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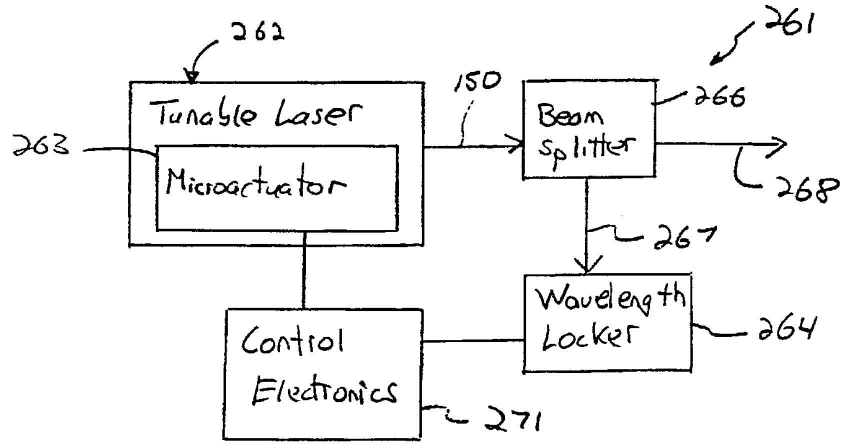
(54) Title: TUNABLE LASER WITH MICROACTUATOR



(57) Abstract: A tunable laser (501) comprising a laser source (502) for providing light along an optical path with a wavelength. A diffractive element (504) is positioned in the optical path and spaced from the laser source for redirecting the light received from the laser source. A reflective element (506) is positioned in the optical path and spaced from the diffractive element for receiving the light redirected by the diffractive element and for further redirecting the light back along the optical path to the reflective element. The diffractive element receives the light further redirected by the reflective element and returns the light along the optical path to the laser source. The optical path created by the laser source, the diffractive element and the reflective element causes the light to lase at the wavelength. A microactuator (507) is coupled to one of the diffractive element and the reflective element for moving such element to select the wavelength of the light. A rotary microactuator (507) that can be used with the tunable laser is provided.

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TUNABLE LASER WITH MICROACTUATOR

The present invention is applicable to the field of tunable lasers and is more specifically applicable to a tunable laser for use in telecommunications.

In telecommunications networks that utilize wavelength division multiplexing (WDM), widely tunable lasers enable transmission of information at different wavelengths. Many proposed network configurations require transmitters that can be tuned to transmit at any of N distinct wavelengths. Even in networks where the individual transmitter wavelengths are held fixed, tunable sources are desirable for maintaining stability of the wavelength. Also, because the same part can be used for any channel, a tunable transmitter is useful from an inventory control perspective.

One prior art tunable laser design, disclosed in U.S. Patent 5,771,252, uses an external optical cavity. As disclosed therein, a laser diode is used in combination with a diffraction grating and a rotating mirror to form an external optical cavity. The diffraction grating is fixed. As the mirror is rotated, light propagating within the optical cavity is fed back to the laser diode. The feedback causes the laser diode to "lase" with a changeable frequency that is a function of the rotation angle of the mirror. Unless accounted for, the frequency of the laser may "mode hop" due to the distinct, spatial longitudinal modes of the optical cavity. It is desirable that the longitudinal mode spectrum of the output beam of the laser diode change without discontinuities. This condition may be satisfied by careful selection of the pivot point about which the mirror is rotated, whereby both the optical cavity length and the grating feedback angle can be scanned such that the single pass optical path length of the external optical cavity is equal to the same integer number of half-wavelengths available across the tuning range of the laser cavity. If this condition is satisfied, rotation of the mirror will cause the frequency of the output beam to change without discontinuities and at a rate corresponding to the rotation of the mirror. U.S. Patent 5,319,668 also describes a tunable laser. Both U.S. Patent 5,771,252 and U.S. Patent 5,319,668 disclose an expression for an optical cavity phase error, which represents the deviation in the number of wavelengths in the cavity from the desired constant value as a function of wavelength. The expression for optical cavity phase error includes terms related to the dispersion of the laser and other optical elements. U.S. Patent 5,771,252 teaches a pivot point whereby the cavity phase error and its first and second derivatives with respect to the wavelength all go to zero at the center wavelength. For all practical purposes, the two methods describe the same pivot point.

The grating-based external cavity tunable laser (ECLs) of U.S. Patent 5,771,252 is a relatively large, expensive device that is not suitable for use as a transmitter in a large-scale WDM network. Because of the size and distance between components, assembly and alignment of the prior art ECL above is difficult to achieve. Known prior art ECLs use stepper motors for coarse positioning and piezoelectric actuators for fine positioning of wavelength selective components. Because piezoelectric actuators exhibit hysteresis, precise temperature control is needed. In addition, prior art ECL lasers are not robust in the presence of shock and vibration.

Another prior art tunable laser design utilizes a Vertical-Cavity Surface-Emitting Laser (VCSEL). In one embodiment of this device, a MEMS (micro-electro-mechanical-system) mirror device is incorporated into the structure of the VCSEL and is used to tune the wavelength of the laser. Wide tuning range has been demonstrated in such devices for operation around 830 nanometers, but so far the development of a reliable, high performance VCSEL at 1550 nanometers has proved elusive. This device is very difficult to build because the MEMS device must be physically incorporated into the structure of the VCSEL. Furthermore, development of the MEMS actuators in InP-based materials is a formidable challenge.

In other prior art, angular motors have been used in angular gyroscopes and as fine tracking servo actuators for magnetic heads for disk drives. In "Angular Micropositioner for Disk Drives," D. A. Horsley, A. Singh, A.P. Pisano, and R. Horowitz, Proceedings of the 10th Int. Workshop on Micro Electro Mechanical Systems, 1997, p. 454-458, a deep polysilicon device is described with radial flexures extending from a central fixed column, and radial, parallel plate electrodes that effect rotation of less than 0.5 degree. Batch Fabricated Area Efficient Milli-Actuators, L.-S. Fan, et. al., Proceedings 1994 Solid State Sensor and Actuator Workshop, Hilton Head, p. 38-42 shows a rotary flexural actuator with what appears to be two central flexures from central supports; the rotational range is not given but appears to be small. Dual Axis Operation of a Micromachined Rate Gyroscope, T. Juneau, A.P. Pisano, and J.H. Smith, Proceedings 1997 Int. Conf. On Solid State Sensors and Actuators, V.2, pp. 883-890 describes a polysilicon, surface micromachined gyro, which has four radial springs supporting a central circular mass. The springs are supported on the outside, and have a small strain relief feature. The angular drive range is not specified, but appears to be small. All of these prior art devices provide limited angular range. These prior art devices completely fill a circular area in a plan view, thus making it difficult or impossible to arrange such an actuator to provide a remote pivot location, as is required by ECLs.

Tunable Distributed Bragg Reflector (DBR) lasers are currently commercially available, however, these lasers have a limited tuning range. Total tuning of about 15 nanometers and continuous tuning without mode hops over about 5 nanometers range is typical.

A tunable laser based on sampled grating DBR technology is presently available. The DBR device is tunable over about 50 nanometers, but the fabrication is difficult and the control electronics are complex, requiring four different control currents.

Another prior art approach to making a tunable laser is to fabricate multiple Distributed Feedback (DFB) lasers on a single chip and couple them together with an arrayed waveguide structure. Each DFB is fabricated with a slightly different grating pitch so that each lases at a slightly different wavelength. Wavelength tuning is accomplished by activating the laser that matches the particular wavelength of interest. The main problems with this approach are cost and insertion loss. Furthermore, fabrication of multiple lasers on the same chip with different operating wavelengths may require direct e-beam writing of the gratings. Also, if one wants to cover a very wide tuning range, the number of lasers required is prohibitively large.

Additionally, the multiple laser approach is lossy because coupling N lasers together into one output waveguide results in an efficiency proportional to 1/N.

What is needed, therefore, is a tunable laser that provides advantages over the prior art.

FIG. 1 shows a schematic plan view, partially cut away, of a tunable laser with microactuator of the present invention.

FIG. 2 shows a schematic plan view of another embodiment of a tunable laser with microactuator of the present invention.

FIG. 3 shows a schematic plan view of a further embodiment of a tunable laser with microactuator of the present invention.

FIG. 4 shows a schematic plan view of yet another embodiment of a tunable laser with microactuator of the present invention.

FIG. 5 shows a schematic plan view of yet a further embodiment of a tunable laser with microactuator of the present invention.

FIG. 6 shows a schematic plan view of another embodiment of a tunable laser with microactuator of the present invention.

FIG. 7 shows a block diagram of a further embodiment of a tunable laser with microactuator of the present invention.

FIG. 8 shows a schematic plan view of another embodiment of a tunable laser with microactuator of the present invention that is similar to the tunable laser of FIG. 7.

FIG. 9 shows a block diagram of yet another embodiment of a tunable laser with microactuator of the present invention that is similar to the tunable laser of FIG. 8.

FIG. 10 shows a perspective view of a further embodiment of a tunable laser with microactuator of the present invention.

FIG. 11 shows an enlarged perspective view of a portion of the tunable laser with microactuator of FIG. 10.

FIG. 12 shows an enlarged plan view, partially cut away, of a portion of the tunable laser of FIG. 10 taken along the line 12-12 of FIG. 11.

FIG. 13 shows an enlarged side elevational view, partially cut away, of a portion of the tunable laser of FIG. 10 taken along the line 13-13 of FIG. 11.

FIG. 14 shows a block diagram of a module containing a tunable laser with microactuator of the present invention.

Referring now to FIG. 1, there is seen a preferred embodiment of a micro-electro-mechanical-system (MEMS) based widely-tunable external cavity laser (ECL) of the present invention. Advantages of the present invention over that of the prior art that will be apparent from the description provided below include: the ability to use commonly available inexpensive Fabry-Perot (FP) laser diodes; high operating frequencies; wide operating bandwidth; reduced size and mass, thermal and mechanical stability; precise alignment of optical components made simple by use of photolithographically-defined features in a silicon substrate, high production yields; and simple output frequency control schemes. Other advantages will become apparent from a reading of the following description of the present invention.

A widely-tunable laser (ECL) or tunable laser 100 of the present invention includes a laser or laser source 101, a collimating lens 102, any suitable surface relief configuration such as a diffraction element 103, a reflector 104 and a MEMS based actuator 105. The laser source 101, collimating lens 102, diffraction element or grating 103 and microactuator 105 are all carried by a mounting block, made from any suitable material such as ceramic. The reflector 104 is mounted on microactuator 105. Laser source 101 has a first or front facet 101a and a second or rear facet 101b that together define an internal cavity. The laser source 101 is a single output laser in that the outgoing laser beam exits front facet 101a of the laser source. A highly reflective coating is providing on the rear facet 101b and an anti-reflective or AR coating is provided on the front facet 101a.

In the preferred embodiment, the laser source 101 is preferably a laser diode and more preferably a Fabry-Perot laser diode and the reflector 104 is preferably a retroreflector. The reflector 104 utilizes a high reflectivity coating on its surface. In the preferred embodiment, the grating 103 is replicated in glass, which provides several advantages compared to traditional polymer gratings, including thermal stability, replication and stability using thin substrates, and the ability to be handled, diced, cleaned and otherwise processed. The diffraction grating can be provided with any suitable groove configuration, and any groove configuration disclosed herein is merely exemplary. Grating 103 preferably has an efficiency of 50%, so that 50% of the light is in the cavity of tunable laser 100 and 50% of the light goes into the first diffracted order.

In the preferred embodiment, the reflector actuator 105 is a rotary actuator and preferably a rotary electrostatic microactuator. Microactuator 105 can be constructed in the manner disclosed in U.S. Patent 5,998,906 and in International Publication No. WO 00/36740 that published on June 22, 2000, the entire contents of each of which are incorporated herein by this reference. More specifically, microactuator 105 is formed on a substrate 111. A plurality of first and second comb drive assemblies 112 and 113 are carried by substrate 111 for pivoting reflector 104 in first and second opposite angular directions about an axis of rotation extending perpendicular to planar substrate 111 and through a virtual pivot point 114. Each of the first and second comb drive assemblies 112 and 113 includes a first comb drive member or comb drive 117 mounted on substrate 111 and a second comb drive member or comb drive 118 overlying the substrate 111. First, second and third spaced-apart spring members or springs 121, 122 and 123 are included in microactuator 105 for supporting or suspending second comb drives 118 over substrate 111 and for providing radial stiffness to the movable second comb drives

118 and thus reflector 104 carried thereby.

Substrate 111 is made from any suitable material such as silicon and is preferably formed from a silicon wafer. The substrate has a thickness ranging from 200 to 600 microns and preferably approximately 400 microns. First and second comb drive assemblies 112 and 133 and suspension beams or springs 121-123 are formed atop the substrate 111 by a second or top layer 124 made from a wafer of any suitable material such as silicon and secured to the substrate 111 by any suitable means such as fusion bonding. First and second comb drive assemblies 112 and 113 and springs 121-123 are formed from top wafer 124 by any suitable means and preferably by means of deep reactive ion etching (DRIE) techniques or the Lithographie Gavanometrie and Abformung (LIGA) process, which permit such structures to have a high aspect ratio and thus enhance the out-of-plane stiffness of such structures.

