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(54) **PRECISION LASER MICROMACHINING
SYSTEM FOR DRILLING HOLES**

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(57) **ABSTRACT**

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A laser drilling system for drilling holes in a work piece with a laser. The system includes: a laser for creating a laser beam and directing the laser beam along an optical path; a mask having at least one aperture, the mask and the aperture being located in the optical path to cause the creation of a sub-beam; a lens for forming a reduced-size image of the sub-beam onto the work piece and a translation stage for moving the mask to change the position of the sub-beam on the work piece. The laser beam has a wavefront cross-section with an area greater than the size of the aperture and is incident upon the mask and the aperture to create the sub-beam.

Related U.S. Application Data

(62) Division of application No. 10/329,036, filed on Dec. 24, 2002.

(60) Provisional application No. 60/375,741, filed on Apr. 26, 2002.

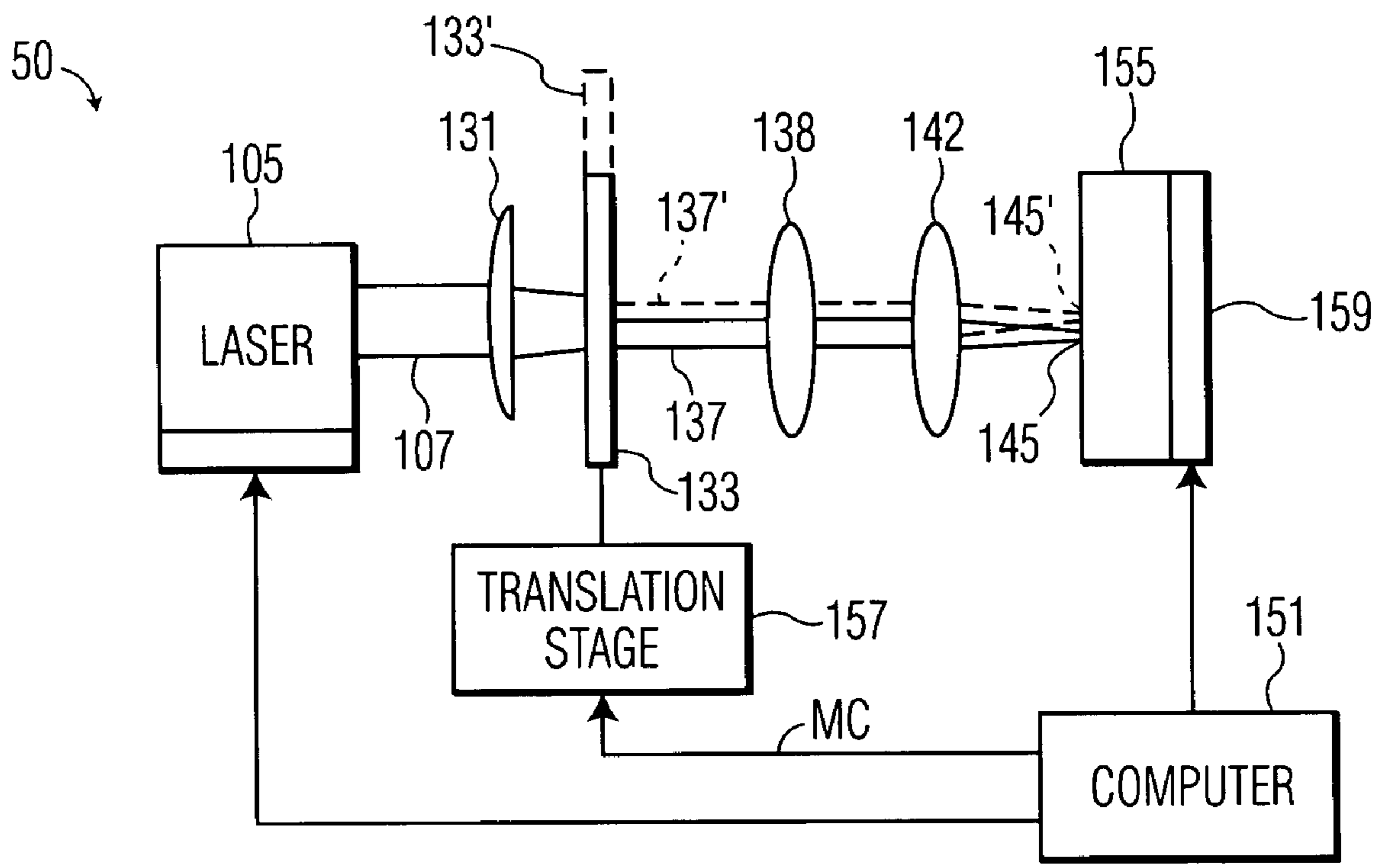


FIG. 1

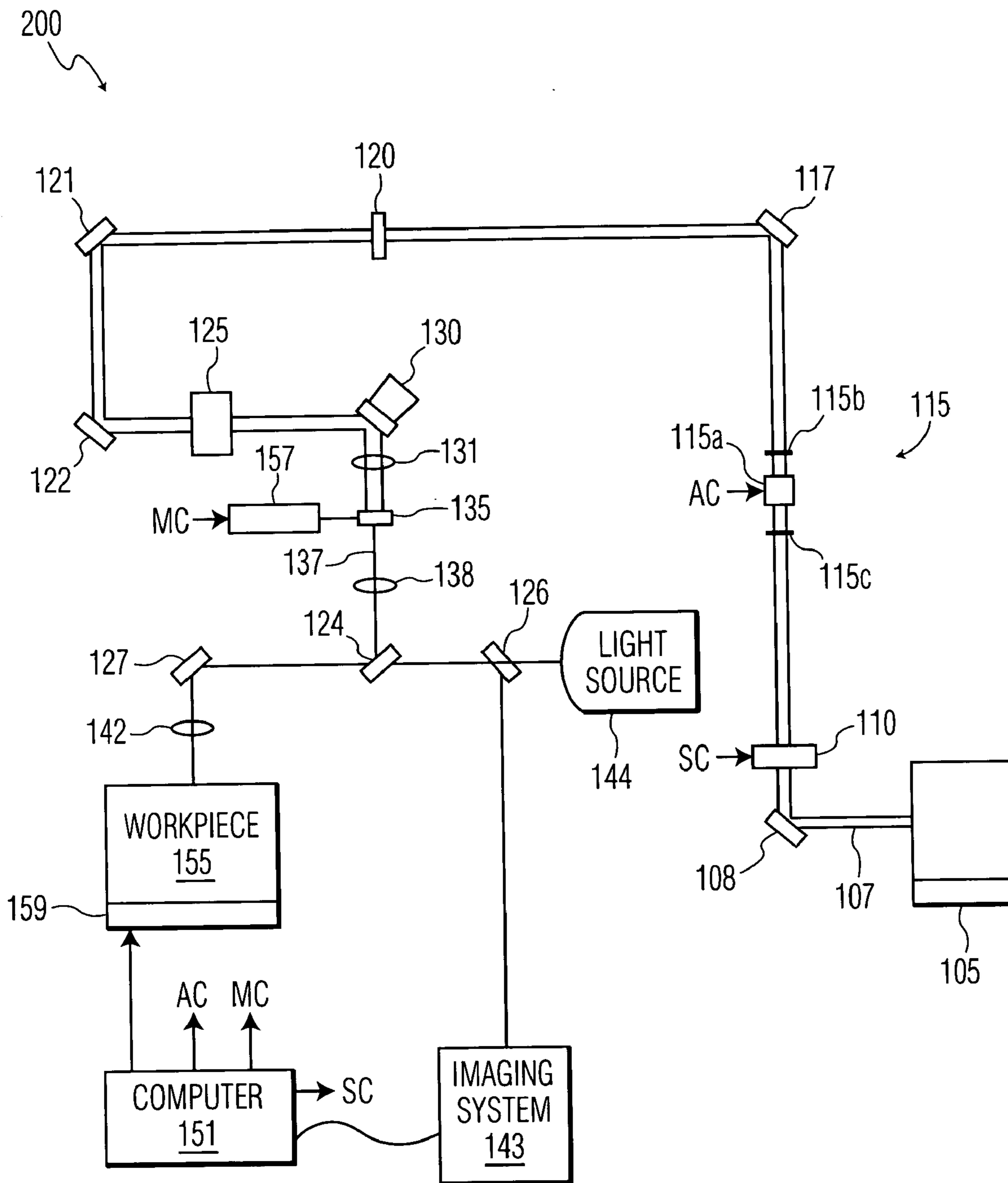


FIG. 2

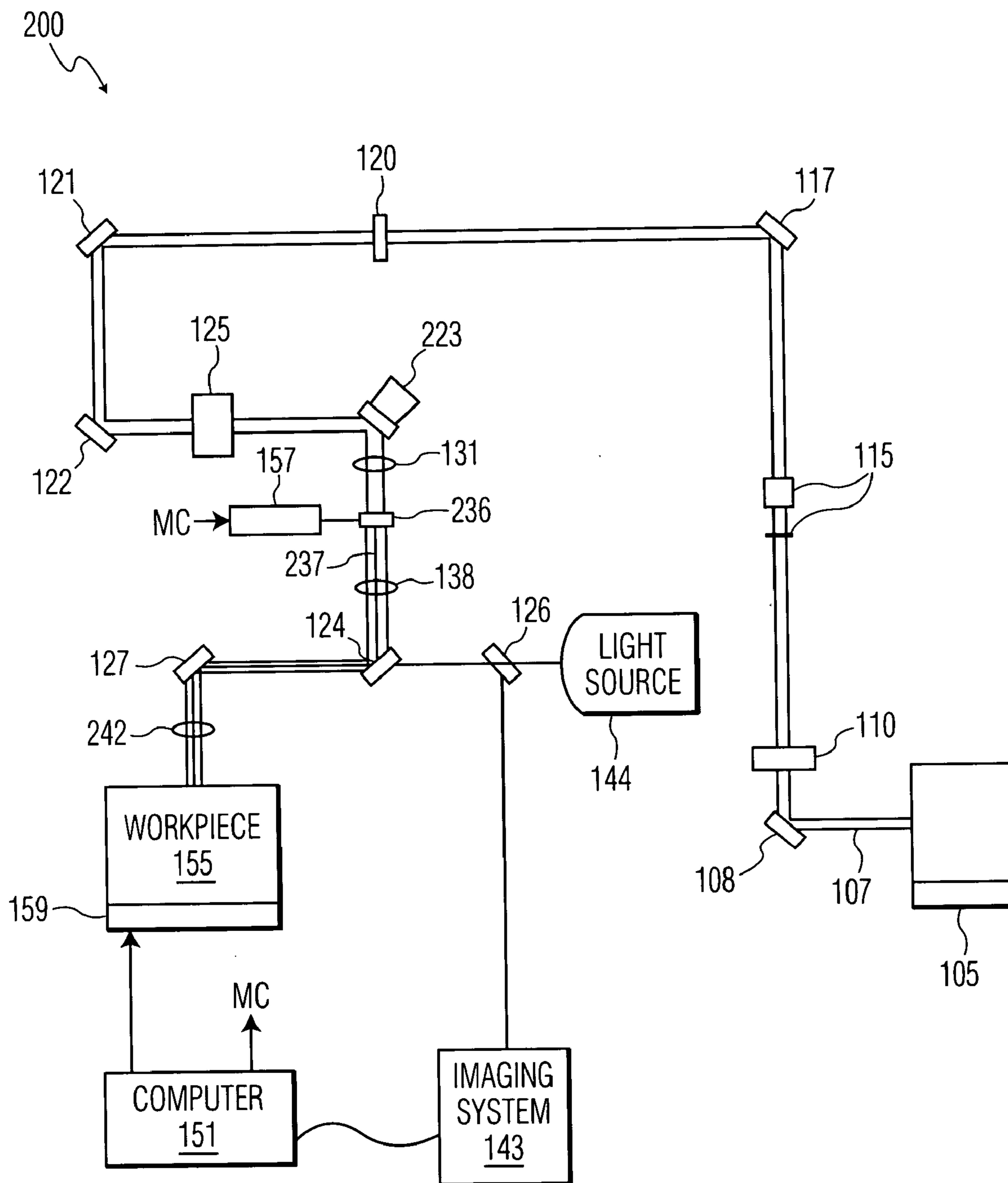


FIG. 3

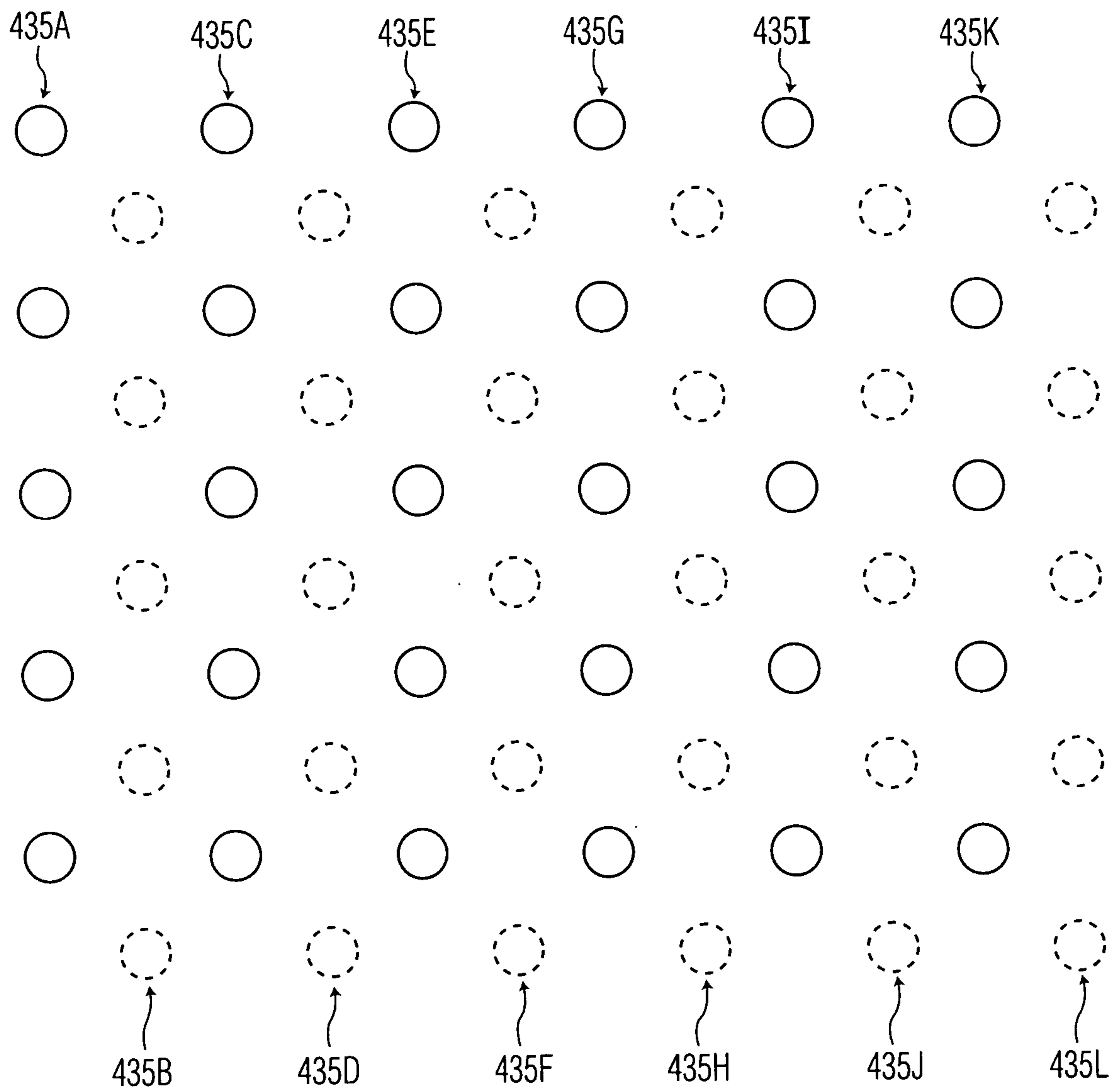


FIG. 4

PRECISION LASER MICROMACHINING SYSTEM FOR DRILLING HOLES

