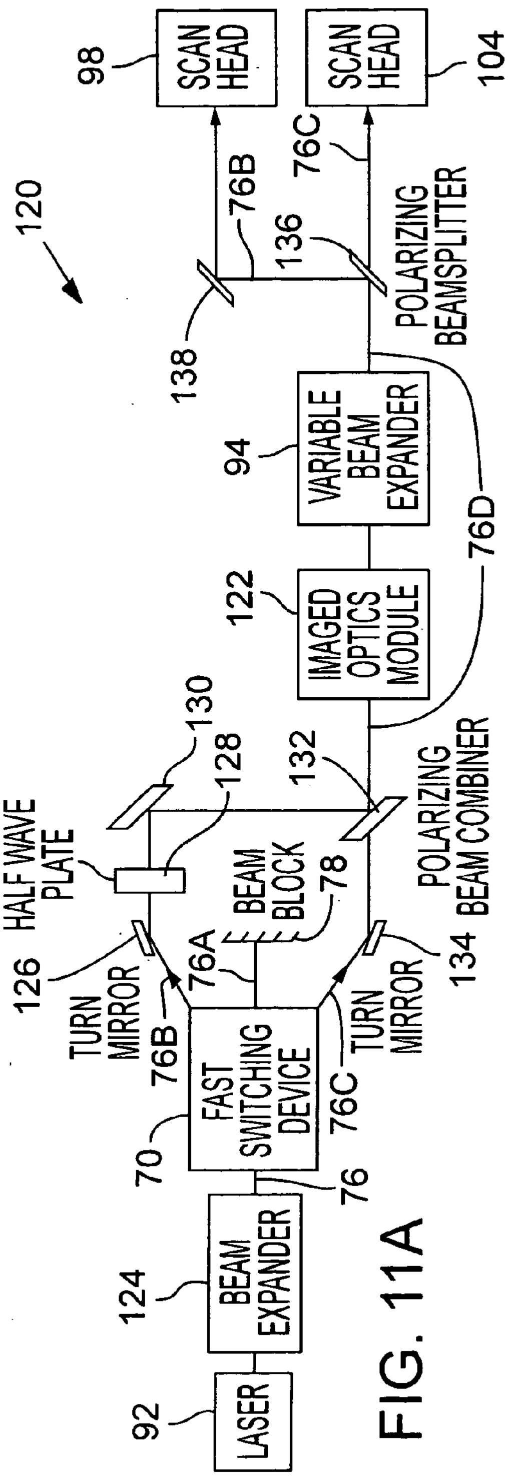


FIG. 11A

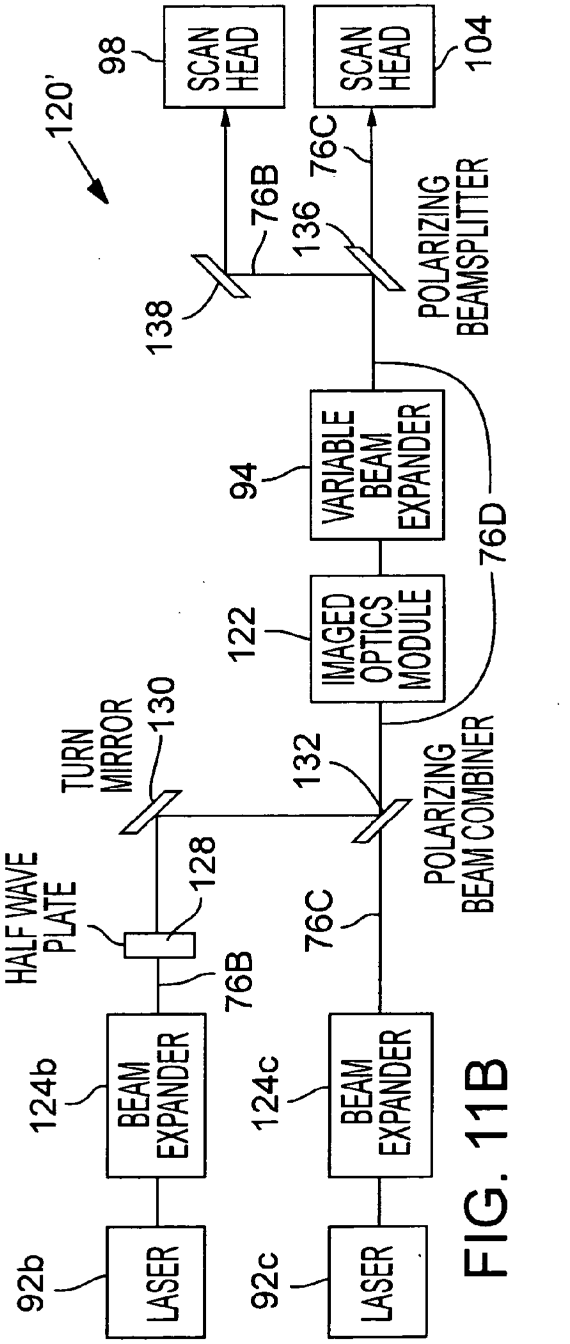


FIG. 11B

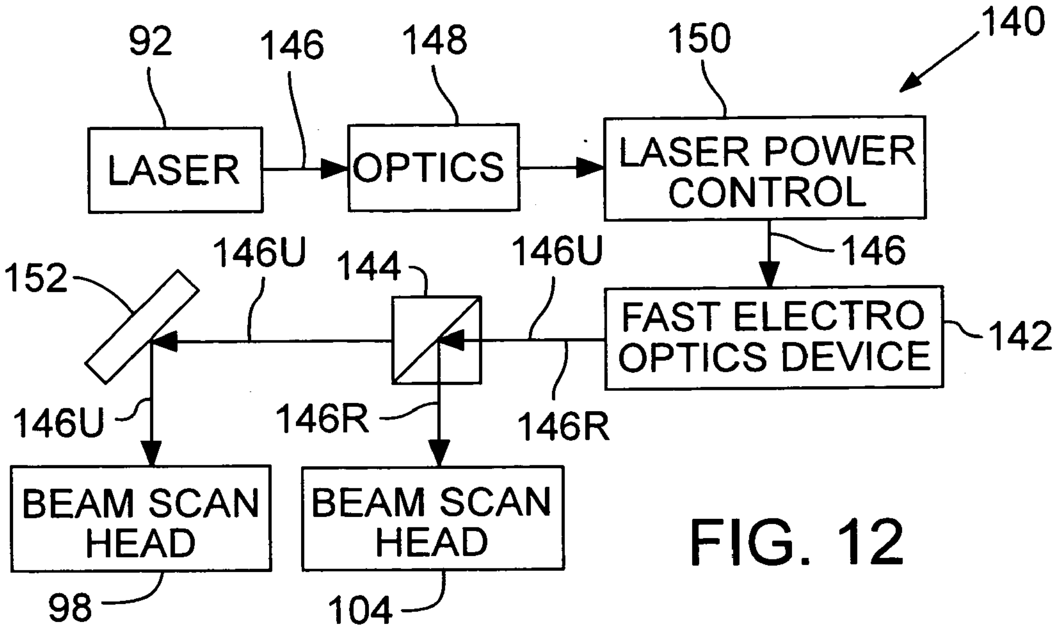

140
92
146
148
150
LASER
OPTICS
LASER POWER CONTROL
146
152
146U
144
146U
FAST ELECTRO OPTICS DEVICE
142
146U
146R
146R
BEAM SCAN HEAD
BEAM SCAN HEAD
98
104

FIG. 12

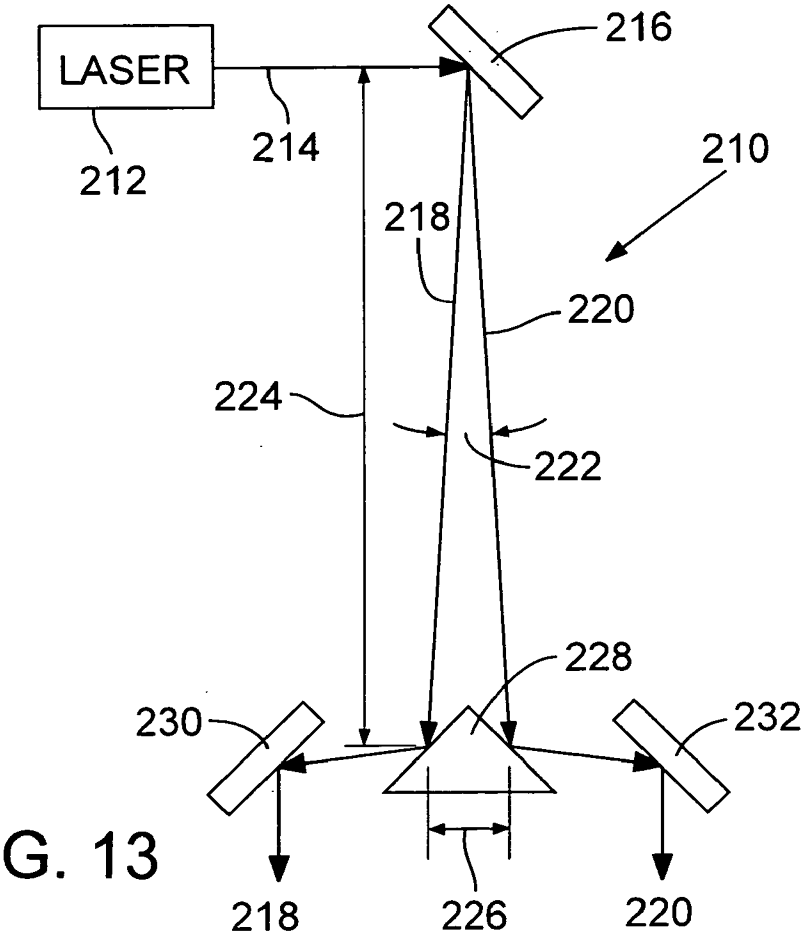

LASER
216
212
214
210
218
220
224
222
228
230
232
218
226
220

FIG. 13

EFFICIENT MICRO-MACHINING APPARATUS AND METHOD EMPLOYING MULTIPLE LASER BEAMS

RELATED APPLICATION

[0001] This is a continuation-in-part of U.S. patent application Ser. No. 10/611,798, filed Jun. 30, 2003.

FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0002] Not applicable

TECHNICAL FIELD

[0003] This invention relates to lasers and, more particularly, to a method and an apparatus for increasing workpiece machining throughput by alternately switching a single laser beam among two or more beam paths such that one of the beam paths is employed for machining one workpiece while another the beam path is positioned for machining another workpiece.

BACKGROUND OF THE INVENTION

[0004] Lasers are widely employed in a variety of research, development, and industrial operations including inspecting, processing, and micromachining a variety of electronic materials and substrates. For example, to repair a dynamic random access memory ("DRAM"), laser pulses are used to sever electrically conductive links to disconnect faulty memory cells from a DRAM device and then to activate redundant memory cells to replace the faulty memory cells. Because faulty memory cells needing link removals are randomly located, the links that need to be severed are randomly located. Thus, during the laser link repairing process, the laser pulses are fired at random pulse intervals. In another words, the laser pulses are running at a wide variable range of pulse repetition frequencies ("PRFs"), rather than at a constant PRF. For industrial processes to achieve greater production throughput, the laser pulse is fired at the target link without stopping the laser beam scanning mechanism. This production technique is referred to in the industry as "on-the-fly" ("OTF") link processing. Other common laser applications employ laser pulses that are fired only when they are needed at random times.

[0005] However, the laser energy per pulse typically decreases with increasing PRF while laser pulse width increases with increasing PRF, characteristics that are particularly true for Q-switched, solid-state lasers. While many laser applications require randomly time-displaced laser pulses on the demand, these applications also require that the laser energy per pulse and the pulse width be kept substantially constant. For link processing on memory or other IC chips, inadequate laser energy will result in incomplete link severing, while excessive laser energy will cause unacceptable damage to the passivation structure or the silicon substrate. The acceptable range of laser pulse energies is often referred to as a "process window." For many practical IC devices, the process window requires that laser pulse energy vary by less than 5 percent from a selected pulse energy value.