Although a variety of configurations of first and second comb drive assemblies 112 and 113 can be provided, microactuator 105 is shown as having two sets 126 and 127 of first and second comb drive assemblies 112 and 113 disposed symmetrically about a centerline 128 extending radially outwardly from virtual pivot point 114. Each comb drive assembly set 126 and 127 includes one first comb drive assembly 112 and one second comb drive assembly 113 extending radially outwardly from the pivot point 114. Each of the first and second comb drive assemblies 112 and 113 has a length ranging from 300 to 3000 microns and more preferably approximately 1000 microns.

First comb drives 117 of first and second comb drive assemblies 112 and 113 are rigidly mounted to substrate 111. Each of the first comb drives 117 has a radially-extending bar 131 and a plurality of comb drive fingers 132 extending from one side of the bar in radially spaced-apart positions along the length of the bar or truss 131. The comb drive fingers 132, shown schematically in FIG. 1, can have a variety of shapes and configurations including the exemplary configurations shown in U.S. Patent 5,998,906 and in International Publication No. WO 00/36740. In the illustrated embodiment of microactuator 105, each comb drive finger 132 is joined substantially perpendicularly to the bar 131 and extends from the bar substantially along an arc that preferably has a center at virtual pivot point 114.

Second comb drives 118 of the first and second comb drive assemblies 112 and 113 are spaced above substrate 111 by an air gap so as to be movable relative to the substrate and first comb drives 117. The second comb drives 118 have a construction similar to the first comb drives 117 and, more specifically, are each made with a bar 136 that extends radially outwardly the from axis of rotation of microactuator 105 at virtual pivot point 114. A plurality of comb drive fingers 137 substantially similar to comb drive fingers 132 extend from one side of the bar in radially spaced-apart positions towards the corresponding first comb drive 117. The arcuate comb fingers 137 are offset relative to stationary comb fingers 132 so that the comb fingers 137 of the second comb drive 118 can interdigitate with the comb fingers 132 of the respective first comb drive 117 when the second comb drive 118 is pivoted or rotated about axis 114 towards the stationary first comb drive 117. The second comb drives 118 in each set 126 and 127 of comb drive assemblies in microactuator 105 are back to back and thus share a common bar or truss 136.

Means including springs 121-123 are included within rotary electrostatic microactuator for movably supporting second comb drives 118 over substrate 111. First and second or outer springs 121 and 122 and third or central spring 123, which extends along radial centerline 128 of microactuator 105, each have a length approximating the length of first and second comb drive assemblies 112 and 113. Each of the springs 121-123, shown schematically in FIG. 1, has a first end portion 141 joined to substrate 111 by means of an anchor 142 and a second end portion 143 secured to an arcuate suspension member or shuttle 144 extending along the outer radial extremity of microactuator 105 between first and second springs 121 and 122. The outer radial extremities of second comb drive bars 136 are joined to rigid shuttle 144 and in this manner supported above substrate 111 by means of springs 121-123.

Rotary microactuator 105 has a radial dimension ranging from 500 to 5000 microns and more preferably approximately 2500 microns and has an angular dimension relative to pivot point 114 which can range from 20 to 120 degrees and preferably approximately 45 degrees. Microactuator 105 is spaced from pivot point a distance ranging from 500 to 5000 microns and preferably approximately 2000 microns. Rotary microactuator 105 resembles a truncated or foreshortened sector of a circle that is spaced radially outwardly from virtual pivot point 114. The microactuator can also be described as having the shape of a truncated fan.

Second comb drives 118 of first and second comb drive assemblies 112 and 113 are movable in an angular direction of travel about virtual pivot point 114 by means of flexible springs 121-123. The second comb drives 118, shown in an intermediate or rest position in FIG. 1, are movable in a first or counterclockwise position so that first and second comb drives 117 and 118 of the first comb drive assemblies 112 move toward each other so as to cause the respective movable comb fingers 137 to substantially fully interdigitate with the respective stationary comb fingers 132. The second comb drives 118 are also movable in a second or clockwise direction from their intermediate position of FIG. 1 so that the first and second comb drives 117 and 118 of the second comb drive assemblies 113 move toward each other so as to cause the respective movable comb fingers 137 to fully interdigitate with the respective stationary comb fingers 132. Each of the first and second comb drive assemblies 112 and 113 can thus be moved between a first position, in which comb fingers 132 and 137 are not substantially fully interdigitated, through an intermediate position to a second position, in which the comb fingers 132 and 137 are substantially fully interdigitated. When the first and second comb drives 117 and 118 of a comb drive assembly 112 or 113 are in their fully spaced-apart positions, respective comb fingers 132 and 137 can be fully disengaged or partially interdigitated and be within the scope of the present invention.

Reflector 104 is secured to the movable structure 145 of microactuator 105, that is springs 121-123, second comb drives 118 and shuttle 144, and is preferably secured to the top of shuttle 144 and one or more of second comb drives 118 by any suitable means such as an adhesive. Reflector 104 can thus be moved by microactuator 105 in a counterclockwise direction about virtual pivot point 114 from its intermediate position shown in FIG. 1 to a position farther away from diffraction grating 103 when first comb drive assemblies 112 are substantially fully interdigitated and second comb drive assemblies 113 are not substantially fully interdigitated. Alternatively, the reflector can be moved about virtual pivot point 114 by the microactuator in a clockwise direction towards diffraction grating 103 when first comb drive assemblies 112 are not substantially fully interdigitated and second comb drive assemblies 113 are substantially fully interdigitated.

A controller and power source, not shown in FIG. 1, is provided for supplying a suitable control signal, such as a drive voltage, to microactuator 105 for rotating reflector 104 about virtual pivot point 114 when it is desired to adjust the wavelength of output beam 150 of tunable laser 100 or otherwise move the reflector 104 relative to the substrate 111. Movable structure 145 is electrically coupled to the controller by means of anchors 142, which further serve as bond pads. Bar 131 of each first comb drive 117 is joined at its inner radial extremity to a bond pad 146 which can be electrically coupled to the controller. Suitable electrical signals can be provided by the controller to movable structure 145 and first comb drives 117 for selectively moving reflector 104 relative to diffraction grating 103.

Means in the form of a closed loop servo control can be included in tunable laser 100 for monitoring and maintaining the position of second comb drives 118 and thus reflector 104. For example, the controller can determine the position of the movable comb drives 118 by means of a conventional algorithm included in the controller or related control electronics for measuring the capacitance between comb drive fingers 137 of the movable comb drives 118 and comb drive fingers 132 of the stationary comb drives 117. A signal separate from the drive signal to the comb drive members can be transmitted by the controller to the microactuator for measuring such capacitance. Such a method does not require physical contact between the comb drive fingers. The wavelength of output beam 150 can be calibrated to the capacitance of the microactuator 105, and thus the wavelength of output beam 150 can be fixed over time with such capacitance sensing. This method of servo control can be implemented at low cost and does not require extra optical components. Because the capacitance of the microactuator 105 and performance of the capacitance-sensing electronics are temperature dependent, a thermal electric cooler (TEC) may be needed to stabilize the temperature of the tunable laser.

In the present invention, output beam 150 of tunable laser 100 preferably has a beam diameter of 0.25 millimeters. Light from the laser source 101 is directed through the lens 102 towards the grating 103, by the grating 103 towards the reflector 104, by the reflector 104 back towards the grating 103, and by the grating 103 back towards the laser source 101. The optical path traversed by the laser light between the front facet 101a of laser source 101 and the reflector 104 forms an external cavity, which causes an output beam 150 of the laser source 101 to lase at a particular wavelength that is a function of the rotation angle of the reflector 104. As can thus be seen, movement of reflector 104 by microactuator 105 determines the wavelength of the output beam 150 of the tunable laser. In the exemplary embodiment, the tunable laser 100 can be tuned over +/- 26 nanometers with +/- two degrees of motion of the actuator or microactuator 105. Single-mode operation occurs when the spacing of the external cavity modes are greater than the line width of the grating 103. The line width of the grating 103 is determined by the angle of incidence and by the beam size. In an exemplary embodiment, the grating 103 line width is about 21 GHz and the external cavity modes are spaced by about 30 GHz. The ultimate line width is determined by the external cavity mode spacing and by the quality of the external cavity. In the exemplary embodiment, with high reflectivity coatings on the reflector 104 and on the rear facet of the laser source 101, the line width is less than 1 Mhz.

For optimum performance of the tunable laser 100, it is desired that the wavelength of the output beam 150 be continuously tunable, that is no mode hops occur as the laser source 101 is tuned over a range of wavelengths. This condition can be satisfied by selecting a virtual pivot point 114 about which the reflector 104 rotates, such that an optical path length of the cavity formed between a rear facet of the laser source 101 and the reflector 104 measured in integer number of half wavelengths remains constant over the desired tuning range.

U.S. Patent 5,319,668 and U.S. Patent 5,771,252 disclose methods for calculating a pivot point, such as virtual pivot point 114, and the entire contents of such patents are incorporated herein by this reference. The two calculations made in these two prior art patents result in pivot point locations that differ in position by only 40 nanometers. The calculations used in both of these patents are applicable to the present invention because the component and manufacturing tolerances of the present invention are greater than 40 nanometers. In fact, adequate performance of the present invention may be obtained by choosing a pivot point such that the cavity phase error and only the first derivative of the error go to zero at the center wavelength. This condition gives an acceptably accurate location for the pivot point. The virtual pivot point 114 of the present invention allows for a compact geometry and results in a lower-cost device with better optical performance than if a real pivot point, that is a pivot point through which the structure of the microactuator 105 extends, is used. Better optical performance is achieved because the compact geometry results in greater spacing of the external optical cavity modes and greater side-mode suppression.

In an exemplary embodiment, the optical path length of the external cavity, that is the aggregate optical path length between the rear facet of the laser source 101, the grating 103 and the front of the reflector 104, is approximately five millimeters; and the center wavelength, grating pitch, angle of incidence, and diffraction angle of the grating 103 are 1540 nanometers, 1000 lines per millimeter, 85 degrees, and 33 degrees, respectively. Although the overall tuning range of the tunable laser 100 is a function of the width of the gain curve of the laser source 101, which in the preferred embodiment of the present invention can be tuned over a range on the order of 40 nanometers, it is understood that a much broader gain profile may be achievable using, for example, a Fabry-Perot strongly-pumped quantum-well laser design, referenced in *Electronics Letters*, Vol. 26, No. 11, pp. 742-743, "External Grating Laser With Wide Tuning Range of 240nm," by Epler *et* *al.*

Tunable laser 100 can be used in a telecommunications system, for example a fiber optic telecommunications system, to select a transmission wavelength and transmit information over that wavelength. The output beam 150 of the tunable laser 100 can be modulated directly to carry such information by varying the laser source 101 current in accordance with the data stream to be transferred. External modulation of the output beam 150 can also be utilized for transmitting the information.

Referring now to FIG. 2, there is disclosed an alternative embodiment of the tunable laser of the present invention. As illustrated in FIG. 2, it is envisioned that the present invention could be implemented in an alternative embodiment in which a external cavity tunable laser 160 is provided. Tunable laser 160 has similarities to tunable laser 100 and like reference numerals have been used to describe like components of tunable lasers 160 and 100. The tunable laser 160 has a MEMS microactuator 161 to pivot diffraction grating 103. Although diffractive element 103 is shown in FIG. 2 as having certain shaped grooves thereon, it should be appreciated that any suitable diffractive element can be utilized and that any grooves utilized on such a diffractive element can be of any suitable shape. Microactuator 161 is preferably a rotary microactuator, such as a rotary electrostatic microactuator, and more preferably a rotary electrostatic microactuator such as microactuator 105. Alternatively, microactuator 161 can be of the type disclosed in International Publication No. WO 00/36740. Grating 103 is mounted atop the movable structure of microactuator 161 in the manner discussed above with respect to tunable laser 100.

Tunable laser 160 shown in FIG. 2 further includes a laser source in the form of laser source 162, which is preferably a laser diode and more preferably a Fabry-Perot laser diode having opposite front and rear facets 162a and 162b. The laser source 162 is a dual output laser source in that an outgoing beam is provided at both the front and rear facets 162a and 162b. A first collimating lens 163 focuses the laser light from one end of laser source 101 onto grating 103 and a second collimating lens 164 focuses the outgoing laser beam 150. In tunable laser 160, because the grating 103 provides the reflective function of the reflector 104 of tunable laser 100, a reflector need not be used in tunable laser 160 and the optical cavity length can be reduced from the optical cavity length of tunable laser 100 shown in FIG. 1. It is easier to modulate a tunable laser at very high frequencies when a shorter external optical cavity length is utilized and therefore it is desirable to keep such external optical cavity length as short as possible. However, it may be more difficult to achieve single-mode operation of tunable laser 160, in comparison to tunable laser 100, because the there is only a single-pass reflection of the output beam 150 from the grating 103 in tunable laser 160.