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. patent application Ser. No. 10/329,036, filed Dec. 24, 2002 which claims priority of U.S. Provisional Application No. 60/375,741 filed on Apr. 26, 2002, the contents of which are incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to precision laser micromachining. More specifically, it relates to a method of and a system for laser micromachining to obtain precise alignment of drilling laser beams and for fabricating products, having sub-micron features, with precision and accuracy. One embodiment may be used to fabricate photonic devices such as photonic crystals.

BACKGROUND OF THE INVENTION

[0003] Photonic devices and microphotronics provide exciting potential for furthering the advancement of technology historically served by microelectronics. Photonic devices may be used as frequency selection filters to enable large volumes of data to travel along optical fibers and to be routed to their final destinations. As light traveling in a fiber is incident upon a frequency selection photonic crystal, the light at the desired wavelength travels through the photonic crystal and is routed to its destination, while the light at all other frequencies is reflected. Currently, photonic crystals are commonly manufactured with layered GaAs and AlGaAs or layered Si and SiO₂. Microphotonic devices are expected to replace microelectronic devices once cost-effective methods of manufacturing photonic devices are developed. One reason that optical circuits have not been widely implemented is that there are manufacturing problems related to making photonic devices meet index of refraction specifications.

[0004] Lasers may be used to drill holes in or otherwise machine a work piece, including, glass or silicon or other dielectric materials to form waveguides or microoptical structures in the materials. The behavior of light in a photonic crystal may be better understood by analogy to the behavior of electricity in a conventional crystal. Crystals are characterized by a periodic arrangement of atoms or molecules. The lattice of atoms or molecules may introduce gaps in the energy band structure of the crystal through which electrons cannot propagate. A photonic crystal is a lattice of discontinuities in the refractive index of a material. One example is a lattice of holes in a waveguide. If the dielectric constants of the waveguide material and the material in the holes is sufficiently different, light is substantially confined by the interfaces. Scattering of the light at the interfaces can produce many of the same effects for photons as are produced for electrons by the lattice of atoms or molecules.