[0006] Various approaches have been implemented to ensure operation within a process window or to expand the process window. For example, U.S. Pat. No. 5,590,141 for METHOD AND APPARATUS FOR GENERATING AND EMPLOYING A HIGH DENSITY OF EXCITED IONS IN A LASANT, which is assigned to the assignee of this patent application, describes solid-state lasers having lasants exhibiting a reduced pulse energy drop off as a function of increasing PRF and, therefore, a higher usable PRF. Such lasers are, therefore, capable of generating more stable pulse energy levels when operated below their maximum PRFs.

[0007] U.S. Pat. No. 5,265,114 for SYSTEM AND METHOD FOR SELECTIVELY LASER PROCESSING A TARGET STRUCTURE OF ONE OR MORE MATERIALS OF A MULTIMATERIAL, MULTILAYER DEVICE, which is also assigned to the assignee of this patent application, describes using a longer laser wavelength such as 1,320 nanometers ("nm") to expand the link process window to permit a wider variation of the laser pulse energy during the process.

[0008] U.S. Pat. No. 5,226,051 for LASER PUMP CONTROL FOR OUTPUT POWER STABILIZATION describes a technique of equalizing the laser pulse energy by controlling the electrical current of the pumping diodes. The technique works well in practical applications employing a laser PRF below about 25 KHz or 30 KHz.

[0009] The above-described laser processing applications typically employ infrared ("IR") lasers having wavelengths from 1,047 nm to 1,324 nm, running at PRFs not over about 25 to 30 KHz. However, production needs are demanding much higher throughput, so lasers should be capable of operating at PRFs much higher than about 25 KHz, such as 50 KHz to 60 KHz or higher. In addition, many laser processing applications are improved by employing ultraviolet ("UV") energy wavelengths, which are typically less than about 400 nm. Such UV wavelengths may be generated by subjecting an IR laser to a harmonic generation process that stimulates the second, third, or fourth harmonics of the IR laser. Unfortunately, due to the nature of the harmonic generation, the pulse-to-pulse energy levels of such UV lasers are particularly sensitive to time variations in PRF and laser pulse interval.

[0010] U.S. Pat. No. 6,172,325 for LASER PROCESSING POWER OUTPUT STABILIZATION APPARATUS AND METHOD EMPLOYING PROCESSING POSITION FEEDBACK, which is also assigned to the assignee of this patent application, describes a technique of operating the laser at a constant high repetition rate in conjunction with a position feedback-controlled laser pulse picking or gating device to provide laser pulse picking on demand at a random time interval that is a multiple of the laser pulse interval. This technique affords good laser pulse energy stability and high throughput.

[0011] A typical laser pulse picking or gating device is an acousto-optic modulator ("AOM") or electro-optic modulator ("EOM", also referred to as a Pockels cell). Typical EOM material such as KD*P or KDP suffers from relatively strong absorption at the UV wavelengths, which results in a lower damage threshold of the material at the wavelength used and local heating along the laser beam path within the device, causing changes of the half wave-plate voltage of the device. Another disadvantage of the EOM is its questionable ability to perform well at a repetition rate over 50 KHz.

[0012] AOM material is, on the other hand, quite transparent to UV light of 250 nm up to IR light of 2,000 nm, which allows the AOM to perform well throughout typical laser wavelengths within the range. An AOM can also easily accommodate the desirable gating of pulses at a repetition rate of up to a few hundred KHz. One disadvantage of the AOM is its limited diffraction efficiency of about 75-90 percent.

[0013] **FIG. 1** shows a typical prior art AOM **10** driven by a radio frequency ("RF") driver **12** and employed for a laser pulse picking or gating application, and **FIGS. 2A** to **2D** (collectively, **FIG. 2**) show corresponding prior art timing graphs for incoming laser pulses **14**, AOM RF pulses **15**, and AOM output pulses **16** and **20**. **FIG. 2A** shows constant repetition rate laser pulses **14***a*-**14***k* that are emitted by a laser (not shown) and propagated to AOM **10**. **FIG. 2B** demonstrates two exemplary schemes for applying RF pulses **15** to AOM **10** to select which ones of laser pulses **14***a*-**14***k*, occurring at corresponding time periods **22***a*-**22***k*, are propagated toward a target. In a first scheme, a single RF pulse **15***cde* (shown in dashed lines) is extended to cover time periods **22***c*-**22***e* corresponding to laser pulses **14***c*, **14***d*, and **14***e*; and, in a second scheme, separated RF pulses **15***c*, **15***d*, and **15***e* are generated to individually cover the respective time periods **22***c*, **22***d*, and **22***e* for laser pulses **14***c*, **14***d*, and **14***e*. **FIGS. 2C and 2D** show the respective first order beam **20** and zero order beam **16** propagated from AOM **10**, as determined by the presence or absence of RF pulses **15** applied to AOM **10**.

[0014] Referring to **FIGS. 1 and 2**, AOM **10** is driven by RF driver **12**. When no RF pulses **15** are applied to AOM **10**, incoming laser pulses **14** pass through AOM **10** substantially along their original beam path and exit as beam **16**, typically referred to as the zero order beam **16**. When RF pulses **15** are applied to AOM **10**, part of the energy of incoming laser pulses **14** is diffracted from the path of the zero order beam **16** to a path of a first order beam **20**. AOM **10** has a diffraction efficiency that is defined as the ratio of the laser energy in first order beam **20** to the laser energy in incoming laser pulses **14**. Either first order beam **20** or zero order beam **16** can be used as a working beam, depending on different application considerations. For simplicity, laser pulses **14** entering AOM **10** will hereafter be referred as "laser pulses" or "laser output," and pulses delivered to the target, because they are picked by AOM **10**, will be referred to as "working laser pulses" or "working laser output."

[0015] When first order beam **20** is used as the working beam, the energy of the working laser pulses can be dynamically controlled from 100 percent of its maximum value down to substantially zero, as the power of RF pulses **15** changes from their maximum power to substantially zero, respectively. Because the practical limited diffraction efficiency of an AOM under an allowed maximum RF power load is about 75 percent to 90 percent, the maximum energy value of the working laser pulses is about 75 percent to 90 percent of the energy value in laser pulses **14**. However, when zero order beam **16** is used as the working beam, the energy of the working laser pulses can be dynamically controlled from 100 percent of the maximum energy in laser pulses **14** down to 15 percent to 20 percent of the maximum value, as the power of RF pulses **15** changes from substantially zero to its maximum power, respectively. For memory link processing, for example, when no working laser pulse is demanded, no leakage of system laser pulse energy is permitted, i.e., the working laser pulse energy should be zero, so first order laser beam **20** is preferably used as the working beam.