It should be appreciated that any of the tunable lasers disclosed herein can use a laser source having an electroabsorptive modulator for achieving high data transfer rates and be within the scope of the present invention. At high data rates a decrease in laser modulation response can occur. In this regard, a lifetime of a photon for a laser source, such as laser source 101 of tunable laser 100, is given by $1/(c\cdot\alpha)$, where c is the speed of light and α is the total loss of the photon distributed over the equivalent free-space cavity. In a solitary laser, a photon spends all its time in a highly absorbing medium so that the photon lifetime is short. In tunable laser 100, a photon spends a large fraction of time in loss-less free space so the lifetime of the proton is proportionally longer. When modulating tunable laser 100 at high frequency, it is desirable that the photons disappear when the current is turned off, which does not happen quickly when the lifetime of the photon is long.

An exemplary embodiment of a tunable laser utilizing an electroabsorptive modulator is shown in FIG. 3 where a tunable laser 181 similar to tunable laser 100 is disclosed. Like reference numerals have been used to describe like components of tunable lasers 181 and 100. Reflector 104 in tunable laser 181 is pivoted about a virtual pivot point 114 in the same manner as in tunable laser 100. In the schematic drawing of FIG. 3, the microactuator for moving reflector 104 has not been shown for simplicity. It should be appreciated, however, that a suitable MEMS-based microactuator such as an electrostatic microactuator like microactuator 105 is included in tunable laser 181 for moving reflector 104 in the manner discussed herein.

Where a short photon lifetime is desired, an electroabsorptive modulator 182 can be positioned in the external optical cavity, preferably adjacent the front facet of the laser source of tunable laser 181. An advantage with this approach is that modulator 182 can be fabricated on the same chip as the laser source. In one preferred embodiment, shown in FIG. 3, a laser source 183 substantially similar to laser source 101 is provided, except that a modulator 182 is formed forwardly of the laser source 183 from the same chip 184 as the laser source 183. Chip 184 has a front facet 184a, which is the front facet of modulator 182, having an antireflective coating thereon, and a rear facet 184b, which is the rear facet of laser source 183, having a highly reflective coating thereon. The electroabsorptive or EA modulator 182 absorbs photons at a speed corresponding to its modulation frequency. In the exemplary embodiment of FIG. 3, EA modulator 182 is used to modulate output beam 150 at up to 10 gigabits/sec.

Referring now to FIG. 4, a tunable laser 201 is shown that has similarities to the tunable lasers discussed above. Like reference numerals have been used to describe like components of tunable lasers 201, 100, 160 and 181. Tunable laser 181 includes a reflector 202 that is pivotable about virtual pivot point 114 in the same manner as reflector 104 by a microactuator that is preferably an electrostatic microactuator and more preferably a rotary electrostatic microactuator like electrostatic microactuator 105. The microactuator of tunable laser 201 is not shown in FIG. 4 for simplicity. The reflector of tunable laser 201 has a first or front reflective surface 202a and an optional second or rear reflective surface 202b.

The tunable laser 181 includes wavelength monitoring means such as a secondary optical system for determining the position of reflector 202 and thus the wavelength of output beam 150. In this regard, an optional monitor laser source 206, which can be a laser diode of any suitable type such as laser source 101, and an optional additional focusing lens 207 for focusing the reference laser beam 208 from source 206 onto the rear reflective surface 202. An optional optical sensing device of any suitable type such as a position sensing device or PSD 209 is included for receiving the reflected beam from monitoring laser source 206.

Optical sensor or PSD 209 is calibrated with respect to grating 103 and reflector 202 so that the location on the PSD contacted by beam 208 determines the angle of the beam 208 relative to the reflector 202. The electrical signal from the PSD is used in a servo loop with a controller and power supply (not shown) to set the drive signal applied to microactuator 105. Reflector 202 can thus be properly positioned with respect to substrate 111 and diffraction grating 103. An advantage of this embodiment is that the wavelength of the reference beam 208 can be matched to the sensitivity of the commercially available PSD.

Referring now to FIG. 5, there is shown a further embodiment of the tunable laser of the present invention having an optional position sensing device or PSD for monitoring the wavelength of output beam 150. Tunable laser 221 of FIG. 5 has similarities to the tunable lasers disclosed above and like reference numerals have been used to describe like components of tunable lasers 221, 100, 110, 181 and 201. Reflector 104 of tunable laser 241 is pivotable about virtual pivot point 114 in the same manner as in tunable laser 100 by a microactuator that is preferably an electrostatic microactuator and more preferably a rotary electrostatic microactuator like electrostatic microactuator 105. The microactuator of tunable laser 221 is not shown in FIG. 5 for simplicity. Tunable laser 221 has as PSD 209 for receiving at least a portion of the light from laser source 101 to monitor the wavelength of light beam 150. The first order diffracted beam of tunable laser 221 is reflected from a suitable diffractive element such as diffraction grating 222 after reflection by the mirror 104 and is measured by PSD 209 to determine the wavelength of the output beam 150. The signal from the PSD is used in a servo loop with a controller and power supply (not shown) to set the drive signal applied to the microactuator of tunable laser 221.

Referring now to FIG. 6, there is shown another embodiment of the tunable laser of the present invention having an optional position sensing device or PSD for monitoring the wavelength of output beam 150. Tunable laser 241 of FIG. 6 has similarities to the tunable lasers disclosed above and like reference numerals have been used to describe like components of tunable lasers 241, 100, 160, 181, 201 and 221. Reflector 104 of tunable laser 241 is pivotable about virtual pivot point 114 in the same manner as in tunable laser 100 by a microactuator that is preferably an electrostatic microactuator and more preferably a rotary electrostatic microactuator like electrostatic microactuator 105. The microactuator of tunable laser 241 is not shown in FIG. 5 for simplicity. Either the first order beam 242 or the second order beam 243 can be directed to PSD 209 to measure the angle of reflector 104 and thus determine the wavelength of output beam 150. Diffraction grating 222 of laser 241 has grooves with a sufficient width such that both first and second order diffracted output beams are produced from the beam provided by laser source 101. The electrical signal from the PSD 209 is used in a servo loop with a controller and power supply (not shown) to set the drive signal applied to the microactuator of tunable laser 241 when a change in the wavelength of output beam 150 is required or an adjustment in the position of reflector 104 is otherwise needed. It should be appreciated that in tunable lasers 201, 221 and 241, the electrical signal provided by the PSD can in addition be used for servo control of the power of the laser source 101.

As discussed above with respect to tunable laser 100, a capacitance measurement of the microactuator can be used as an indication of the position of the attached reflector or microreflector and thus the wavelength of output beam 150. Such a capacitance measurement technique can be used with any of the tunable lasers of the present invention and can be used in addition to or alternatively of the measurement techniques disclosed with respect to tunable lasers 201, 221 and 241.

In yet another wavelength monitoring technique of the present invention, the wavelength of output beam 150 can be measured as a function of the capacitance behavior of the microactuator of the tunable laser at a number of different temperatures. A thermistor or other temperature sensor can be used to measure any suitable temperature of the tunable laser, such as the ambient temperature within the package or module containing the tunable laser. This temperature can be used, along with the desired wavelength of output beam 150, to determine the voltage or other control signal to the microactuator controlling the reflective element for servo control. For example, the drive signal for the microactuator controlling the reflector can be determined from a look-up table containing such signal as a function of the temperature of the tunable laser and the wavelength of the output beam 150. In an exemplary embodiment, a stability of better than one part in one thousand is achievable with capacitance sensing.

Referring now to FIG. 7, another embodiment of the wavelength monitoring means of the present invention is disclosed. The apparatus or system 261 disclosed in FIG. 7 includes a tunable laser 262, that can be any of the tunable lasers disclosed above for providing a tunable output beam 150, and an optional wavelength measuring device or locker that can be external of the tunable laser 262. The tunable laser has a suitable microactuator 263, such as any of the type disclosed above. At least a portion of the output beam is directed through an optional optical sensor or wavelength locker 264. In this regard, a beam splitter 266 is provided for diverting a portion 267 of the output beam to the wavelength locker. The remaining portion 268 of the beam 150 emerges from the beam splitter as a reduced intensity output beam. The wavelength locker is used to measure any deviation in the wavelength of tunable laser 262 from the desired wavelength. An error signal is supplied by the wavelength locker if any such deviation in wavelength is detected. The error signal may be used in a servo loop to set the voltage or other drive signal applied to microactuator 263. More specifically, the error signal is directed to a controller and supply, referred to in FIG. 7 as control electronics 271, that is electrically coupled to the microactuator 263. A full discussion of wavelength locking techniques is set forth in the article "Wavelength Lockers Keep Lasers in Line", Photonics Spectra, February 1999, pp. 104-110 by Ed Miskovic. It should be appreciated that similar techniques can be used to stabilize or measure the wavelength of output beam 150. System 261 can be used in addition to or as an alternative to the wavelength monitoring techniques discussed above with respect to tunable lasers 201, 221 and 241.

In one exemplary operation of system 261 having both coarse and fine servo control of the wavelength of output beam 150, capacitive sensing of the reflector microactuator can be used by the control electronics 271, for example with a look-up table, to determine the coarse position of the microactuator as a function of the desired wavelength of output beam 150 and optionally the temperature of tunable laser 262. A wavelength locker, or other wavelength monitoring device, can thereafter be used by the control electronics 271, for example with another look-up table, to determine the fine position of the microactuator as a function of the error signal provided by the wavelength locker and optionally the temperature of the tunable laser 262.

A further embodiment of the wavelength monitoring means of the present invention is disclosed in FIG. 8, where a tunable laser 276 having similarities to tunable lasers 100 and 160 is shown with an internal optical sensor or wavelength locker 277. Like reference numerals have been used in FIG. 8 to describe like components of tunable lasers 276, 100 and 160. A reference beam 278 substantially identical to output beam 150 is directed from rear facet 162b of laser source 162 to wavelength locker 277, which is shown as being located internal of tunable laser 276. An additional collimating lens 279 is disposed between rear facet 162b of the laser source 162 and the wavelength locker 277 for focusing the laser light beam 278 from light source 162 onto the wavelength locker. In the manner discussed above with respect to tunable laser 261, wavelength locker 277 supplies an electrical signal corresponding to any deviation in the wavelength of reference beam 278 from the desired wavelength of output beam 150 to the controller providing the drive signal to microactuator 105. Reflector 104 is then moved to correct the deviation in wavelength of output beam 150. It should be appreciated that wavelength locker 277 can be external of the tunable laser 276 and be within the scope of the present invention. In addition, any of tunable lasers disclosed herein can be used with a dual output laser source 162 for monitoring and adjusting the wavelength of output beam 150 in the manner disclosed in FIG. 8.

Referring now to FIG. 9, an apparatus and system 286 similar to the system 261 shown in FIG. 7 and described above is illustrated. Like reference numerals have been used to describe like components of systems 286 and 261. System 286 includes a plurality of N tunable lasers 262. Only the first switch 262 and the last switch 262^N are shown in FIG. 9 for simplicity. A portion of the output beam 150 from each tunable laser 262 is directed by a beam splitter 268 to a 1xN switch 287. System 286 is particularly suited where the wavelength of the output beam 150 of each tunable laser 262 needs to be checked for stability only intermittently. Switch 287 is utilized to sequentially or otherwise selectively direct the diverted beam portion or monitor signal 267 from each of the tunable lasers 262 to a single wavelength calibrator/locker 264 to measure any deviation in the wavelength of output beam 150 from the desired wavelength. In the manner discussed above with respect to system 261, the error signal provided by wavelength locker 264 for the selected tunable laser 262 is used in a servo loop to set the voltage or other drive signal applied to microactuator 263 of the tunable laser 262. System 286 permits a single wavelength locker to be shared by the N tunable lasers 262 of system 286. Elimination of N-1 wavelength calibrators/lockers 264 represents a significant cost saving.

A further embodiment of the tunable laser of the present invention is disclosed in FIGS. 10-13. Tuneable laser 501 includes a laser source 502 for producing an output beam 150. A collimating lens 503 is disposed adjacent laser source 502 and directs beam 150 onto a suitable diffractive element such as diffraction grating 504. A portion of beam 150 is directed by diffraction grating 504 onto a suitable reflective element such as reflector 506, which is pivotably mounted on a first microactuator 507. As shown most clearly in FIGS. 10 and 11, beam 150 comprises a first beam portion 150a extending between laser source 502 and collimating lens 503, a second beam portion extending between collimating lens 503 and diffraction grating 504, a third beam portion 150c extending between the diffraction grating 504 and the reflector

506 and a fourth beam portion 150d directed outwardly from tunable laser 501 by the diffraction grating 504. Third beam portion 150c consists of the diffracted portion of second beam 150b that, due to low incidence angle at which second beam portion contacts diffraction grating 504, is relatively wide as it is directed towards reflector 506. Third beam portion 150c is redirected back from the reflector 506 at a right angle to the reflector. Collimating lens 503 is coupled to a second microactuator 508 which is capable of moving the collimating lens in a direction perpendicular to first and second beam portions 150a and 150b.