[0005] Photonic crystal fabrication precisely aligns the holes that constitute the photonic crystal in the described lattice structure. Current laser micromachining methods, such as direct writing, do not provide a way to drill features with the sub-micron accuracy and precision needed for photonic crystals. This is because it is difficult to accurately

align the laser beam or to produce multiple holes positioned in the desired lattice arrangement with an accuracy that is desirable to produce an effective photonic structure. The current method of producing holes (single and multiple holes) uses a moveable work piece holder on which a photonic crystal is mounted. The laser beam is aligned at the desired location(s) on the crystal by maintaining the laser beam in a single location and moving the work piece holder with the work piece mounted onto it. The problem is that the holder cannot be moved with a level of accuracy suitable for manufacturing photonic crystals. In addition to the spatial positioning errors, photonic structures may also suffer from blurring of the image of the laser beam as the feature sizes decrease to less than or equal to the size of the wavelength of the beam. What is needed is a way to mass manufacture a photonic crystal within specifications, including a way to align the beam and work piece in a laser drilling system for drilling holes in a photonic crystal where the feature size is less than or equal to the wavelength of the drilling laser beam.

SUMMARY OF THE INVENTION

[0006] The invention is embodied in an apparatus and a method for drilling holes in a work piece with a laser. A laser beam is received by the optical system and directed along an optical path. The system directs the laser beam through a moveable mask aperture creating a sub-beam that is reduced in size by a lens system as it is imaged onto a work piece. Multiple features are formed in the work piece by moving the mask.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The invention is best understood from the following detailed description when read in connection with the accompanying drawings. It is emphasized that, according to common practice, the various features of the drawings are not to scale. On the contrary, the dimensions of the various features are arbitrarily expanded or reduced for clarity. Included in the drawings are the following figures:

[0008] FIG. 1 is a block diagram of a first exemplary embodiment of the invention.

[0009] FIG. 2 is a block diagram of a second exemplary embodiment of the invention using a single aperture mask.

[0010] FIG. 3 is a block diagram of a third exemplary embodiment of the invention using a multiple aperture mask.

[0011] FIG. 4 is an image of a multiple aperture mask which shows the image in two different positions.

DETAILED DESCRIPTION OF THE INVENTION

[0012] The present invention provides a way to mass manufacture photonic crystals having feature sizes less than or equal to the wavelength of the laser beam used in the manufacturing process. The present invention also provides a way to improve beam stability within a laser drilling system. Furthermore, the present invention provides a way to align the beam and work piece in a laser drilling system to enable drilling holes in a photonic crystal. The present invention may be used to create a very dense pattern of sub-micron features.

[0013] The present invention also provides a way to drill features with a laser drilling system where the feature size is less than or equal to the wavelength of the drilling laser beam. In addition, the present invention provides a way to increase throughput of a laser drilling system by parallel processing with sub-beams created by a multiple aperture mask.

[0014] FIG. 1 is a block diagram of a first exemplary embodiment of the invention. It shows a laser drilling system 50 which positions the light of a laser beam from an ultrafast laser 105 on a work piece 155 for laser machining. Light means any energy that may be generated by a laser. The system 50 includes a laser 105 which generates a laser beam 107.

[0015] In the exemplary embodiment, ultrafast laser 105 may be a conventional femtosecond laser with Ti: Sapphire crystal, such as a Clark-MXR 2000. In another embodiment, laser 105 may be a picosecond laser. As used herein, the term "ultrafast laser" includes both femtosecond and picosecond lasers. Because the energy across the wavefront exhibits a Gaussian distribution, an ultrafast laser is capable of producing a feature having a size that is smaller than the spot-size, produced by the laser wavefront. In one example described by Li et al. in Jap. J. Appl. Phys. 40 (2001), pp. 3476-3477, a laser beam with a 387 nm wavelength was used to drill features having a size of approximately 160 nm. In an exemplary embodiment of the present invention, laser beam 107 may have a pulse width of 150 fs, a wavelength of 775 nm, a pulse repetition rate of 330 Hz, and a pulse energy of 880 micro-Joules. In an alternative embodiment, laser beam 107 may have a 387 nm wavelength. In all of these embodiments, the work piece was exposed to fluence greater than the ablation threshold only over a central portion of the wavefront. In other embodiments, the laser beam may have other pulse widths, wave lengths, pulse repetition rates, and pulse energy appropriate for the desired machining task.

[0016] When laser beam 107 exits laser 105, it travels along the optical path until it is incident upon lens 131 which expands laser beam 107. In an alternative embodiment, the laser beam 107, as it exits laser 105, is already wider than the hole in mask 133 and expander lens 131 may not be used. In yet another alternative embodiment, lens 131 may be a conventional lens that focuses beam 107 beyond the location of aperture 135 so that less laser energy is wasted when it is masked by aperture 135. Accordingly, an expander lens is an optional feature of the embodiment shown in FIG. 1. Expanded laser beam 107 exits lens 131 and propagates until it is incident upon mask 133. In one exemplary embodiment, mask 133 may have a single aperture. In another embodiment, mask 133 may have multiple apertures. Regardless of whether expander lens 131 is used, the laser beam that is incident upon mask 133 desirably has a wavefront cross-section with an area greater than the size of the aperture in mask 133. Mask 133 is mounted on translation stage 157, which can be a one direction stage in the X direction or a two direction stage in the X and Y directions. In the exemplary embodiments, the X direction is into or out of the plane of the paper and the Y direction is up or down on the paper. Mask 133 masks a portion of laser beam 107 and creates sub-beam 137.

[0017] After sub-beam 137 exits mask 133, it is incident upon "eyepiece lens" 138 and microscope objective lens 142

which focus a reduced-size image 145 of mask 133 in sub-beam 137 on work piece 155. In an exemplary embodiment, the combination of two lenses, 138 and 142, may create a demagnification, for example, of thirty upon work piece 155. Thus, the size of the image 145 of the mask 133 on the work piece is $\frac{1}{30}$ th the size of the image at mask 133. This demagnification of thirty means that image 145 is moved one-thirtieth of the distance that mask 133 is moved. In one example, therefore, when aperture 133 is moved 1 mm, image 145 moves 33 microns ($1 \text{ mm}/30=33 \text{ microns}$) along the surface of work piece 155. One benefit of this de-magnification is that any translation errors made by translation stage 157 in moving aperture 133 are reduced by a factor of thirty when image 145 is incident upon work piece 155. In other embodiments, lenses of different magnification may have other focal lengths. Work piece 155 is mounted on translation stage 159 which may be an XYZ translation stage movable in any of the X, Y and Z directions. A computer 151 controls the movement of both translation stages 157 and 159. Computer 151 also controls laser 105 by turning it on and off as needed.