[0016] With reference again to **FIG. 2**, RF pulses **15** are applied to AOM **10** at random time intervals and only when working laser pulses are demanded, in this case, at random integral multiples of the laser pulse interval. The random output of working laser pulses results in random variable thermal loading on AOM **10**. Variable thermal loading causes geometric distortion and temperature gradients in AOM **10**, which cause gradients in its refractive index. The consequences of thermal loading distort a laser beam passing through AOM **10**, resulting in deteriorated laser beam quality and instability in the laser beam path or poor beam positioning accuracy. These distortions could be corrected to some degree if they could be kept constant. However, when the system laser pulses are demanded randomly, such as in laser link processing, these distortions will have the same random nature and cannot be practically corrected.

[0017] Test results on an AOM device, such as a Model N23080-2-1.06-LTD, made by NEOS Technologies, Melbourne, Fla., showed that with only two watts of RF power, the laser beam pointing accuracy can deviate as much as one milliradian when the RF is applied on and off randomly to the AOM. This deviation is a few hundred times greater than the maximum deviation allowed for the typical memory link processing system. Laser beam quality distortion resulting from the random thermal loading on the AOM **10** will also deteriorate the focusability of the laser beam, resulting in a larger laser beam spot size at the focusing point. For applications such as the memory link processing that require the laser beam spot size to be as small as possible, this distortion is very undesirable.

[0018] What is needed, therefore, is an apparatus and a method for randomly picking working laser pulses from a high repetition rate laser pulse train without causing distortion of the laser beam and adversely affecting positioning accuracy caused by random thermal loading variation on the AOM. What is also needed is an apparatus and a method of generating working laser pulses having constant laser energy per pulse and constant pulse width on demand and/or on-the-fly at a high PRF and with high accuracy at different pulse time intervals for variety of laser applications such as laser link processing on memory chips. Moreover, what is needed is an efficient, high-throughput apparatus and method for utilizing the working laser pulses.

SUMMARY OF THE INVENTION

[0019] An object of this invention is, therefore, to provide an apparatus and a method for picking laser pulses on demand from a high repetition rate pulsed laser.

[0020] The following are several of the advantages of the invention. Embodiments of this invention perform such pulse picking with minimal thermal loading variation on the AOM to minimize distortion of the laser beam and positioning accuracy. They include an apparatus and a method for generating system on demand laser pulses having stable pulse energies and stable pulse widths at selected wavelengths from the UV to near IR and at high PRFs for high-accuracy laser processing applications, such as memory link severing. The embodiments of this invention provide an efficient, high-throughput apparatus and method for utilizing the working laser pulses.

[0021] A workpiece processing system of this invention employs a laser coupled to a beam switching device that causes a laser beam or laser pulses to switch between first and second beam positioning heads such that when the first beam positioning head directs the laser beam to process a first workpiece, the second beam positioning head moves to a next target location on a second workpiece or a second set of locations on the first workpiece. When the first beam positioning head completes processing of the first workpiece and the second beam positioning head reaches its target position, the beam switching device causes the beam to switch to the second beam positioning head and then the second beam positioning head directs the laser beam to target locations on the second workpiece while the first beam positioning head moves to its next target position.

[0022] An advantage of the present laser beam switching system is that the first and second workpieces receive almost the full power of the laser beam for processing. The total time utilization of the laser beam is increased by almost a factor of two, depending on the processing-to-moving time ratio. This greatly increases system throughput without significantly increasing system cost.

[0023] A preferred beam switching device includes first and second AOMs that are positioned adjacent to each other so that the laser beam (or laser pulses) normally pass undeflected through the AOMs and terminate on a beam blocker. When RF energy is applied to the first AOM, about 90 percent of the laser beam is diffracted as a first laser beam and 10 percent remains as a residual laser beam that terminates in the beam blocker. Likewise, when RF energy is applied to the second AOM, about 90 percent of the laser beam is diffracted as a second laser beam and 10 percent remains as a residual laser beam that terminates in the beam blocker. In this embodiment, the laser generating the laser beam is constantly running at its desired pulse repetition rate.

[0024] Employing the beam switching device is advantageous because constant operation of the laser eliminates thermal drifting of the laser output. Moreover, by operating the first and second AOMs with pulse picking methods of this invention, thermal loading variations in the AOMs will be minimized, thereby increasing laser beam positioning accuracy.

[0025] Another advantage of employing the first and second AOMs as a beam switching device is that they can operate as a laser power control device, eliminating a need for a separate laser power controller in a typical laser-based workpiece processing system. Power control is possible because the response times of the AOMs are sufficiently fast for programming laser pulse amplitudes of the switched laser beam during processing of individual target locations on the workpieces. A typical laser processing application is blind via formation in etched-circuit boards, in which it is often necessary to reduce the laser pulse energy when the laser beam reaches the bottom of the via being formed.

[0026] Additional aspects and advantages of this invention will be apparent from the following detailed description of preferred embodiments, which proceeds with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] **FIG. 1** is a simplified schematic view of a prior art AOM device and an RF driver, transmitting a zero order beam, a first order beam, or both of them.

[0028] **FIGS. 2A-2D** are corresponding prior art timing graphs of, respectively, laser pulses, RF pulses, and first and zero order AOM output laser pulses.

[0029] **FIGS. 3A-3C** are corresponding exemplary timing graphs of, respectively, laser outputs, RF pulses, and working laser outputs as employed in a preferred embodiment.

[0030] **FIGS. 4A-4C** are alternative corresponding exemplary timing graphs of, respectively, laser outputs, RF pulses, and working laser outputs that demonstrate the use of the AOM for energy control of the working laser outputs.

[0031] **FIG. 5** is a simplified schematic block diagram of a laser beam switching system of this invention.

[0032] **FIG. 6** is a waveform timing diagram representing operational timing relationships among various components of the laser beam switching system of **FIG. 5**.

[0033] **FIG. 7** is a simplified schematic block diagram representing a preferred dual AOM laser beam switching device for use with this invention.

[0034] **FIG. 8** is a waveform timing diagram representing operational timing relationships among various components of a laser beam switching system employing the dual AOM switching device of **FIG. 7**.