The components of tunable laser 501 are carried by a mounting block 511. The laser source 502 is secured to one end of a laser submount block 512 which, in turn, is secured to the top of a laser spacer block 513 attached to one corner of mounting block 511. The second microactuator 508 is secured to the mounting block 511 by means of a lens submount 514, that is attached to the block 511 next to the laser spacer block 513 and at one end of the mounting block 511. The collimating lens 503 is secured to microactuator 508 by a lens substrate 515. A mirror actuator submount block 516 is secured to the central portion of the mounting block 511 next to the laser spacer block 513. The first microactuator 507 is adhered to the top of one end of lens actuator submount 516. The diffraction grating 504 extends alongside lens actuator submount 516 and is secured directly to mounting block 511. The mounting block 511, the laser submount 512, the laser spacer block 513, the lens submount 514 and the lens actuator submount 516 are each made from any suitable material such as ceramic. As shown, tunable laser 501 has a length ranging from five to 25 millimeters and preferably approximately 12 millimeters, a width ranging from four to 15 millimeters and preferably approximately seven millimeters and a height ranging from three to ten millimeters and preferably approximately six millimeters.

Laser source 502 can be of any suitable type and is preferably a laser diode and more preferably a Fabry-Perot laser diode substantially similar to laser source 101 discussed above. Control signals are provided to laser source 502 by means of electrical leads (not shown) which connect to a plurality of electrical pads 517 provided on the top of laser spacer block 513. Suitable leads from a laser driver 518, not shown in FIG. 10 but shown in FIG. 14, are electrically secured to laser lead pads 517 for providing electrical control signals to the laser source 502.

Diffraction grating 504 can be of any suitable type, and, as shown, includes a block 521 having a front face 522 facing reflector 506. Face or surface 522 is ruled with a plurality of grooves (not shown) which can be of any suitable size and shape for diffracting second beam portion 150b. Grating 504 preferably has diffractive characteristics similar to diffraction grating 103.

First microactuator or motor 507 is preferably a MEMS based microactuator of any suitable type and more preferably an electrostatic microactuator. A rotary electrostatic microactuator is particularly preferred and such an electrostatic microactuator can be constructed in the manner disclosed in U.S. Patent 5,998,906 and in International Publication No. WO 00/36740. The details of rotary electrostatic microactuator 507 are not shown in FIGS. 10 and 11. One preferred embodiment of rotary electrostatic microactuator is, however, shown in FIG. 12. In general, microactuator 507 is formed from a substrate 526 that extends substantially in a plane and is substantially similar to substrate 111 of tunable laser 100. A plurality of first and second comb drive assemblies 527 and 528 are carried by substantially planar substrate 526 and are arranged on the substrate in first and second sets 531 and 532. Each of the first and second comb drive assemblies includes a first comb drive member or comb drive 533 mounted on substrate 526 and a second comb drive member or comb drive 534 overlying the substrate 526. At least first and second spaced-apart suspension members or spring member are included in microactuator 507 for supporting or suspending second comb drives 534 over the substrate 526 and for providing radial stiffness to the movable second comb drives 534. As shown, first and second outer suspension members or springs 536 and 537 and a central suspension member or spring 538 are provided. Second comb drives 534 are part of a movable structure 539 overlying the substrate 526.

The substrate 526 is preferably formed from a silicon wafer having a thickness ranging from 400 to 600 microns and preferably approximately 400 microns. First and second comb drive assemblies 527 and 528, springs 536-537 and movable structure 539 are formed atop the substrate 526 by a second or top layer 542 made from a wafer of any suitable material such as silicon. Top layer or wafer 542 has a thickness ranging from 10 to 200 microns and preferably approximately 85 microns and is preferably fusion bonded to the substrate 526 by means of a silicon dioxide layer (not shown). The components of microactuator 507 are preferably etched from wafer 542 by deep reactive ion etching (DRIE) techniques or the Lithographie Gavanometrie and Abformung (LIGA) process for the reasons discussed above with respect to tunable laser 100. Springs 536-538 and movable structure 539 are spaced above the substrate 526 by an air gap (not shown), that ranges from 3 to 30 microns and preferably approximately 15 microns so as to be electrically isolated from the substrate 526.

First and second sets 531 and 532 of comb drive assemblies are symmetrically disposed about a radial centerline 543 of microactuator 507 and each include a first comb drive assembly 527 and a second comb drive assembly 528. Second comb drive assembly 528 of the first set 531 is disposed adjacent centerline 543 and first second comb drive assembly 527 of the second set 532 is disposed adjacent the centerline 543. A first comb drive assembly 527 is spaced farthest from centerline 543 in the first set 531 and a second comb drive assembly 528 is spaced farthest from the centerline in the second set 532. Each of the comb drive assemblies 527 and 528 is centered along a radial line which intersects radial centerline 543 at the virtual pivot point (not shown) of microactuator 507. Each of the first and second comb drive assemblies 527 and 528 has a length ranging from 300 to 3000 microns and preferably approximately 1300 microns, and commences a radial distance from the pivot point of microactuator 507 ranging from 500 to 5000 microns and preferably approximately 2000 microns.

First comb drive 533 of each of first and second comb drive assemblies 527 and 528 is immovably secured to substrate 526. Each comb drive 533 has a radially-extending bar or truss 546 provided with a first or inner radial portion 546a and a second or outer radial portion 546b. A plurality of comb drive fingers 547 extend from one side of bar 546 in radially spaced-apart positions along the length of the bar. Comb drive fingers or comb fingers 547 can be of any suitable shape and are preferably approximately arcuate in shape. Comb fingers 547 extend perpendicularly from bar 546 and thereafter substantially arc along a radius that preferably commences at the axis of rotation or virtual pivot point of microactuator 507. In a preferred embodiment, piecewise linear segments are used to form the comb fingers 547 for approximating such an arcuate shape.

Second comb drives 534 are spaced above substrate 526 so as to be movable relative to the substrate and first comb drives 533. The second comb drives 534 have a construction similar to first comb drives 533 and, more specifically, are formed with a radially-extending bar or truss 551 having a first or inner radial portion 551a and a second or outer radial portion 551b. A plurality of comb drive fingers or comb fingers 552 extend from one side of bar 551 in radially spaced-apart positions along the length of the bar 551. Comb fingers 552 are substantially similar in construction and size to comb fingers 547 of the related comb drive assembly 527 or 528. Movable comb fingers 552 of each second comb drive 534 are offset relative to the respective stationary comb fingers 547 so that comb fingers 552 can interdigitate with comb fingers 547 when the second comb drive 534 is pivoted about the virtual pivot point or pivot point of microactuator 507 towards the respective first comb drive 533.

The inner radial portions 551a of the two second comb drive bars 551a in each of the first and second sets 531 and 532 of comb drive assemblies are rigidly interconnected by a connector bar or beam 553 that extends radially inside the respective first comb drives 533 of such set 531 or 532. The outer radial portions 551b of second comb drive assembly 528 in first set 531 and of first comb drive assembly 527 in second set 532 are rigidly interconnected so that the second comb drives 534 in microactuator 507 move in unison about the pivot point of such microactuator. Movable structure 539 includes second comb drives 534 and first and second connector beams 553 and has a thickness ranging from 15 to 200 microns and preferably approximately 85 microns.

Means including spaced-apart first and second outer springs 536 and 537 and optional central spring 538 are included within rotary electrostatic microactuator 507 for movably supporting second comb drives 534 and the remainder of movable structure 539 over substrate 526. First and second outer springs 536 and 537 are symmetrically disposed about radial centerline 543 and central spring 538 extends between first and second sets 531 and 532 of comb drive assemblies. Each of the springs 536-538, when in its rest position as shown in FIG. 12, is centered on a radial line extending through the virtual pivot point of microactuator 507. Central spring 538 extends along radial centerline 543. The springs are spaced approximately 20 to 30 degrees apart about the virtual pivot point of microactuator 507.

Each of the springs 536-538 is formed from a single beam-like spring member 556 having a first or inner radial end portion 556a and a second or outer radial end portion 556b. The inner radial end portion 556a of the spring member 556 is secured to substrate 526 at an anchor 557. The balance of the spring member 556 is spaced above the substrate by an air gap. The outer radial end portion 556b of outer springs 536 and 537 is secured to the outer radial extremity of the adjacent second comb drive bar 551 and the outer radial end portion 556b of central spring 538 is secured to the outer radial extremity of the adjacent second comb drive bars 551 forming the inner boundary of each of first and second sets 531 and 532 of comb drive assemblies. Each of the spring members 556 has a length ranging from 300 to 3000 microns and preferably approximately 1000 microns and has a width ranging from one to 20 microns and preferably approximately five microns. First and second elongate sacrificial bars 558 and 559 of the type described in U.S. Patent 5,998,906 extend along each side of each spring member 556 for ensuring even etching and thus the desired rectangular cross section of the spring member 556. Sacrificial bars 558 and 559 are disposed along opposite sides of the spring member 556 and extend parallel thereto. Springs 536-538 each have a thickness similar to movable structure 539 and preferably the same as movable structure 539. Although three springs 536-538 are disclosed for microactuator 507, it should be appreciated that two such springs or greater than three such springs can be provided.

Each of the second comb drives 534 of first and second comb drive assemblies 527 and 528 is movable in a direction of travel about the pivot point of microactuator 507 between a first position in which comb fingers 547 and 552 of the comb drive assembly are not substantially fully interdigitated and a second position in which such comb fingers 547 and 552 are substantially fully interdigitated. Each of the comb drive assemblies 527 and 528 is shown in FIG. 12 in a position intermediate its first and second positions, at which second comb drive assembly 528 of the first set 531 and first comb assembly 527 of the second set 532 are not interdigitated. Although comb fingers 547 and 552 can be partially interdigitated when a second comb drive 534 is in its first position, the comb fingers can be fully disengaged and thus not interdigitated when the second comb drive is in its first position. When in their second position, movable comb fingers 552 extend between respective stationary comb fingers 547. The movable comb fingers 552 approach but preferably do not engage stationary bar 546 of the respective first comb drive 533 and, similarly, the stationary comb fingers 547 approach but preferably do not engage movable bar 551 of the respective second comb drive 534.

Electrical means is included for driving the second comb drives 534 between their first and second positions. Such electrical means includes a suitable controller and preferably a controller and voltage generator 561, not shown in FIG. 12 but shown in FIG. 14, that is electrically connected to the first and second comb drives 533 and 534 of first microactuator 507. In this regard, the outer radial end portion 546b of each first comb drive bar 546 is electrically connected by means of a lead 562 to a bond pad 563 provided on a side of microactuator 507. Movable structure 539 is electrically connected by a lead 566 to a bond pad 567 also provided on a side of substrate 526. The lead 566 extends from such bond pad 567 to inner radial portion 556a of second spring 536. The bond pads 563 and 567 are electrically coupled by suitable wires or leads to a plurality of leads 568 formed on the top surface of actuator submount 516 (see FIGS. 10 and 11). A suitable plurality of electrical leads or wires (not shown) extend from leads 568 to controller 561.

Means in the form of a closed looped servo control can be included in tunable laser 501 for monitoring the position of movable structure 539 relative to substrate 526. For example, controller 561 can include a conventional algorithm of the type discussed above with respect to microactuator 105 for measuring the capacitance between comb fingers 552 of movable comb drives 534 and comb fingers 547 of the stationary comb drives 533.

The structural components of microactuator 507, that is movable structure 539, springs 536-538 and first comb drives 533, have the shape of a truncated fan when viewed in plan (see FIG. 12). In this regard, such components resemble a truncated or foreshortened sector of a circle, that is such components do not extend to the virtual pivot point of microactuator 507 but instead are spaced radially outwardly from such virtual pivot point. As such, the virtual pivot point of microactuator 507 intersects the plane of substrate 526 at a point outside the confines of the components of such actuator and more specifically outside the confines of movable structure 536. Movable structure 539 subtends an angle about the virtual pivot point of microactuator 507 of less than 180° and preferably less than 90°. In the specific embodiment of microactuator 507 shown in FIG. 12 and discussed above, movable structure 539 subtends an angle of approximately 45 degrees about such virtual pivot point.

Movable structure 539 is movable about the virtual pivot point of microactuator 507 in opposite first and second angular directions from its at rest or intermediate position shown in FIG. 12. When movable structure 539 moves in a counterclockwise direction about such virtual pivot point, second comb drives 534 of the second comb drive assembly 528 in each of the first and second sets 531 and 532 move to their respective second positions so that comb fingers 547 and 552 of the second comb drive assemblies 528 are substantially fully interdigitated. When movable structure 531 is moved in a clockwise direction about the virtual pivot point of microactuator 507, second comb drives 534 of the first comb drive assembly 527 in each of the first and second sets 531 and 532 move to their respective second positions so that comb fingers 547 and 552 of the first comb drive assemblies 527 are substantially fully interdigitated.