[0018] Under the control of computer 151, ultrafast laser 105 is turned on, causing laser beam 107, sub-beam 137, and image 145 to be created. Image 145, through sub-beam 137, ablates work piece 155 to drill a hole in it. After the hole is drilled, computer 151 turns off laser 105. If another hole is to be drilled in work piece 155, computer 151 directs translation stage 157 to move the mask 133. Depending upon whether translation stage is an X direction or an XY direction stage, computer 151 may cause mask 133 to be moved in the X direction and/or the Y direction. Computer 151 then turns on laser 105 again. The movement of mask 133 to a new position causes image 145, through sub-beam 137, to be moved to a new position 137' and further causes image 145 to be moved to a new position 145' on work piece 155. The image 145' of mask 133, through sub-beam 137', ablates work piece 155 by drilling a second hole. Computer 151 then turn off laser 105. This procedure is followed until all of the holes of the pattern have been drilled.

[0019] In the exemplary embodiment of the invention, translation stage 159 does not move the work piece while it is being machined. Instead, stage 159 is used to position the work piece relative to beams 137, 137' before the machining operation begins.

[0020] FIG. 2 is a block diagram of a second embodiment of a drilling system 200. The system 100 includes a laser 105 which generates a laser beam 107 with a wavelength of 775 nm. In an alternative embodiment, the wavelength of laser beam 107 may be 387 nm. In such an alternative embodiment, the other characteristics of the system may be adjusted accordingly. Laser beam 107 travels along an optical path until it is incident upon first mirror 108. First mirror 108 is a conventional laser mirror having a high reflectivity at least at the wavelength of the laser beam 107. In this exemplary embodiment, first mirror 108 is highly reflective of 775 nm wavelength light. First mirror 108 redirects beam 107 along an optical path where it is incident upon shutter 110 which opens and closes to selectively illuminate work piece 155. Shutter 110 is a conventional laser shutter used to control the propagation of laser beam 107. In an exemplary embodiment, shutter 110 is an electric shutter controlled by a shutter control signal, SC, provided by computer 151. In another embodiment, shutter 110 may be controlled by timing elec-

tronics (not shown) that start and stop the propagation of laser beam **107** along the optical path. In yet another embodiment, shutter **110** may be operated directly by an operator using manual controls.

[0021] Laser beam **107** exits shutter **110** and propagates along the optical path to attenuator **115** which filters the energy in laser beam **107** in order to precisely control the ablation parameters. Attenuator **115** is a high-dynamic, high-precision, variable attenuator. In an exemplary embodiment, attenuator **115** is a half wave plate **115a** between two crossed polarizers **115b** and **115c**. In the exemplary embodiment, the half-wave plate **115a** is rotated responsive to an attenuator control signal, AC, provided by the computer **151** to achieve the desired level of attenuation.

[0022] Laser beam **107** exits attenuator **115** and propagates along the optical path until it is incident upon second mirror **117** which redirects the beam to a nonlinear optical medium for harmonic generation **120**, which in an exemplary embodiment, may be a frequency doubler. Second mirror **117** is a conventional laser mirror which is highly reflective of at least the 775 nm wavelength light. Exemplary frequency doubler **120** halves the wavelength of laser beam **107**. In an exemplary embodiment, frequency doubler **120** is a Beta-Barium Borate (BBO) crystal which receives the 775 nm beam **107** and transforms it into a beam having a wavelength of 387.5 nm. In alternative embodiments, a different nonlinear optical medium for harmonic generation may be used, such as a frequency tripler or a frequency quadrupler. Using frequency doubler **120** to provide a shorter wavelength beam allows laser drilling system **100** to drill holes having a smaller feature size than could be drilled using a longer wavelength beam. Additionally, the increased energy of photons in a beam with a shorter wavelength causes work piece **155** to ablate more easily.

[0023] Laser beam **107**, at a reduced wavelength, exits frequency doubler **120** and propagates along the optical path until it is incident upon third mirror **121**. In an exemplary embodiment, third mirror **121** is a harmonic mirror that reflects a specific wavelength of light. In an exemplary embodiment, third mirror **121** preferentially reflects light having a 387.5 nm wavelength, allowing light at longer wavelengths (e.g. 775 nm) to pass through the mirror. Third mirror **121** redirects laser beam **107** along the optical path until it is incident upon fourth mirror **122** which, in turn, redirects the beam to where it is incident upon quarter-wave plate **125**. In an exemplary embodiment, fourth mirror **122** is also a harmonic mirror that preferentially reflects a light having a 387.5 nm wavelength. Quarter-wave plate **125** changes the polarization of the laser beam from linear to circular, thereby improving the shape of the final ablation in work piece **155**. Circularly polarized light from quarter wave plate **125** is provided to a PZT scan mirror **130**.

[0024] In an alternative embodiment, second mirror **117**, frequency doubler **120**, third mirror **121**, and quarter-wave plate **125** may be eliminated. In such an embodiment, the wavelength of laser beam would not be shortened by frequency doubler **120** and the light would be transmitted from attenuator **115** to PZT scan mirror **130**.

[0025] As described above, the intensity of the wavefront of a laser beam can be modeled as a two-dimensional Gaussian distribution, with the highest intensity at the center of the beam and lower intensities toward the edge of the

beam. For laser drilling with projection imaging, a uniform laser intensity distribution at the work piece is desired so that the drilled holes are uniform. One way of insuring uniform illumination of the mask is to transform the beam to have a more uniform transverse intensity distribution before illuminating the mask. The process of transforming the laser beam is known as beam homogenization or beam shaping.

[0026] In the exemplary embodiment, PZT scan mirror **130** performs the beam homogenization. It moves as needed to guide laser beam **107** through aperture **135**. In an exemplary embodiment, PZT scan mirror **130** is a conventional PZT scan mirror such as a Piezo Jena which is highly reflective of at least the 387.5 nm wavelength light. It homogenizes the beam by scanning the center of laser beam **107** across the mask, for example, in a circular pattern, to keep the fluence of laser beam **107** at the work piece consistent when the aperture **135** is in any position. In another embodiment, where frequency doubler **120** is eliminated, PZT scan mirror **130** may be selected to be highly reflective of at least the 775 nm wavelength light. An exemplary laser beam homogenization system is described in U.S. patent application Ser. No. 09/541,019 entitled LASER BEAM HOMOGENIZATION BY SCANNING A BEAM ONTO A MASK.