[0035] **FIG. 9** is a simplified schematic block diagram of a typical workpiece processing system employing the laser beam switching device of **FIG. 7**.

[0036] **FIG. 10** is a waveform timing diagram representing operational timing relationships among various components of the workpiece processing system of **FIG. 9**.

[0037] **FIGS. 11A and 11B** are simplified block diagrams representing workpiece processing systems of this invention employing a common optical processing path for multiple laser beams propagating from one and two laser sources, respectively.

[0038] **FIG. 12** is a simplified schematic block diagram representing an alternative workpiece processing system of this invention employing a fast EOM and a polarizing beam splitter to implement a laser beam switching device of this invention.

[0039] **FIG. 13** is a simplified pictorial block diagram representing an alternative laser beam switching system employing a fast steering mirror for switching a laser beam along alternate first and second pathways.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0040] Thermal loading variations in AOMs, such as prior art AOM **10**, can be mitigated by employing pulse picking and laser power control methods shown with reference to **FIGS. 3A-3C** and 4A4C, respectively. **FIGS. 3A-3C** (collectively, **FIG. 3**) show corresponding timing graphs of laser outputs **24***a*-**24***k* (collectively, laser outputs **24**), RF pulses **38***a*-**38***k* (collectively, RF pulses **38**) applied to prior art AOM **10**, and working laser outputs **40***a*, **40***c*, **40***d*, **40***e*, and

40*i* (collectively, working laser outputs **40**). In particular, **FIG. 3A** shows laser outputs **24***a*-**24***k* that are emitted by a laser (not shown) at a constant repetition rate and separated by substantially identical laser output intervals **41**. In typical embodiments, the laser output repetition rate may range from about 1 KHz up to about 500 KHz. Exemplary laser output repetition rates range from about 25 KHz to greater than about 100 KHz. For link processing embodiments, each of working laser outputs **40** preferably includes a single laser pulse having a multiple nanosecond pulse width. However, skilled persons will recognize that each of working laser outputs **40** may include a burst of one or more laser pulses, such as disclosed in U.S. Pat. No. 6,574,250 for LASER SYSTEM AND METHOD FOR PROCESSING A MEMORY LINK WITH A BURST OF LASER PULSES HAVING ULTRASHORT PULSE WIDTHS, which is assigned to assignee of this patent application, -or bursts of one or more pulses having pulse widths ranging from about 10 picoseconds to about 1,000 picoseconds.

[**0041**] **FIG. 3B** shows a preferred RF pulse picking scheme employing RF pulses **38** having pulse durations, such as **42***a* and **42***b* (collectively, RF pulse durations **42**) separated by RF pulse intervals **43***a*-**43***j* (collectively, RF pulse intervals **43**) that are substantially regular or uniform to keep thermal loading variations on AOM **10** within a preassigned operational tolerance. Such tolerance may be a specific thermal load window, but the preassigned tolerance may also or alternatively be windows of spot size or beam position accuracy. In one embodiment, the thermal loading variation is maintained within 5 percent and/or the beam pointing accuracy is maintained within 0.005 milliradian. In a preferred embodiment, at least one of RF pulses **38** is generated to correspond with each of laser outputs **24**.

[**0042**] Whenever one of working laser outputs **40** is demanded to impinge on a target such as an electrically conductive link, one of RF pulses **38** is applied to AOM **10** in coincidence with one of laser outputs **24** such that it is transmitted through AOM **10** and becomes the demanded one of working laser outputs **40**.

[**0043**] In **FIG. 3B**, the coincident RF pulses **38** are RF pulses **38***a*, **38***c*, **38***d*, **38***e*, and **38**i. **FIG. 3C** shows the resulting corresponding working laser outputs **40***a*, **40***c*, **40***d*, **40***e*, and **40***i*. When no working laser output is demanded to correspond with laser outputs **24**, RF pulses **38** are applied to AOM **10** in noncoincidence with corresponding ones of laser outputs **24**. In **FIG. 3B**, the noncoincident RF pulses **38** are RF pulses **38***b*, **38***f*, **38***g*, **38***h*, **38***j*, and **38***k*. **FIG. 3C** shows that no working laser outputs **40** correspond with noncoincident RF pulses **38**.

[**0044**] The noncoincident RF pulses **38** are preferably offset from the initiations of respective laser outputs **24** by time offsets **44** that are longer than about 0.5 microsecond. Skilled persons will appreciate that while time offsets **44** are shown to follow laser outputs **24**, time offsets **44** could alternatively precede laser outputs **24** by a sufficient time to prevent targeting of laser working outputs **40**. Thus, RF pulse intervals **43** surrounding one of noncoincident RF pulses **38** may be shorter (such as RF pulse intervals **43***b* and **43***h*) than the overall average RF pulse interval **43** (such as **43***c*, **43***d*, **43***f*, **43***g*, and **43***j*) or longer (such as RF pulse intervals **43***a*, **43***e*, and **43***i*) than the average RF pulse intervals **43**.

[**0045**] With reference again to **FIG. 3C**, nonimpingement intervals **46***b* and **46**c between working laser outputs **40***c* and **40***d* and between working laser outputs **40***d* and **40***e*, respectively, are about the same as the laser output interval **41**. The nonimpingement intervals **46***a* and **46***d* between working laser outputs **40***a* and **40***c* and between working laser outputs **40***e* and **40***i*, respectively, are roughly integer multiples of the laser output interval **41**.

[**0046**] Skilled persons will appreciate that even though working laser outputs **40** are preferably first order beam **20** for most applications, such as link processing, working laser outputs **40** may be zero order beam **16** where leakage is tolerable and higher working laser output power is desirable.

[**0047**] In a preferred embodiment, the coincident and noncoincident RF pulses **38** not only employ about the same RF energy, which is the product of an RF power value and an RF duration, but also employ about the same RF power value and about the same RF duration.