Reflector 506 can be of any suitable type and is preferably formed from an elongate strip-like block 576 made from any suitable material such as silicon. A substantial planar surface or face 576 made form any suitable highly reflective material is provided on the front surface of block 576. The reflector can have a length ranging from 500 to 5000 microns and preferably approximately 2500 microns and a height ranging from 100 to 1000 microns and preferably approximately 400 microns. Reflector 506 is secured to movable structure 536 of microactuator 507 by any suitable means such as an adhesive or solder and extends perpendicularly to the microactuator. In this regard, first and second spaced-apart pads 578 are included on movable structure 539 for receiving first and second spaced-apart posts 579 that extend from the bottom of block 576 (see FIGS. 11 and 12). Springs can be used for securing the reflector 506 to the microactuator 507 in addition to or instead of posts 579. The positioning of reflector 506 on first microactuator 507 and the positioning of the first microactuator on mirror actuator submount 516 relative to diffraction grating 504 can be determined in the manner disclosed in U.S. Patent 5,319,668 and U.S. Patent 5,771,252.

Second microactuator or motor 508 for moving collimating lens 503 is preferably a MEMS based microactuator of any suitable type and more preferably an electrostatic microactuator. A linear electrostatic microactuator is particularly preferred and such an electrostatic microactuator can be constructed in the manner discussed above with respect to first microactuator 507. The details of a preferred linear electrostatic microactuator 508 for tunable laser 501 are shown in FIG. 13, where like reference numerals have been used to describe like components of microactuators 508 and 507. Microactuator 508 shown therein is formed from a planar substrate 586 substantially similar to substrate 526. A plurality of first and second comb drive assemblies 586 and 588, which are preferably linear comb drive assemblies, are carried by substrate 586 and arranged on the substrate in first and second sets 591 and 592. Each of the first and second comb drive assemblies 587 and 588 includes a first comb drive member or comb drive 593 mounted on substrate 586 and a second comb drive member or comb drive 594 overlying the substrate 586. At least first and second spaced-apart suspension members or spring members 596 and 597 are included in microactuator 508 for supporting or suspending the second comb drives 594 over the substrate 586 and for providing stiffness to the second comb drives 594.

Comb drive assembly sets 591 and 592 extend parallel to each other in symmetrical disposition relative to the longitudinal centerline 598 of microactuator 508. A single first comb drive assembly 587 and a single second comb drive assembly 588 are provided in each set 591 and 592 of comb drive assemblies. First comb drive 593 of each of first and second comb drive assemblies 587 and 588 is immovably secured to substrate 586 and has a longitudinally-extending bar or truss 601 having first and second end portions 601a and 601b. A plurality of comb drive fingers or comb fingers 602 extend from one side of bar 601 in longitudinally spaced-apart positions along the length of the bar. Comb fingers 602 can be of any type and are preferably of a type disclosed in International Application No. PCT/US00/09919 filed April 12, 2000. In general, comb fingers 602 are slightly inclined from a 90° position relative to bar 601.

Second comb drives 594 are spaced above substrate 586 so as to be movable relative to the substrate and first comb drives 593. The second comb drives 594 have a construction similar to first comb drives 593 and, more specifically, are each formed with a longitudinally-extending bar or truss 603 having first and second end portions 603a and 603b. The second comb drives 594 of each set 591 and 592 are disposed back-to-back and, as such, share a bar 603. A plurality of comb drive fingers or comb fingers 604 extend from each side of bar 603 to form the back-to-back second comb drives 594 in each set 591 and 592. The comb fingers 604 on each side of the bar 603 are longitudinally spaced-apart along the length of the bar 603. Comb fingers 604 are substantially similar in construction and size to comb fingers 602. The comb fingers 604 of each movable comb drive 594 interdigitate with the comb fingers 602 of the related stationary comb drive 593 when the movable comb drive 594 is moved in a direction substantially perpendicular to longitudinal centerline 598.

First and second springs 596 and 597 are substantially similar in construction to springs 536-538 discussed above and each include a central spring member 606 and first and second sacrificial bars 607 and 608 extending parallel to the spring member along opposite sides of the spring member. Each spring member 606 has a first end portion 606a and a second end portion 606b. The first end portion 606a is secured to substrate 586. The second end portions 606a is secured to second comb drives 594. In this regard, an elongate bar or shuttle 609 extends between the free ends of first and second springs 596 and 597 in a direction substantially perpendicular to longitudinal centerline 598. The second end portion 606a of a spring member 606 is secured to each of the opposite ends of shuttle 609. Second end portion 603b of each second comb drive bar 603 is secured to shuttle 609 between springs 596 and 597. A mounting pad 611 is formed along one side of shuttle 609 for securing collimating lens 503 to the microactuator 507. In the foregoing construction of microactuator 507, first and second sets 591 and 592 of comb drive assemblies are disposed between first and second springs 596 and 597.

The second comb drives 594 of each of first and second comb drive assemblies 587 and 588 are movable from their intermediate positions shown in FIG. 13 to a first position, in which comb fingers 602 and 604 are not substantially fully interdigitated, and to a second position, in which the comb finger 602 and 604 are substantially fully interdigitated. In this manner, the interdigitation of first comb drive assemblies 587 of each set 591 and 592 serves to move shuttle 609 in a sideways direction substantially perpendicular to longitudinal centerline 598 to a first position relative to substrate 586 and the interdigitation of second comb drive assemblies 588 of each set 591 and 592 serves to move shuttle 609 in an opposite direction to a second position relative to the substrate 586. First and second springs 596 and 597 permit such movement and provide longitudinal rigidity to shuttle 609 and second comb drives 594 so as to inhibit snap over between comb fingers

602 and 604. Bumpers 612 are provided on the first end portions 603a of second comb drives 594 and on shuttle 6094 for engaging respective stops 613 mounted formed on substrate 586 to limit the sideways movement of second comb drives 594 and shuttle 609 and thus define the first and second positions of shuttle 609.

Electrical means is included for driving second comb drives 594 and shuttle 609 between their first and second positions. Such an electrical means includes a controller that can be the same controller utilized for controlling first microactuator 507. Controller 561, not shown in FIG. 13 but shown in FIG. 14, is a suitable controller. An electrical lead or trace 616 extends from first end portion 601a of each first comb drive 593 to a bond pad 617 disposed along one side of substrate 586 for permitting electrical control signals to the first comb drives 593. An additional electrical lead or trace 618 extends from first end portion 606a of first spring 596 to a bond pad 619 disposed adjacent bond pads 617 for permitting electrical control signals to the movable second comb drives 594. Bond pads 617 and 619 are electrically coupled by suitable wires or leads (not shown) to a plurality of leads 621 formed on the top surface of lens submount 514 (see FIGS. 10 and 11). A suitable plurality of electrical leads or wires (not shown) extend from leads 621 to controller 561.

Collimating lens substrate 515 is formed from an elongate block made from any suitable material such as silicon. Substrate 515 has first and second end portions 515a and 515b. The first end portion 515a is secured to mounting pad 611 by any suitable means such as an adhesive. Collimating lens 503 is secured to the second end portion 515b of the lens substrate 515. In a preferred embodiment, lens 503 is formed from the material of substrate 515 by etching the substrate 515. Movement of shuttle 609 to one of its first and second positions causes collimating lens 503 to move sideways relative to the longitudinal centerline 598 of microactuator 507. The microactuator 507 is mounted to lens submount 514, as shown in FIGS. 10 and 11, so that the sideways movement of shuttle 609 causes collimating lens 503 to move upwardly and downwardly relative to mounting block 511.

Means in the form of a closed loop servo control can be included in tunable laser 501 for monitoring the position of second comb drives 594 and thus collimating lens 503. Although any suitable controls technique can be utilized, in one preferred embodiment a conventional algorithm of the type discussed above with respect to tunable laser 100 and first microactuator 507 is included in controller 561 for measuring the capacitance of comb finger 602 and 604 of second microactuator 508.

An exemplary module 623 for incorporating an external cavity tunable laser of the present invention is shown in FIG. 14. The module is shown with tunable laser 501 and includes package or support 624 for carrying the tunable laser, the laser driver 518 and control electronics or controller 561. The laser driver is coupled to the controller 561 and to laser source 502, while the controller is electrically coupled to first and second microactuators 507 and 508 of the tunable laser 501. A capacitance sensing and actuator drive 626 is provided and coupled to first and second microactuators 507 and 508 of tunable laser 501 and to controller 561. It should be appreciated that the capacitance sensing and actuator drive can be included in controller 561 as discussed above. An optional thermal electric cooler 627, or TE cooler, is included in module 623 where cooling of the tunable laser 501 is desired.

Output beam 150 is directed from the tunable laser to a fiber pigtail 628 mounted to support 624. A focusing or collimating lens 629 is disposed between the tunable laser and the fiber pigtail for coupling output beam into the fiber pigtail. Module 623 further includes a conventional isolator 631 disposed between the tunable laser 501 and the fiber pigtail 628 for inhibiting the reverse transmission of light into tunable laser 501. Optional beam splitter 266 and wavelength locker 264 are included in module 623, which can further include an optional power detector 632 such as a photodiode for measuring the power of output beam 150. The wavelength locker 264 and the power detector 632 are each coupled to controller 561 for providing electrical signals thereto. Module 623 is relatively compact and has a volume of 50 cubic centimeters or less.

In operation and use, tunable laser 501 can be used to supply a laser beam of distinct wavelength, for example a wavelength in the range from approximately 1520 to approximately 1560 nanometers and preferably approximately 1540 nanometers, for use in an optical system such as in a telecommunications system and preferably a fiber optic telecommunications system. The tunable laser has an external cavity defined by the optical path traveled by output beam from laser source 502 to diffraction grating 504 and then to reflector 506, and back along the same path to the laser source.

The wavelength of output beam 150 is determined by the position of reflector 506 relative to front face 522 of diffraction grating 504. More specifically, wavelength tuning of tunable laser 501 is achieved by changing the pivot angle of reflector 506 to allow a unique diffracted wavelength to couple back into laser source 502, driving the lasing action at that particular wavelength. The gain bandwidth of laser source 502, the grating dispersion, and the external cavity mode structure all superimpose to determine the actual wavelength of output beam 150. In a preferred embodiment of tunable laser 501, the gain bandwidth of laser source 502 is greater than 40 nanometers, while the external cavity mode spacing is only 0.2 nanometers. Hence a large number of external cavity modes are supported by the gain medium of laser source 502. However, the spectral pass band (FWHM) of the diffraction grating peak is only 0.17 nanometers, so that the loss curve of diffraction grating 504 supports only a single external cavity mode.

First microactuator 507 serves to move the reflector 506 relative to diffraction grating 504 for selecting the wavelength of output beam 150 within the operational wavelength range of tunable laser 501. The reflector 506 simultaneously rotates and translates relative to diffraction grating 504 as the reflector pivots about the virtual pivot point of first microactuator 507. The pivoting of movable structure 539 of first microactuator 507 about the virtual pivot point of tunable laser 501 causes reflector 506 to rotate about an axis of rotation extending through the virtual pivot point perpendicular to the plane of microactuator substrate 526 and the plane of mounting block 511. The rotation of reflector 506 about the virtual pivot points causes the reflector to simultaneously rotate relative to diffraction grating 504 and translate relative to diffraction grating 504, that is move closer to or farther away from the diffraction grating, in directions parallel to the plane of substrate 526 and the plane of mounting block 511.

In order to achieve mode-hop-free tuning of the tunable laser 501, the diffraction angle and the external cavity length change together in a way which maintains the superposition between the grating diffraction peak and the external cavity mode. This is equivalent to maintaining the same number of modes in the cavity at all wavelengths. This is also equivalent to maintaining a constant phase in the cavity at all wavelengths. The simultaneous rotation and translation of reflector 506 about the virtual pivot point of tunable laser 501 inhibits such mode hopping by providing that the external optical path traveled by output beam 150 while lasing between the laser source 502 and the reflector 506 remains equal to an integer number of half wavelengths of the selected wavelength of output beam 150 over the range of selectable wavelengths of tunable laser 501.