[0027] PZT scan mirror **130** redirects laser beam **107** until it is incident upon lens **131** which focuses laser beam **107** beyond aperture **135** so that the beam is defocused at the aperture **135**. As described above, this lens may also expand the beam on the mask **135**. Laser beam **107** exits lens **131** and propagates until it is incident upon aperture mask **135**. Mask **135** is mounted on translation stage **157**. In an exemplary embodiment, stage **157** may be a Burley Inch Worm. In an alternative embodiment, stage **157** may move only in one direction (i.e. in either the X direction or the Y direction) or in both directions.

[0028] The exemplary translation stage **157** is controlled by a mask control signal, MC, provided by computer **151** which also controls shutter **110** so that the beam is not projected onto the work piece **155** when the mask or the work piece is being moved. In another embodiment, stage **157** may be controlled manually. Translation stage **157** is an adjustable stage with coarse and precision adjustable stages. Translation stage **157** adjusts the placement of aperture **135** in the optical path. In an exemplary embodiment, the width of laser beam **107** is about 4 mm and is incident upon aperture **135** which has an opening width of about 10 microns.

[0029] Aperture **135** masks a portion of laser beam **107** and creates sub-beam **137**. Sub-beam **137** is reduced in size by the lenses **138** and **142** and is used to ablate work piece **155**. Aperture **135**, therefore, acts as a new starting location for the laser beam. As explained below, the combination of aperture **135**, translation stage **157**, and the lenses **138** and **142**, minimizes wobble and allows for greater accuracy and pointing stability in focusing the laser beam upon work piece **155**. After sub-beam **137** ablates work piece **155** in one location, shutter **110** closes, translation stage **157** moves aperture **135** to a different location, shutter **110** opens, and sub-beam **137** ablates work piece **155** in the new location.

[0030] Sub-beam **137** propagates along the optical path until it is incident upon lens **138**. In an exemplary embodiment, lens **138** is a conventional lens used in laser systems

with a longer focal length to focus sub-beam **137** toward work piece **155**. In an exemplary embodiment, lens **138** has a 60 mm focal length. Sub-beam **137** propagates to sixth mirror **124**. In an exemplary embodiment, sixth mirror **124** is a harmonic mirror that preferably reflects 387.5 nm wavelength light and allows light in the range less than 387.5 nm and in the range greater than 387.5 nm to pass through and out of laser drilling system **100**. In another embodiment, sixth mirror **124** may be a conventional laser mirror that is highly reflective of at least 387.5 nm light.

[0031] Sixth mirror **124** redirects sub-beam **137** along the optical path where it is incident upon eighth mirror **127**, a mirror that is highly reflective of at least 387.5 nm wavelength light. Eighth mirror **127** redirects sub-beam **137** along the optical path until it is incident upon $100\times$ lens **142**, which, in an exemplary embodiment, is a conventional magnifying lens used in laser systems with a shorter focal length. In an exemplary embodiment, $100\times$ lens **142** is manufactured by Mitutoyo.

[0032] The combination of lens **138** and lens **142** provides the same function in this embodiment as the “eyepiece” lens **138** and the microscope objective lens **142** in the first embodiment. In an exemplary embodiment, $100\times$ lens **142** has a 2 mm focal length and a 1cm working distance. The exemplary embodiment may use an Ultra Long Working Distance Lens (ULWD) having a working distance of 1cm as the lens **142**. Alternatively, a conventional 2 mm lens may be used along with an air knife to remove any material that is ablated from the work piece.

[0033] The combination of lens **138** (focal length $f_1=60$ mm) and $100\times$ lens **142** (focal length $f_2=2$ mm) creates a de-magnification of thirty (f_1/f_2) of sub-beam **137** upon work piece **155**. Thus, the size of the image of the mask **135** on the work piece is $1/30^{\text{th}}$ the size of the image at the mask **135**. This de-magnification of thirty means a reduced-size image of sub-beam **137** is moved one-thirtieth of the distance that aperture **135** is moved. In one example, therefore, when aperture **135** is moved 1 mm, sub-beam **137** moves 33 microns ($1\text{ mm}/30=33$ microns) along the surface of work piece **155**. Another benefit of this de-magnification is that any translation errors made by translation stage **157** in moving aperture **135** are reduced by a factor of thirty when sub-beam **137** is incident upon work piece **155**.

[0034] In the exemplary embodiment, an imaging system **143** is used to align the reduced-size image of sub-beam **137** with the target area of workpiece **155**. Imaging system **143** may be used to ensure that the reduced-size image of sub-beam **137** is incident upon work piece **155** at the correct location. In an exemplary embodiment, imaging system **143** may include a charge-coupled device (CCD) array or other digital or analog camera. Imaging system **143** includes a display mechanism (not shown) allowing a system operator to determine where the reduced size image of sub-beam **137** should be incident upon work piece **155**. Alternatively, image data provided by the imaging system may be received by the computer **151** and processed to implement the desired control functions.

[0035] Imaging system **143** is used in conjunction with light source **144** and other parts of laser drilling system **100**. In an exemplary embodiment, light source **144** is a conventional incandescent light source capable of producing a well-focused spot of light. In the exemplary system, light

from light source **144** and light from laser **105** are not transmitted simultaneously through laser drilling system **100**. Before light source **144** is activated, shutter **110** is closed in order to prevent laser beam **107** from being transmitted through the system.

[0036] In an exemplary embodiment, light source **144** is a fiber guided light source which produces a spot of light with a 2 cm diameter. The spot of light generated by light source **144** travels along an optical path, through seventh mirror **126** and sixth mirror **124**, until it is incident upon eighth mirror **127**. As described above, sixth mirror **124** is a harmonic mirror and, so, passes incandescent light applied to its back surface. Seventh mirror **126** is a partially reflective mirror that allows a part of the incandescent light from light source **144** to pass through on one side and partly reflects incandescent light incident on the opposite side. In an exemplary embodiment, seventh mirror **126** may be a thin film pellicle. In another embodiment, seventh mirror **126** may be a low reflection pickoff mirror. In both exemplary embodiments, seventh mirror **126** reflects a few percent of the light from light source **144** while most of the light is transmitted through seventh mirror **126**.