[**0048**] **FIGS. 4A-4C** (collectively, **FIG. 4**) show corresponding timing graphs of laser outputs **24**, RF pulses **38** applied to AOM **10**, and working laser outputs **40** that demonstrate how AOM **10** can be additionally employed to control the output power of working laser outputs **40**. **FIG. 4A** is identical to **FIG. 3A** and is shown for convenience only. **FIGS. 4B and 4C** show RF pulses **38'** and working laser outputs **40'**, with the corresponding RF pulses **38** and working laser outputs **40** shown superimposed on them in dashed lines for convenience. The energy values of working laser outputs **40'** are attenuated by applying less RF power to AOM **10** for RF pulses **38'** than for RF pulses **38**; however, the RF pulse durations **42'** are increased for RF pulses **38'** over the RF durations **42** employed for RF pulses **38** to maintain a substantially constant product of RF power value and RF duration in order to maintain substantially constant thermal loading on AOM **10**. This technique permits on-demand selection for a continuum of output powers between working laser outputs **40** or **40'** without substantial variance in thermal loading on AOM **10**. Skilled persons will appreciate that the RF power values and RF durations **42** of the noncoincident RF pulses **38** can be kept as original or can be altered to be within a specified tolerance of the RF loading variation of the coincident RF pulses **38'**.

[**0049**] RF pulse duration **42'** is preferably selected from about one microsecond to about one-half of laser output interval **41**, more preferably shorter than 30 percent of laser output interval **41**. For example, if the laser repetition rate is 50 KHz and laser output interval **41** is 20 microseconds, RF pulse duration **42'** can be anywhere between one microsecond and ten microseconds. The minimum RF pulse duration **42** or **42'** is determined by the laser pulse jittering time and the response time of AOM **10**. It is preferable to initiate corresponding ones of RF pulses **38** and **38'** surrounding the midpoints of laser outputs **24**. Likewise, it is preferable for RF pulses **38** and **38'** to be delayed or offset about half of the minimum RF pulse duration from the initiation of corresponding laser outputs **24**.

[**0050**] It will be appreciated that the RF power of RF pulses **38** applied to AOM **10** can be adjusted to control the energy of working laser outputs **40** and **40'** to meet target processing needs, while RF pulse durations **42** and **42'** of RF pulses **38** and **38'** can be controlled accordingly to maintain a substantially constant RF energy or arithmetic product of the RF powers and durations of RF pulses **38** and **38'**.

[0051] The above-described techniques for employing an AOM in a workpiece processing application address beam steering accuracy and process window requirements, but do not address workpiece processing throughput and efficiency concerns. Employing a single laser for workpiece processing is time-inefficient because significant time and laser power is wasted while moving the laser output and workpiece target location relative to one another. Using a laser beam for an application, such as etched-circuit board via formation, typically results in only 50 percent laser beam utilization time because of the time needed to move the beam between target locations. Beam splitting does not correct this low time utilization problem. Prior workers have employed multiple laser beams to improve processing throughput, but the additional cost and wasted laser power is still a concern.

[0052] This invention provides apparatus and methods for improving the throughput and efficiency of a single laser workpiece processing system. In this invention, AOMs employing pulse picking techniques are used in combination with a laser beam switching, or multiplexing, technique to improve workpiece processing and efficiency.

[0053] **FIGS. 5 and 6** represent a laser beam switching system **50** and associated timing aspects of this invention in which a laser emits laser pulses **54** that are reflected by an optional fold mirror **56** to a beam switching device **58**. Beam switching device **58** causes laser pulses **54** to switch between first and second beam positioning heads **60** and **62** such that when first beam positioning head **60** is causing laser pulses **54** to process a target location on a first workpiece **64**, second beam positioning head **62** is moving to a target location on a second workpiece **66**. Laser pulses **54** are directed from beam switching device **58** to beam positioning head **62** by an optional fold mirror **68**. When first beam positioning head **60** completes processing of workpiece **64**, either an optional shutter (not shown), such as a Q-switch, turns laser **52** off, as shown in **FIG. 6**, or laser pulses **54** are dumped. to a beam blocker (not shown). When second beam positioning head **62** reaches its target position, laser pulses **54** are switched on by the shutter and second beam positioning head **62** directs laser pulses **54** to target locations on workpiece **66** while first beam positioning head **60** moves to its next target position. **FIG. 6** represents workpiece processing times as intervals P and positioner move times between target positions as intervals M.

[0054] An advantage of laser beam switching system **50** is that first and second workpieces **64** and **66** alternately receive almost the full power of laser pulses **54** for processing. The total time utilization of laser pulses **54** is increased by almost a factor of two, depending on the processing-to-moving time ratio. This greatly increases system throughput without significantly increasing system cost.

[0055] **FIGS. 7 and 8** show a preferred beam switching device **70** and related timing relationships. Beam switching device **70** includes first and second AOMs **72** and **74** positioned in optical series relation so that a laser beam or laser pulses **76** normally pass undeflected through AOMs **72** and **74** and terminate as laser beam **76**A on a beam blocker **78**. However, when a first RF driver **80** applies about 6 Watts of 85 MHz RF signal to first AOM **72**, about 90 percent of laser beam **76** is diffracted as laser beam **76**B and 10 percent remains as laser beam **76**A. Likewise, when a second RF driver **82** applies about 6 Watts of 85 MHz RF signal to second AOM **74**, about 90 percent of laser beam **76** is diffracted as laser beam **76**C and 10 percent remains as laser beam **76**A. In this embodiment, the laser generating laser beam **76** is constantly running at its desired pulse repetition rate.

[0056] When employing beam switching device **70**, no shutter or Q-switch is needed if time intervals are required when switching between laser beams **76**B and **76**C because it is necessary only to shut off the RF signals applied to both first and second AOMs **72** and **74**, thereby dumping all of laser beam **76** on beam blocker **78**.

[0057] Beam switching device **70** is advantageous because constant operation of the laser eliminates thermal drifting of the laser output. Moreover, by operating AOMs **72** and **74** with the pulse picking methods described with reference to **FIGS. 3 and 4**, thermal loading variations will be minimized, thereby increasing laser beam positioning accuracy. Each of first and second AOMs **72** and **74** is preferably a Model N30085, manufactured by NEOS Technologies, Inc., of Melbourne, Florida. The N30085 AOM has a specified 90 percent diffraction efficiency when driven with two Watts of 85 MHz RF power.

[0058] Another advantage of beam switching device **70** is that it can operate as a laser power control device, eliminating a need for a separate laser power controller in a typical laser-based workpiece processing system. Power control is possible because the response times of AOMs **72** and **74** are sufficiently fast for programming laser pulse amplitudes of laser beams **76**B and **76**C during processing of single target locations in workpieces. A typical laser processing application is blind via formation in etched-circuit boards, in which it is often necessary to reduce the laser pulse energy when the laser beam reaches the bottom of the via being formed.