When it is desired to rotate movable structure 539 and thus reflector 506 in a clockwise direction about the virtual pivot point of microactuator 507, a voltage potential is supplied by controller 561 to stationary comb drives 533 of first drive assemblies 527 so as to cause comb fingers 552 of the respective movable comb drives 534 to be electrostatically attracted to comb fingers 547 of the stationary comb drives 533. Such attraction force causes comb fingers 552 to move towards and interdigitate with comb fingers 547. The amount of such interdigitation, and thus the amount movable structure 539 and reflector 506 pivot about the virtual pivot of microactuator 507, can be controlled by the amount of voltage supplied to the stationary comb drives 533 of the first comb drive assemblies 527. When it is desired to pivot movable structure 539 and reflector 506 in a counterclockwise direction about the virtual pivot axis of microactuator 507, a suitable voltage potential can be supplied to stationary comb drives 533 of second comb drive assemblies 528 so as to cause comb fingers 552 of the respective movable comb drives 534 to move towards and interdigitate with comb fingers 547 of the second comb drive assemblies 528. As can be seen, the second comb drives 534 of one of first comb drive assemblies 527 or second comb drive assemblies 528 are in their second positions when the second comb drives 534 of the other of second comb drive assemblies 528 or first comb drive assemblies 527 are in their first positions.

Suitable voltage potentials to drive comb drive assemblies 527 and 528 can range from 20 to 200 volts and preferably range from 60 to 150 volts. Microactuator 507 is capable of a +/- 1.5 degrees of pivotable rotation about the virtual pivot point of the microactuator 507, that is rotational movement of 1.5 degrees in both the clockwise and the counterclockwise directions for an aggregate pivotal movement of three degrees when drive voltages of 120 or 140 volts are utilized. The amount of a angular deflection of movable structure 539 about such virtual pivot point is dependent on the number of comb fingers 547 and 552, the electrostatic gap between the comb fingers and the length and width of springs 536-538.

Radially-extending springs 536-538 provide radial rigidity and stiffness to movable second comb drives 534 and thus inhibit snap over of the comb fingers 547 and 552 during interdigitation. The nonfolded design of springs 536-538 enhances out-of-plane stiffness, that is stiffness in microactuator 507 that is out of the plane of movable structure 539. Such out-of-plane stiffness facilitates support of the relatively large reflector 506 and inhibits misalignments between the reflector 506 and diffraction grating 504 during operation of microactuator 507.

Any of the wavelength monitoring techniques disclosed above, including techniques using wavelength lockers and/or optical sensing devices such as PSDs, can be utilized for monitoring the wavelength of output beam 150 and, if necessary, moving reflector 506 to correct any deviation between the measured wavelength and the selected or desired wavelength of the output beam. In this manner, changes in the geometrical relationship between the components of tunable laser 501, for example changes in the relative relationship of laser source 501, diffraction grating 504 and/or reflector 506 due to temperature and/or mechanical effects, may be compensated for through movement of reflector 506 so that a desired wavelength of output beam 150 is maintained.

In one exemplary method of operating first microactuator 507 to servo control the wavelength of output beam 150, capacitive sensing of the reflector microactuator 507 can be used by controller 561, for example with a look-up table, to determine the coarse position of the microactuator 507 as a function of the desired wavelength of output beam 150 and optionally the temperature of tunable laser 501. The coarse position of the microactuator 507 and reflector 506 carried thereby can also be determined using a position sensing device, such as discussed above with respect to tunable lasers 201, 221 and 241. A wavelength locker such as wavelength locker 264, or other wavelength monitoring device, can be used to intermittently or continuously monitor the wavelength of beam 150 and provide error signals to controller 561 for determining, for example with another look-up table, the fine position of the microactuator 507 as a function of the error signal and optionally the temperature of the tunable laser 501.

The power of output beam 150 can also be monitored by any suitable power detector such as a photodiode (not shown) to permit positioning of collimating lens 503 so as to maximize such optical output power. Repositioning of collimating lens 503 may be desirable should the relative relationship of certain components of tunable laser 501, such as diffraction grating 504 and reflector 506, be improper due to initial misplacement or due to the operational environment of tunable laser 501 or module 623. For example, variable temperatures, shock or vibration may result in undesirable misalignment of the diffraction grating 504 and/or the reflector 506 that can be corrected by repositioning collimating lens 503. In addition, nonperfect rotation of reflector 506 may also necessitate movement of collimating lens 503. In this regard, a power detector such as power detector 632 can be coupled to controller 561 and collimating lens 503 moved by second microactuator 508 until such measured output power is maximized. Movement techniques for collimating lens 503 can include periodic dithering of the lens 503 or periodic movements in accordance with other control schemes so that the collimating lens 503 is positioned relative to second beam portion 150b to enhance coupling of the beam 150 back into laser source 502.

In one exemplary method of operating second microactuator 508 to servo control the output power of tunable laser 501, capacitive sensing of the lens microactuator 508 can be used by controller 561, for example with a look-up table, to determine the coarse position of collimating lens 503 as a function of the desired wavelength of output beam 150 and optionally the temperature of tunable laser 501. Collimating lens 503 can thereafter be periodically or otherwise dithered and the power of output beam 150 monitored by power detector 632 so that controller 561 can determine the fine position of collimating lens 503 and thus maximize the coupling of second beam portion 150b into laser source 502.

Second microactuator 508 is operated by controller 561, in substantially the same manner discussed above with respect to first microactuator, for moving collimating lens 503. The microactuator 508 can provide +/- 30 microns of movement from the home or rest position shown in FIG. 13. Springs 596 and 597 provide sufficient longitudinal stiffness to inhibit snap over of comb fingers 602 and 604 and undesired movement of the collimating lens in a direction orthogonal to longitudinal centerline 598 of the microactuator 508.

As discussed above with respect to tunable laser 100, the output beam 150 of tunable laser 501 can be modulated by varying the current to laser source 502 and/or by means of external modulation for transmitting information in a fiber optic or other telecommunications system in which tunable laser 501 is utilized.

The tunable lasers of the present invention are advantageous for numerous reasons. Among others, they are each very small in size and mass, which enables the use of simple closed-loop methods to control the components to accurately set and hold the wavelength of the output beam 150. In contrast to the prior art, which may require novel laser structures, such as, for example, a long-wavelength vertical-cavity surface-emitting laser (VCSEL), the present invention can be implemented using an inexpensive and readily available Fabry-Perot laser diode as the laser source. Use of a Fabry-Perot laser in the present invention is further beneficial because, unlike VCSELs, a Fabry-Perot laser can operate at long operating wavelengths, for example, up to and over 1700 nanometers, and in particular 1540 nanometers, which is one wavelength currently used by telecommunications equipment.

Because the laser source and the microactuator of the tunable lasers of the present invention can be made separately, the wafer fabrication processes for their manufacture can be made simpler, which can provide high manufacturing yields.

Because the pivot or rotation angle of the rotary microactuators of the present invention, and hence the reflector mounted thereon, can be held steady under simple closed loop control, the wavelength of output beam 150 may also be held steady. Furthermore, unlike prior art tunable VCSELs, in which wavelength versus actuator voltage must be re-calibrated as the laser ages, the stable dispersive properties of the diffraction gratings of the present invention do not change with age. As a result, further calibration of the module 623 is not necessarily required after an initial calibration step. Even if in some embodiments the wavelength of the output beam 150 can not be held stable over the lifetime of the module 623, the wavelength stability of the present invention is sufficient that only intermittent re-calibration is envisioned.

Except when capacitance sensing of the type discussed above is used for servo control, in which case a thermal electric cooler may be necessary, the tunable lasers of the present invention exhibit sufficient thermal stability that a thermal electric cooler is not necessary. Such thermal electric coolers are undesirable because they are relatively unreliable and are prone to fail.

The tunable lasers of the present invention offer the additional advantages of low cost, a wide tuning range, which can be greater than 40 nanometers, a narrow linewidth, simple control circuitry, a stable operating wavelength, and a high output power.

It should be appreciated that the movable collimating lens and the servo control techniques of the present invention can be utilized in any suitable tunable laser including any of those discussed above. A suitable tunable laser for movable such a collimating lens and/or having such servo control apparatus and techniques need only include a laser source and a diffractive element such as a diffraction grating. A reflective element such as reflector 506 can optionally be included. Any suitable motor can be provided for moving such a collimating lens to enhance the operation of such a tunable laser. In addition, the microactuators of the present invention are not limited for use in tunable lasers, the telecommunications industry or optical apparatus, it being appreciated that the microactuators disclosed herein can be used in a wide range of applications in addition to those discussed herein.

A variety of laser sources can be used each of the tunable lasers disclosed and described herein. In one alternate embodiment, a Fabry-Perot laser source with as high a relaxation oscillation frequency as possible can be used for the laser source of the present invention. Such a laser source would permit the tunable lasers herein to achieve high data transfer rates. Such a laser source would preferably maximize the differential gain, maximize the internal photon density, and minimize the photon lifetime. Multiple-Quantum-Well (MQW) lasers provide these characteristics and have been demonstrated to operate with modulation bandwidths well in excess of 10 GHz. See for example *IEEE Photonics Technology Letters*, Vol. 9, No. 3, pp. 306-308, "24-GHz Modulation Bandwidth and Passive Alignment of Flip-Chip Mounted DFB Laser Diodes", by Lindgren, *et al.* With this approach, direct modulation as high as 2.5 Gb/sec are possible for any of the tunable lasers disclosed herein.

In other embodiments, any of the tunable lasers disclosed herein can be designed to operate at frequencies corresponding to multiples of longitudinal mode spacing (i.e., multiples greater than the relaxation oscillation frequency).

The present invention may comprise a tunable laser, including: a source means for providing a light along an optical path with any wavelength selected from a continuous bandwidth of wavelengths; a diffractive element positioned in the optical path and from the source by a first distance to redirect the light; a reflective element positioned in the optical path and from the diffractive element by a second distance to receive the redirected light from the diffractive element, and the reflective element positioned in the optical path and from the diffractive element by the second distance to redirect the light towards the diffractive element; the diffractive element positioned in the optical path and from the source by the first distance to re-direct the light towards the source; and a micro-actuator means for selecting the wavelength from the continuous range of wavelengths by altering the optical path of the light.

The present invention may comprise a laser assembly that includes a source for providing a light along an optical path with any wavelength from a continuous range of wavelengths; a diffractive element positioned in the optical path and from the source by a first distance to redirect the light; a reflective element positioned in the optical path and from the diffractive element by a second distance to receive the redirected light from the diffractive element, and the reflective element positioned in the optical path and from the diffractive element by the second distance to redirect the light towards the diffractive element; the diffractive element positioned in the optical path and from the source by the first distance to re-direct the light towards the source; and a micro-actuator for selecting the wavelength from the continuous range of wavelengths by altering the optical path of the light.

The present invention may also comprise a tunable laser, including: a source means for providing a light along an optical path with any wavelength selected from a continuous bandwidth of wavelengths; a diffractive element positioned in the optical path and from the source by a first distance to redirect the light; a reflective element positioned in the optical path and from the diffractive element by a second distance to receive the redirected light from the diffractive element, and the reflective element positioned in the optical path and from the diffractive element by the second distance to redirect the light towards the diffractive element; the diffractive element positioned in the optical path and from the source by the first distance to re-direct the light towards the source; and a micro-actuator means for selecting the wavelength from the continuous range of wavelengths by altering the optical path of the light.

The present invention may further include a tunable laser comprising a laser source for providing light along an optical path with a wavelength, a diffractive element positioned in the optical path and spaced from the laser source for redirecting the light received from the laser source, a reflective element positioned in the optical path and spaced from the diffractive element for receiving the light redirected by the diffractive element and for further redirecting the light back along the optical path to the reflective element, the diffractive element receiving the light further redirected by the reflective element and returning the light along the optical path to the laser source whereby the optical path created by the laser source, the diffractive element and the reflective element causes the light to lase at the wavelength, and a microactuator coupled to one of the diffractive element and the reflective element for moving such element to select the wavelength of the light.

The present invention may also include a tunable laser comprising a laser source for providing light along an optical path with a wavelength, a diffractive element positioned in the optical path and spaced from the laser source for redirecting the light received from the laser source, a reflective element positioned in the optical path and spaced from the diffractive element for receiving the light redirected by the diffractive element and for further redirecting the light back along the optical path to the reflective element, the diffractive element receiving the light further redirected by the reflective element and returning the light along the optical path to the laser source whereby the optical path created by the laser source, the diffractive element and the reflective element causes the light to lase at the wavelength, and a collimating lens disposed between the laser source and the diffractive element and a microactuator coupled to the collimating lens for moving the collimating lens to enhance the return of the light to the laser source.

The present invention may also comprise a method for providing light with any wavelength selected from a continuous range of wavelengths, including the following steps: providing the light along an optical path; providing a diffractive element in optical path to diffract the light; providing reflective element in the optical path to reflect the light; and selecting a particular wavelength of light from the continuous range of wavelengths by altering the optical path through displacement of a micro-actuator. The method may also include the step of displacing the reflective element with the micro-actuator to alter the optical path.