[0037] Eighth mirror **127** redirects the light from light source **144** along the optical path through $100\times$ lens **142**, where it is incident upon work piece **155**. Work piece **155** reflects a portion of the incandescent light back along the optical path, through $100\times$ lens **142** where the reflected light is incident upon eighth mirror **127**. Eighth mirror **127** redirects the reflected incandescent light through sixth mirror **124** after which the incandescent light is incident upon seventh mirror **126**. Seventh mirror **126** redirects the incandescent light so that it is incident upon imaging system **143**. Imaging system **143** creates an image of the surface of work piece **155** in real time. The image created by imaging system **143** is transferred to computer **151**. In an exemplary embodiment, computer **151** is a conventional computing means, such as a personal computer with a monitor (not shown) that may be used to display an image of the work piece generated by the imaging system **143**.

[0038] In an exemplary embodiment, imaging system **143** is used to align the laser drilling system, using one or more test holes, and to measure the offset between the test hole and the target location along the waveguide of a photonic crystal. The term “offset” means the distance and angle between the practice hole(s) and the actual target location of laser drilling system **100**. Either an operator or computer **151** directs the movement of aperture **135** through XY translation stage **157** to drill holes in work piece **155** based on the offset measurement derived from the image seen through imaging system **143**. A support, translation stage **159**, supports work piece **155** during ablation, and adjusts and maintains the position of work piece **155** in the focal plane of sub-beam **137** created by lens **138** and lens **142**. Translation stage **159** is an XYZ translation stage. In an exemplary embodiment, it may be controlled by computer **151**. In an alternative embodiment, it may be controlled manually. The translation stage **159** may also be used to change the position of the work piece between drilling the test hole and the actual photonic structure.

[0039] The method of operating laser drilling system **100** involves the following steps. First, XYZ translation stage **159**, attached to work piece **155**, is used to set the focus

position of laser sub-beam **137** on work piece **155**. The focus position in the Z direction is set by drilling several trial holes in the work piece and then viewing the trial holes through imaging system **143**, with the laser beam being blocked by shutter **110**. The practice area is an area that will not be included within the final product of work piece **155** and is used only for alignment purposes. When the operator observes through imaging system **143**, good trial holes with correct measurements, the operator knows that the laser and work piece are in the proper relative focus positions.

[0040] Second, after the practice holes have been drilled properly, the operator or computer **151** determines the actual position of sub-beam **137** upon work piece **155** with imaging system **143**. Third, translation stage **159** is adjusted in the X and/or Y directions to move the work piece position while holding the Z direction focus position. Fourth, better alignment between the reduced-size image of sub-beam **137** and the target area on work piece **155** may be accomplished by using imaging system **143** to measure the offset. Thus, once the offset has been determined, the reduced-size image of sub-beam **137** is aligned with the actual target area upon work piece **155** by moving aperture **135** via translation stage **157** as performed manually or as directed by computer **151**. This is an alternative to using the stage **159** to move the work piece. This step is performed by having the system operator first look at the real time image of the practice hole produced by imaging system **143** showing the location of the position of the practice hole upon work piece **155**. The system operator then adjusts the position of aperture **135** (and/or translation device **159**) according to the direction and distance desired (as seen in the real time image) to align the reduced-size image of sub-beam **137** upon the target area of work piece **155**. Using the holes drilled by the system, the patterns drilled can take the form of any shape. The holes forming the patterns may be arranged in parallel rows, parallel columns, or may be arranged in any format.

[0041] The fifth step is drilling the specified feature in the target area of work piece **155**. Then, if the desired pattern in work piece **155** requires additional features to be drilled, aperture **135** is moved by the operator or computer **151** so that reduced-size sub beam **137** is at the next target area where drilling repeats. Movement of aperture **135** is done by controlling the movement of translation stage **157**. During the machining of a feature on the work piece, only the mask **135** is moved. The method ends when the pattern is completed and the specified work piece geometry is drilled in work piece **155**.

[0042] In an exemplary embodiment, the laser drilling system may form holes having a 200 nm diameter and a pitch (the distance between the centers of two adjacent holes) of 420 nm. In an alternative embodiment, the holes may have a 200 nm diameter and a 400 nm pitch.

[0043] Referring to **FIG. 3**, a third exemplary embodiment is shown in which the same reference numbers refer to like elements. **FIG. 3** shows a laser drilling system **200** which is a system for parallel processing precision holes in work piece **155**. The majority of the elements of the laser drilling system shown in **FIG. 3** are the same as those in the laser drilling system shown in **FIG. 2**, with the exception of multiple aperture mask **236** and sub-beams **237**. As described below, the focal lengths of the lenses **138**, **242**

which demagnify sub beam **237** onto work piece **155**, may be the same as, or different from, the focal lengths of those lenses shown in **FIG. 2**.

[0044] Multiple aperture mask **236** is fastened to adjustable translation stage **157**. Multiple aperture mask **236** masks out much of the energy of beam **107** to create a plurality of sub-beams **237**. The pattern of multiple aperture mask **236** is designed to provide a drilling pattern to ablate work piece **155**. In an exemplary embodiment in which four holes are to be drilled along a waveguide to form a photonic crystal, the pattern of multiple aperture mask **236** may consist of a pattern of multiple holes thirty times larger than the desired pattern, due to the reduction in size provided by lens **138** and lens **242**. In another exemplary embodiment, lens **242** has a magnification of 50×. In another embodiment, lens **242** is replaced with a lens having a 20× magnification. The combination of multiple aperture mask **236** and 50× lens **242** reduces the size of the original multi-hole mask by a factor equal to the focal length of lens **138** divided by the focal length of 50× lens **242** (f_1/f_2) while maintaining the exact pattern on the mask. In another embodiment, the focal length of lens **138** is 60 mm, the focal length of 50× lens **242** is 2 mm, and the demagnification is equal to 30. It will be understood that lenses **138** and **242** may have any power of magnification and any focal length that, in combination, will produce a desired demagnification. It will also be understood that a $1/30$ demagnification is an example. Other demagnification may be used depending upon the task to be performed by the system. Whatever the demagnification may be, the aperture pattern of the mask **236** is imaged onto the work piece **155**.