[0059] **FIGS. 9 and 10** show, respectively, a typical workpiece processing system **90** employing beam switching device **70** and related operational timing relationships. A laser **92** and a variable beam expander **94** cooperate to produce laser beam **76** that propagates through beam switching device **70**, which operates as described with reference to **FIGS. 7 and 8** to produce laser beams **76**A, **76**B, and **76**C. Laser beam **76**A terminates in beam blocker **78**. Laser beam **76**B is reflected by an optional fold mirror **96** and directed by a first XY scanner **98** to target locations **1**, **2**, **3**, and **4** on a first workpiece **100**. Likewise, laser beam **76**C is reflected by an optional fold mirror **102** and directed by a second XY scanner **104** to target locations **1**, **2**, **3**, and **4** on a second workpiece **106**. First and second XY scanners **98** and **104** are mounted on respective first and second X positioning stages **108** and **110**, and first and second workpieces **100** and **106** are mounted on a Y positioning stage **112**. Skilled workers will understand that the scanners and workpieces are mounted on a split axis configured positioner system but that planar and stacked configurations may alternatively be employed. Skilled workers will also understand that the target locations on the first and second workpieces may be on a common substrate and/or may not share corresponding target locations.

[0060] **FIG. 10** shows laser beam **76**B processing (drilling) target location **1** on workpiece **100** while second XY scanner **104** is moving the position of laser beam **76**C to target location **1** on workpiece **106**. When laser beam **76**C is processing target location **1** on workpiece **106**, first XY scanner **98** is moving the position of laser beam **76**B to target location **2** on workpiece **100**. This process continues for target locations **2**, **3**, and **4** until processing of target location **4** on workpiece **106** is complete, at which time first and second X positioning stages **108** and **110** and Y positioning stage **112** execute a long move to position first and second XY scanners **98** and **104** over target locations **5**, **6**, **7**, and **8** of respective workpieces **100** and **106**. The X and Y linear positioning stages operate in constant motion in cooperation with the XY scanners. Positioning systems suitable for use with this invention are described in U.S. Pat. No. 5,751,585 for HIGH SPEED, HIGH ACCURACY MULTI-STAGE TOOL POSITIONING SYSTEM, which is assigned to the assignee of this patent application.

[0061] **FIG. 11 A** shows a workpiece processing system **120** of this invention that employs a common modular imaged optics assembly **122** and variable beam expander **94** for optically processing both laser beams **76**B and **76**C. In this embodiment, laser **92** and an optional fixed beam expander **124** cooperate to produce laser beam **76** that propagates through beam switching device **70**, which operates as described with reference to **FIGS. 7 and 8** to produce laser beams **76**A, **76**B, and **76**C. Laser beams **76**B and **76**C propagate along separate propagation path portions. A first turn mirror **126** directs laser beam **76**B through a half-wave plate **128**, which changes the polarization state of laser beam **76**B by 90 degrees relative to the polarization state of laser beam **76**C. The 90 degree phase-displaced laser beam **76**B is directed by a second turn mirror **130** to a polarizing beam combiner **132**. Laser beam **76**C is directed by a third turn mirror **134** to polarizing beam combiner **132**, which combines into a common propagation path portion the separate path portions along which laser beams **76**B and **76**C propagate. Laser beams **76**B and **76**C merge into a common laser beam **76**D, which propagates along the common path portion through imaged optics assembly **122** and optional variable expander **94** and into a polarizing beam splitter **136**. Second polarizing beam splitter **136** separates common laser beam **76**D into laser beams **76**B and **76**C. Laser beam **76**B is directed by a fourth turn mirror **138** into, for example, first XY scanner **98**; and laser beam **76**C is directed into, for example, second XY scanner **104**.

[0062] Beam expander **124** sets the shape of laser beams **76**B and **76**C in the form of a Gaussian spatial distribution of light energy. Imaged optics assembly **122** shapes the Gaussian spatial distribution of lasers **76**B and **76**C to form output beams of uniform spatial distribution for delivery to XY scanners **98** and **104**. A preferred imaged optics assembly is of a diffractive beam shaper type such as that described in U.S. Pat. No. 5,864,430.

[0063] **FIG. 11B** shows an alternative workpiece processing system **120'**, in which beam switching device **70** is removed and laser beams **76**B and **76**C propagate from separate laser sources **92***b* and **92***c*, respectively. The size of laser beam **76**B is set by a beam expander **124***b*, and the size of laser beam **76**C is set by a beam expander **124***c*. The use of separate laser sources **92***b* and **92***c* facilitates optical component configurations in which one or more of turn mirrors **126**, **130**, and **134** can be eliminated, as shown in **FIG. 11B**.

[0064] Each of workpiece processing systems **120** and **120'** is advantageous because only one set of expensive beam imaging optics is required. Moreover, for workpiece processing system **120**, employing beam switching device **70** permits implementation with smaller optical components because switching is accomplished with a smaller beam width than that which would be found with downstream switching components.

[0065] **FIG. 12** shows another alternative workpiece processing system **140** of this invention employing a fast EOM **142** and a polarizing beam splitter **144** to implement switching of a laser beam **146** between first and second XY beam scanning heads **98** and **104**. In workpiece processing system **140**, laser **92** emits laser beam **146**, which propagates through and is optically processed by an optics module **148** and a laser power controller **150**. Laser beam **146** exits laser power controller **150** and enters fast EOM **142**, which alternately polarizes laser beam **146** into respective unrotated-polarization and rotated-polarization laser beams **146**U and **146**R. Polarizing beam splitter **144** receives unrotated laser beam **146**U and directs it to a turn mirror **152** to first XY scanning head **98**. Polarizing beam splitter **144** receives rotated laser beam **146**R and directs it to second XY scanning head **104**.

[0066] A disadvantage of workpiece processing system **140** is that current practical EOMs are limited in laser pulse repetition rates and are unable to withstand high amounts of ultraviolet laser beam power. Another limitation is that dumping unneeded laser beam energy requires shuttering or turning off laser **92**, such as by a Q-switch positioned inside the cavity of laser **92**.