The present invention may include also a rotary electrostatic microactuator comprising a substrate extending substantially in a plane, a plurality of comb drive assemblies carried by the substrate, each of the comb drive assemblies having a first comb drive member mounted on the substrate and a second comb drive member, each of the first and second comb drive members being provided with arcuate comb drive fingers, first and second spaced-apart springs, each of the first and second springs having a first end portion secured to the substrate and a second end portion secured to at least one of the second comb drive members for suspending the second comb drive members over the substrate, the second comb drive members being part of a movable structure pivotable about an axis of rotation, the second comb drive member of each comb drive assembly being pivotable about the axis of rotation between a first position in which the comb drive fingers of the first and second comb drive members of said comb drive assembly are not substantially fully interdigitated and a second position in which the comb drive fingers of the first and second comb drive members of said comb drive assembly are substantially fully interdigitated, the movable structure extending radially outwardly from the axis of rotation and having a shape of a truncated sector of a circle when viewed in plan, the axis of rotation of rotation intersecting the plane of the substrate at a location spaced radially inwardly from the movable structure.

Although, the foregoing discussion has presented particular embodiments of the present invention, it is to be understood that the above description is not to be limited to only the described telecommunications application and embodiments. For example, other applications include remote sensing or spectroscopy applications. It will also be appreciated by those skilled in the art that it would be possible to modify the size, shape, appearance and methods of manufacture of various elements of the invention, or to include or exclude various elements and stay within the scope and spirit of the present invention.

What is claimed is:

1. A tunable laser comprising a laser source for providing light along an optical path with a wavelength, a diffractive element positioned in the optical path and spaced from the laser source for redirecting the light received from the laser source, a reflective element positioned in the optical path and spaced from the diffractive element for receiving the light redirected by the diffractive element and for further redirecting the light back along the optical path to the reflective element, the diffractive element receiving the light further redirected by the reflective element and returning the light along the optical path to the laser source whereby the optical path created by the laser source, the diffractive element and the reflective element causes the light to lase at the wavelength, and a microactuator coupled to one of the diffractive element and the reflective element for moving such element to select the wavelength of the light.

2. The tunable laser of Claim 1 wherein the optical path extends from the laser source to the diffractive element and then to the reflective element an optical path length and wherein the wavelength has a half wavelength and can be selected from a range of wavelengths, the microactuator moving said one of the diffractive element and the reflective element so that the optical path length equals an integer number of half wavelengths of the selected wavelength over the range of wavelengths.

3. The tunable laser of Claim 2 wherein the range of wavelengths extends from approximately 1520 nanometers to approximately 1560 nanometers.

4. The tunable laser of Claim 1 wherein the selected wavelength is 1540 nanometers.

5. The tunable laser of Claim 1 wherein the microactuator is coupled to the reflective element for moving the reflective element.

6. The tunable laser of Claim 5 wherein the microactuator is coupled to the reflective element for pivoting the reflective element about a pivot point.

7. The tunable laser of Claim 6 wherein the pivot point is spaced apart from the microactuator.

8. The tunable laser of Claim 1 wherein the microactuator includes a micromachined actuator.

9. The tunable laser of Claim 1 wherein the microactuator is an electrostatic microactuator having interdigitatable comb fingers.

10. The tunable laser of Claim 9 further comprising a controller for measuring the capacitance between the interdigitatable comb fingers and providing a drive signal to the microactuator in response to the signal.

11. The tunable laser of Claim 1 wherein the reflective element includes a retroreflector.

12. The tunable laser of Claim 1 wherein the laser source includes a Fabry-Perot laser.

13. The tunable laser of Claim 1 further comprising an optical sensor for sensing a light beam reflected from one of the diffractive element and the reflective element so as to measure the wavelength of the light and producing an error signal corresponding to any deviation between the measured wavelength and the selected wavelength and a controller electrically coupled to the optical sensor and the microactuator for receiving the error signal and providing a control signal to the microactuator in response to the error signal.

14. The tunable laser of Claim 13 wherein the optical sensor is a position sensing device.

15. The tunable laser or Claim 14 further comprising an additional laser source for supplying the light beam.

16. The tunable laser of Claim 14 wherein the light beam is supplied by the laser source.

17. The tunable laser of Claim 13 wherein the optical sensor is a wavelength locker.

18. The tunable laser of Claim 1 further comprising an optical sensor for sensing the light so as to measure the wavelength of the light and producing an error signal corresponding to any deviation between the measured wavelength and the selected wavelength and a controller electrically coupled to the optical sensor and the microactuator for receiving the error signal and providing a control signal to the microactuator in response to the error signal.

19. The tunable laser of Claim 18 wherein the optical sensor is selected from the group consisting of a position sensing device and a wavelength locker.

20. The tunable laser of Claim 1 further comprising a collimating lens disposed between the laser source and the diffractive element and an additional microactuator coupled to the collimating lens for moving the collimating lens to enhance the return of the light to the laser source.

21. The tunable laser of Claim 20 wherein the additional microactuator is an electrostatic microactuator.

22. The tunable laser of Claim 1 further comprising an electroabsorptive modulator disposed in the optical path.

23. The tunable laser of Claim 22 wherein the electroabsorptive modulator is disposed between the laser source and the diffractive element.

24. A tunable laser comprising a laser source for providing light along an optical path with a wavelength, a diffractive element positioned in the optical path and spaced from the laser source for redirecting the light received from the laser source, a reflective element positioned in the optical path and spaced from the diffractive element for receiving the light redirected by the diffractive element and for further redirecting the light back along the optical path to the reflective element, the diffractive element receiving the light further redirected by the reflective element and returning the light along the optical path to the laser source whereby the optical path created by the laser source, the diffractive element and the

reflective element causes the light to lase at the wavelength, and a collimating lens disposed between the laser source and the diffractive element and a microactuator coupled to the collimating lens for moving the collimating lens to enhance the return of the light to the laser source.

25. The tunable laser of Claim 24 wherein the microactuator is an electrostatic microactuator.

26. The tunable laser of Claim 24 further comprising a power detector for monitoring the power of the light and a controller electrically coupled to the power detector and the microactuator for providing a control signal to the microactuator for moving the collimating lens to increase the power of the light.

27. A rotary electrostatic microactuator comprising a substrate extending substantially in a plane, a plurality of comb drive assemblies carried by the substrate, each of the comb drive assemblies having a first comb drive member mounted on the substrate and a second comb drive member, each of the first and second comb drive members being provided with arcuate comb drive fingers, first and second spaced-apart springs, each of the first and second springs having a first end portion secured to the substrate and a second end portion secured to at least one of the second comb drive members for suspending the second comb drive members over the substrate, the second comb drive members being part of a movable structure pivotable about an axis of rotation, the second comb drive member of each comb drive assembly being pivotable about the axis of rotation between a first position in which the comb drive fingers of the first and second comb drive members of said comb drive assembly are not substantially fully interdigitated and a second position in which the comb drive fingers of the first and second comb drive members of said comb drive assembly are substantially fully interdigitated, the movable structure extending radially outwardly from the axis of rotation and having a shape of a truncated sector of a circle when viewed in plan, the axis of rotation of rotation intersecting the plane of the substrate at a location spaced radially inwardly from the movable structure.

28. The rotary microactuator of Claim 27 wherein the movable structure subtends an angle of 90° or less about the axis of rotation.

29. The rotary microactuator of Claim 27 wherein each of the first and second springs have inner and outer radial portions, the inner radial portions being secured to the substrate.

30. The rotary microactuator of Claim 27 wherein the arcuate comb drive fingers have a radius commencing substantially at the axis of rotation.

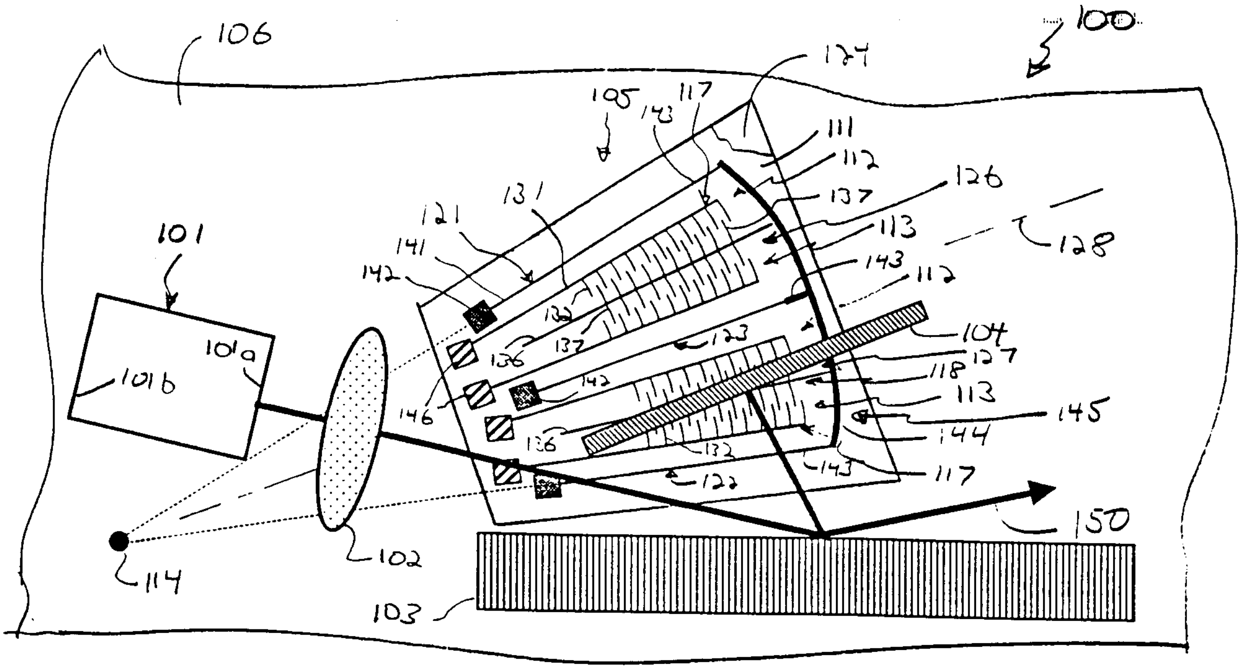
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FIG. 1

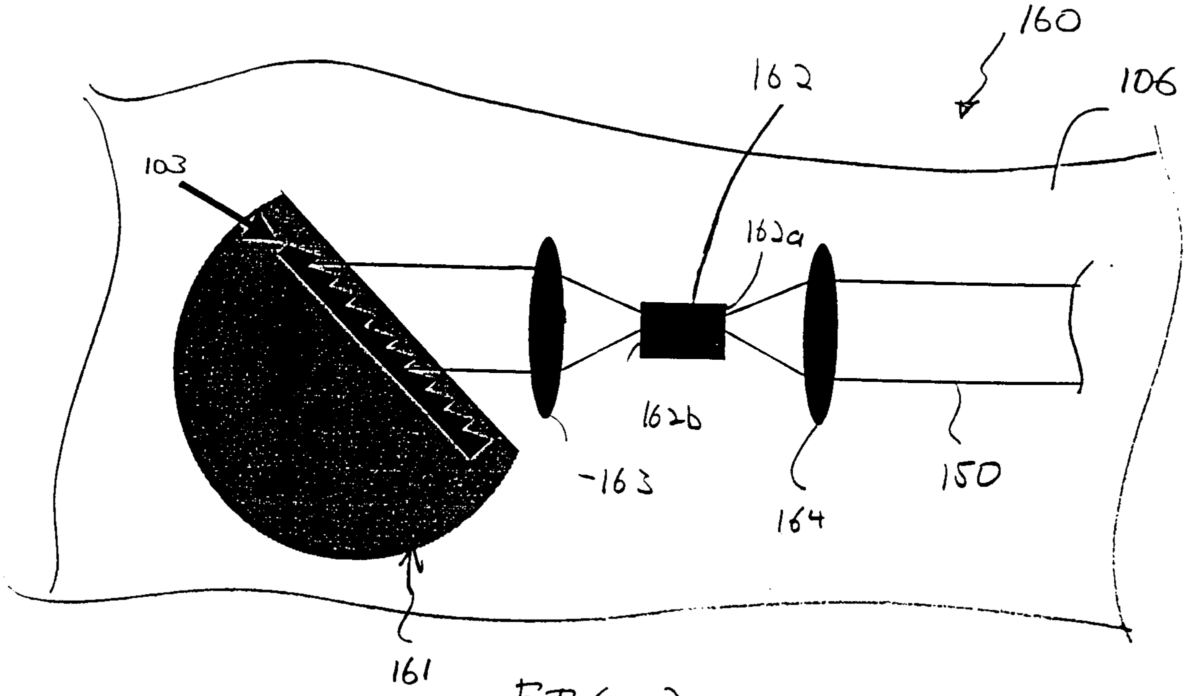
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FIG. 2