[0045] In operation, laser drilling system **200** in **FIG. 3** is identical to laser drilling system **200** in **FIG. 2**, until laser beam **107** is incident upon fifth mirror **223**. Fifth mirror **223** need not be a scanning mirror. It may, instead, be a conventional laser mirror. In either case, fifth mirror **223** redirects laser beam **107** along the optical path until it is incident upon lens **131**. Lens **131** focuses laser beam **107** beyond multiple aperture mask **236** ensuring that the area is greater than the area of the multiple aperture pattern in the mask. Laser beam **107** passes through multiple aperture mask **236** which masks a portion of the beam. The part of beam **107** which is not masked by multiple aperture mask **236** becomes sub-beams **237**. Sub-beams **237** propagate along the optical path and are incident upon lens **138** through which the beam propagates toward sixth mirror **124**. Sixth mirror **124** redirects sub-beams **237** until they are incident upon eighth mirror **127**. Eighth mirror **127** redirects sub-beams **237** along the optical path until they are incident upon lens **242** which focuses a reduced-size image of sub-beams **237**, as it appears at the mask **236**, upon work piece **155**. Reduced-size sub-beams **237** ablate work piece **155** to form the desired features.

[0046] A very dense pattern of sub-micron holes (that is, holes that are located less than microns apart) may not be imaged using the embodiments described above due to resolution constraints of imaging system **143** as the feature sizes approach the wavelength of the laser beam, particularly when the feature sizes become equal to, or less than, the laser wavelength. The images of the features on the work piece become blurred when the features become so small. Blurring occurs because each laser beam has wave characteristics which permit the beam to be focused to a certain

minimum spot size before hitting its limit. The limit, called the diffraction limit, is approximately equal to the wavelength of the laser beam.

[0047] Blurring may cause problems with the precise alignment of reduced-size sub-beams **237** upon work piece **155**. Therefore, in another embodiment, where a very dense pattern is desired in the final product, the laser drilling system **200** in **FIG. 3** may use the same multiple aperture mask **236** more than once to form overlapping images on the work piece. This embodiment is illustrated in **FIG. 4** which shows an exemplary mask **435** having a series of holes in columns **435A**, **435C**, **435E**, **435G**, **435I**, and **435K**. After a first set of holes is drilled in these columns, mask **236** is moved, resulting in the columns of holes being moved in the X and Y directions to new locations indicated by columns **435B**, **435D**, **435F**, **435H**, **435J**, and **435L**. The system may then drill a second set of holes at the new locations of the holes. It will be understood that the holes may be moved only in the X direction or only in the Y direction. Although **FIG. 4** shows round holes as an exemplary embodiment, holes of other shapes may be drilled by the embodiment shown in **FIG. 4** and by all of the embodiments of the invention.

[0048] In yet another embodiment where a very dense pattern is required in the final product, a multiple aperture mask **236** that is less dense may be used in combination with a second aperture mask **236**. In this embodiment, holes may be first drilled using the first mask following by drilling holes using the second mask.

[0049] The method of operating laser drilling system **200** involves the following steps. In the first step, a practice set of shapes is drilled in a practice area of work piece **155**. The practice area is an area that will not be included within the final product of work piece **155** and is used only for alignment purposes. In the second step, the actual position of the practice set of shapes upon the work piece is determined with imaging system **143**. The third step is aligning reduced-size sub-beams **237** with the actual target area upon work piece **155** by moving mask **236**. This step is performed when the system operator looks at the image of the practice set of shapes, produced by the imaging system **143** showing the location of the practice set of shapes upon work piece **155**. The operator adjusts the position of multiple aperture mask **236** according to the direction and distance desired, as seen in the image of the practice set of shapes, to align reduced-size sub-beams **237** upon the target area of work piece **155**. The fourth step is drilling a shape in the target area of work piece **155** where laser drilling system **200** generates reduced-size sub-beams **237**, which ablate the target area of work piece **155** to meet specifications. Then, if the desired pattern in work piece **155** calls for an additional set of shapes to be drilled, mask **236** is moved to the next target area and drilling is repeated.

[0050] Using the embodiment shown in **FIG. 3**, the exemplary holes shown in **FIG. 4** may have a diameter 200 nm and a pitch of 360 nm.

[0051] Although the invention has been described in terms of exemplary embodiments, it is contemplated that it may be practiced as described above with variations within the scope of the appended claims.

We claim:

1. A laser drilling system for drilling holes in a work piece with a laser, said system comprising:

a laser for creating a laser beam and directing the laser beam along an optical path;

a mask having at least one aperture, the mask and the aperture being located in the optical path, wherein the laser beam has a wavefront cross-section with an area greater than the size of the aperture and is incident upon the mask and the aperture to cause the creation of a sub-beam;

a lens for forming a reduced-size image of the sub-beam onto the work piece;

a translation stage for moving the mask to change the position of the sub-beam on the work piece.

2. The laser drilling system of claim 1, wherein the lens is a microscope objective lens.

3. The laser drilling system of claim 1 wherein the laser beam has a wavelength and the system further comprises a nonlinear optical medium for harmonic generation in the optical path to decrease the wavelength of the laser beam.

4. The laser drilling system of claim 3, wherein the nonlinear optical medium for harmonic generation is a frequency doubler.

5. The laser drilling system of claim 4, further comprising at least one frequency selective mirror in the optical path between the frequency doubler and the work piece for preferentially reflecting the decreased wavelength beam relative to light at the wavelength of the laser.

6. The laser drilling system of claim 1, further comprising a shutter for controlling the propagation of the laser beam along the optical path and an attenuator for attenuating the laser beam when the shutter allows the laser beam to propagate.

7. The laser drilling system of claim 1, further comprising a scan mirror in the optical path for homogenizing the laser beam before it is applied to the mask.

8. The laser drilling system of claim 1, wherein the mask has at least two apertures for causing the creation of at least two parallel sub-beams.

9. The laser drilling system of claim 1, further comprising an imaging system for viewing the work piece.

10. The laser drilling system of claim 1, further comprising a circular polarizer for producing a circularly polarized laser beam.

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