[0067] On the other hand, workpiece processing system **140** is advantageous because it is simpler than the dual AOM beam switching device **70** described with reference to **FIG. 7** and has a high extinguishing ratio that allows practically all of the power in laser beam **146** to impinge on target locations as laser beams **146**U and **146**R.

[0068] **FIG. 13** shows an alternative embodiment of a laser beam switching system **210** in which a laser **212** emits a laser beam **214** that is deflected by a fast steering mirror ("FSM") **216** along alternate first and second paths **218** and **220**. FSM **216** preferably employs a mirror having a deflection angle that is controlled by materials that translate voltages into angular displacements. FSM **216** operates similar to a galvanometer driven rotating mirror but at angular speeds up to 10 times faster than galvanometers and over an angular deflection range **222** of up to about 5 milliradians. Deflecting a typical laser beam diameter with such a limited angular deflection range requires a path length **224** that is sufficiently long, preferably about one meter, to separate first and second beam paths **218** and **220** by a sufficient distance **226**, preferably about 10 millimeters, for inserting between them an HR coated right angle prism **228** that further separates and directs first and second beams baths **218** and **220** for reflection by respective first and second turning mirrors **230** and **232** to associated laser beam scanning heads (not shown). Switching laser beam **214** at a location where it is smallest in diameter, such as before any beam expander, would minimize path length **224** required to sufficiently separate first and second paths **218** and **220** where they are reflected by right angle prism **228**.

[0069] FSM **216** may be a two-axis device that could further provide switching of laser beam **214** to more than two positions. For example, laser beam **214** could be directed to a beam blocker during long moves as described with reference to **FIGS. 9 and 10** to maintain constant thermal conditions in laser **212** and minimize duty cycle related laser beam power stability problems.

[**0070**] Laser beam switching system **210** allows implementing a single laser workpiece processing system having the same workpiece processing throughput as a two laser system, provided the move times are over 3 ms and the workpiece processing time and laser beam switching time are less than 1.0 ms.

[**0071**] Laser beam switching system **210** is advantageous because the use of a single laser and associated optics reduces cost by 20 percent to 40 percent, depending on the type of laser required, as compared with a two laser system.

[**0072**] Skilled workers will recognize that portions of this invention may be implemented differently from the implementations described above for preferred embodiments. For example, galvonometer and rotating mirror devices may also be used as laser beam switching devices; IR, visible, and UV lasers may be employed; target locations may be on single or multiple workpieces; laser beam switching may be effected to more than two or three beam paths; multiple lasers may be employed and each of their respective laser outputs switched among multiple paths; AOMs may be switched by single or multiple RF sources; and the scanning heads employed may further include galvanometers, FSMs, and other than XY coordinate positioning techniques.

[**0073**] It will be obvious to skilled workers that many other changes may be made to the details of the above-described embodiments without departing from the underlying principles of the invention. The scope of the present invention should, therefore, be determined only by the following claims.

1. A system configured to direct a laser beam selectively in multiple beam propagation directions in a coordinated manner to achieve high-speed processing of material in different regions of a target specimen, comprising:

a laser source emitting a laser beam that includes a series of laser pulses;

a beam switching device receiving the series of laser pulses and, in response to a beam switching signal, directing first and second groups of the laser beam pulses to propagate along respective first and second beam axes;

a first positioning mechanism responding to a first control signal to provide relative movement of the first beam axis and the target specimen to selectively position the first beam axis at different first target regions of the target specimen and to process material in the first target regions of the target specimen;

a second positioning mechanism responding to a second control signal to provide relative movement of the second beam axis and the target specimen to selectively position the second beam axis at different second target regions of the target specimen to process material in the second target regions of the target specimen;

a controller producing the beam switching signal and the first and second control signals to effect coordinated system operation in first and second operational sequences;

the first operational sequence including the beam switching device directing the first group of laser beam pulses for incidence on a selected one of the first target regions, the first positioning mechanism providing the relative movement to enable the first group of laser pulses to process material in the selected first target region, and, during the material processing by the first group of laser pulses, the second positioning mechanism providing the relative movement to position the second beam axis to a selected one of the second target regions; and

the second operational sequence including the beam switching device directing the second group of laser beam pulses for incidence on the selected second target region, the second positioning mechanism providing the relative movement to enable the second group of laser pulses to process material in the selected second target region, and, during the material processing by the second group of laser pulses, the first positioning mechanism providing the relative movement to position the first beam axis from the selected first target region to a next selected one of the first target regions.

2. A beam switching device that receives a laser beam and provides beam outputs that propagate selectively along different beam axes, comprising:

a controller producing a control drive signal in first and second states;

first and second optically associated acousto-optic modulators, the first acousto-optic modulator receiving an incoming laser beam, and the first and second acousto-optic modulators cooperating in response to the first and second states of the control device signal to produce respective first and second laser beam outputs propagating from the second acousto-optic modulator; and

the first laser beam output including a major component propagating along a first beam axis and a minor component propagating along a first minor component axis, and the second laser output including a major component propagating along a second beam axis that is angularly offset from the first beam axis and a minor component propagating along a second minor component axis that is substantially coincident to the first minor component axis.

3. The beam switching device of claim 2, further comprising a beam blocker positioned to terminate the minor components propagating along the first and second minor component axes.

4. The beam switching device of claim 2, in which:

the controller includes first and second RF drivers that are operationally associated with the respective first and second acousto-optic modulators; and

in the first state of the control drive signal, the first, RF driver causes the first acousto-optic modulator to pass the incoming laser beam as an undeflected beam incident on the second acousto-optic modulator and the second RF driver causes the second acousto-optic modulator to diffract the incident undeflected beam to form the major component to propagating along the first beam axis and the minor component propagating along the first minor component axis.

5. The beam switching device of claim 2, in which:

the controller includes first and second RF drivers that are operationally associated with the respective first and second acousto-optic modulators; and

in the second state of the control drive signal, the second RF driver causes the second acousto-optic modulator to pass incident light as an undeflected beam and the first RF driver causes the first acousto-optic modulator to diffract the incoming laser beam to form the major component propagating along the second beam axis and the minor component to propagating along the second minor component axis.

6. The beam switching device of claim 2, in which the first and second optically associated acousto-optic modulators are positioned in optical series.

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