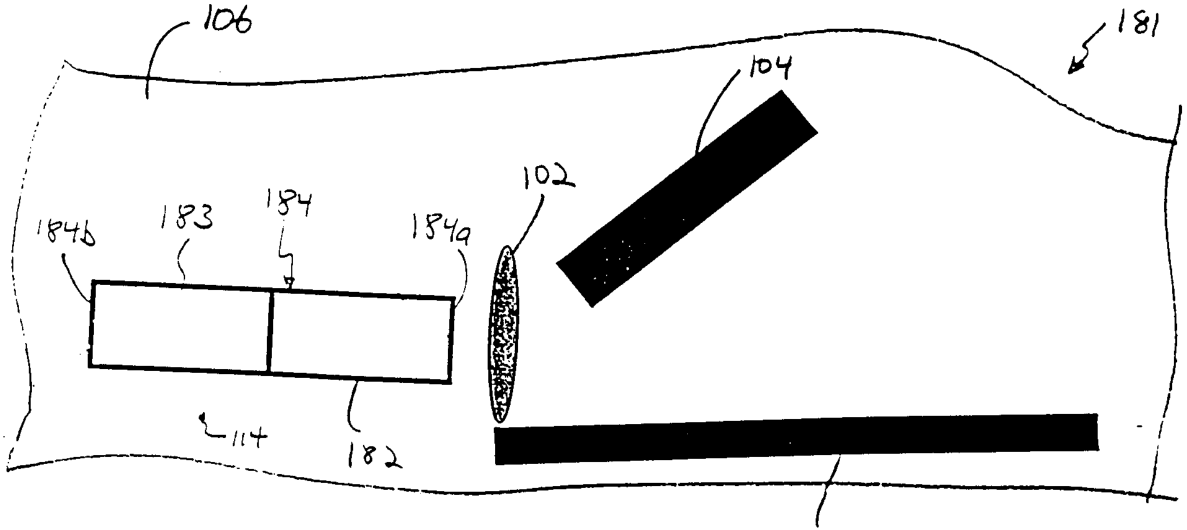


FIG. 3

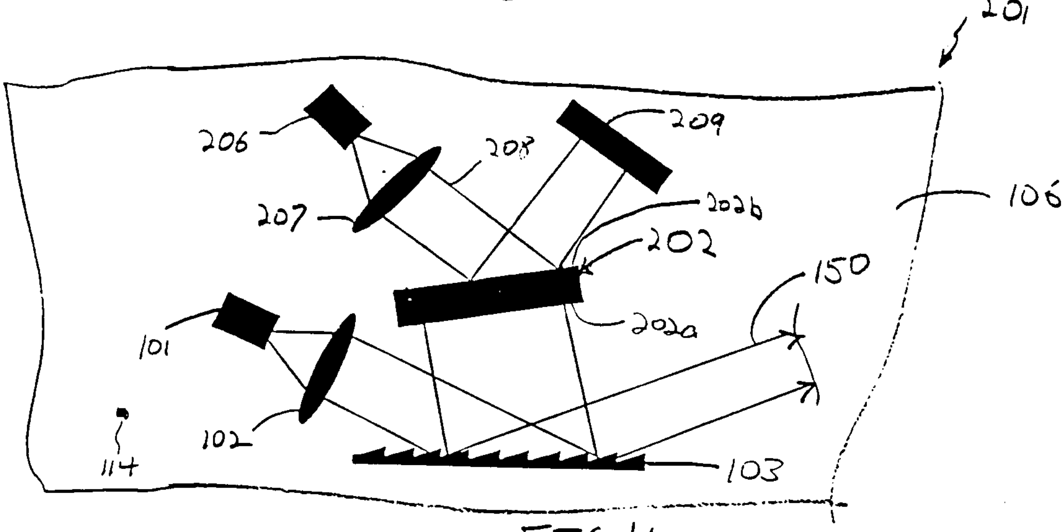


FIG. 4

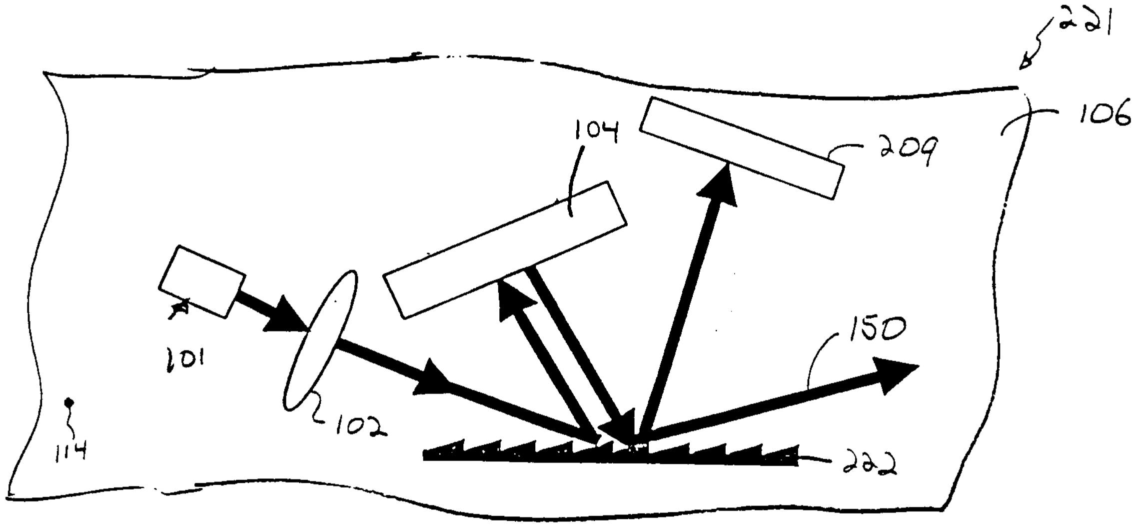


FIG. 5

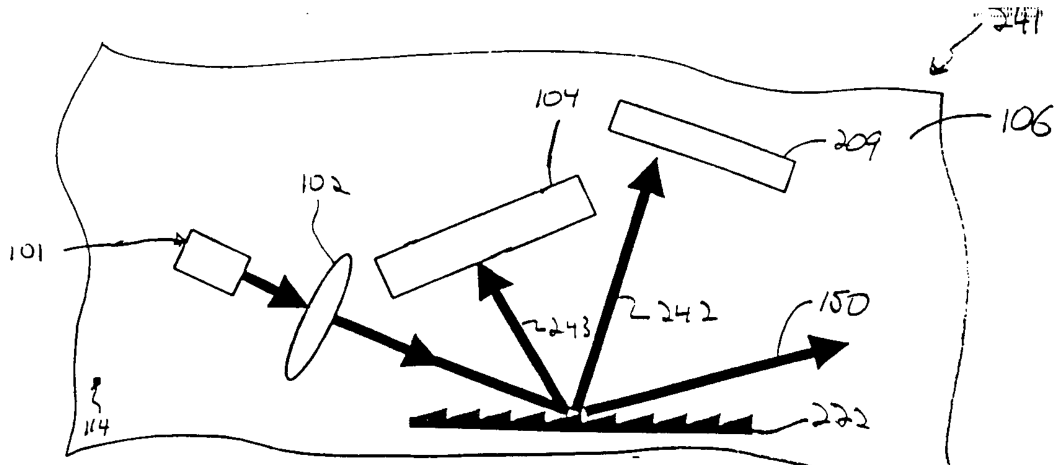


FIG. 6

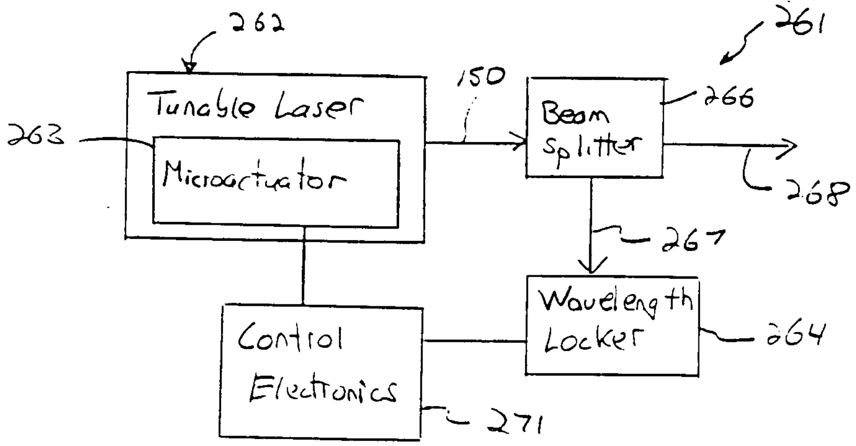


FIG. 7

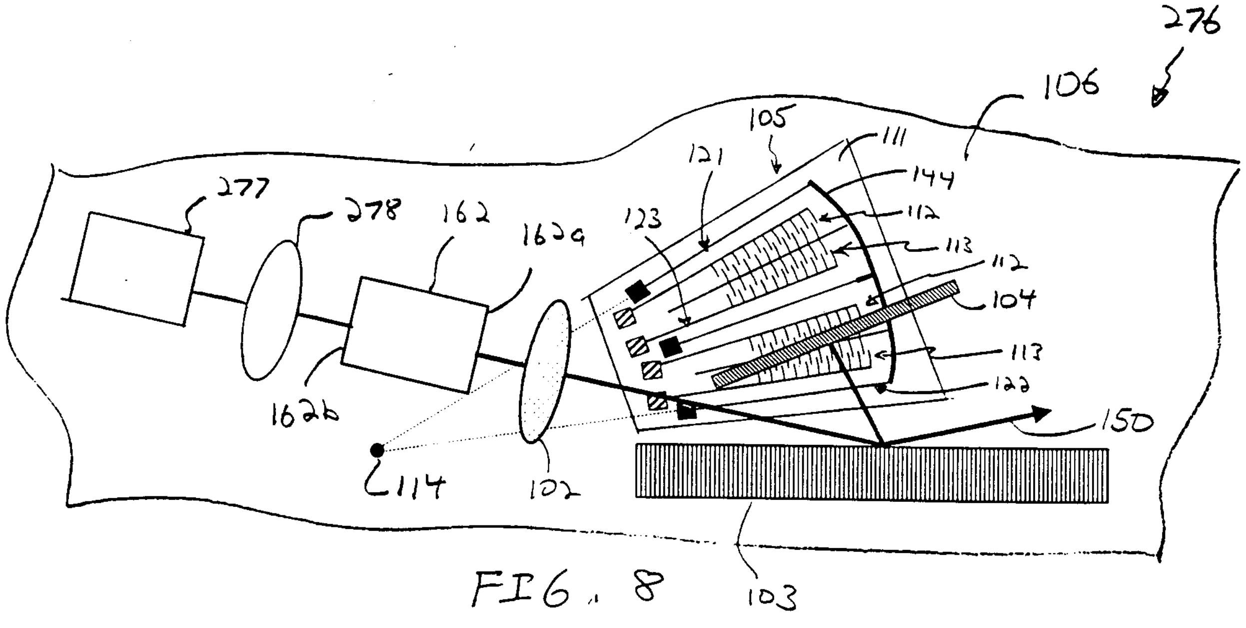
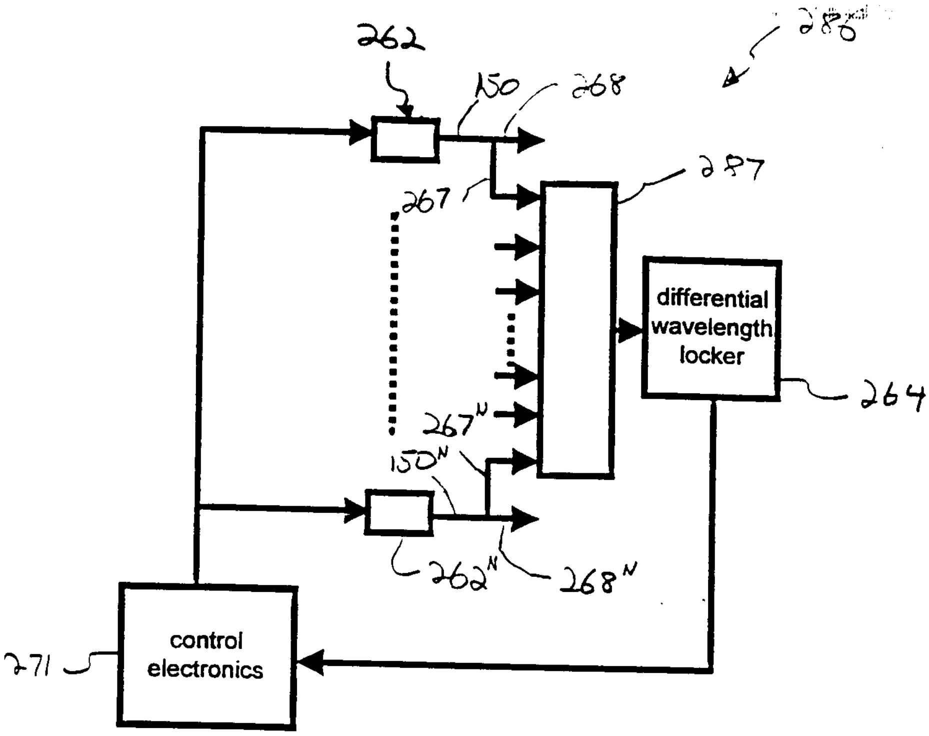


FIG. 8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control electronics
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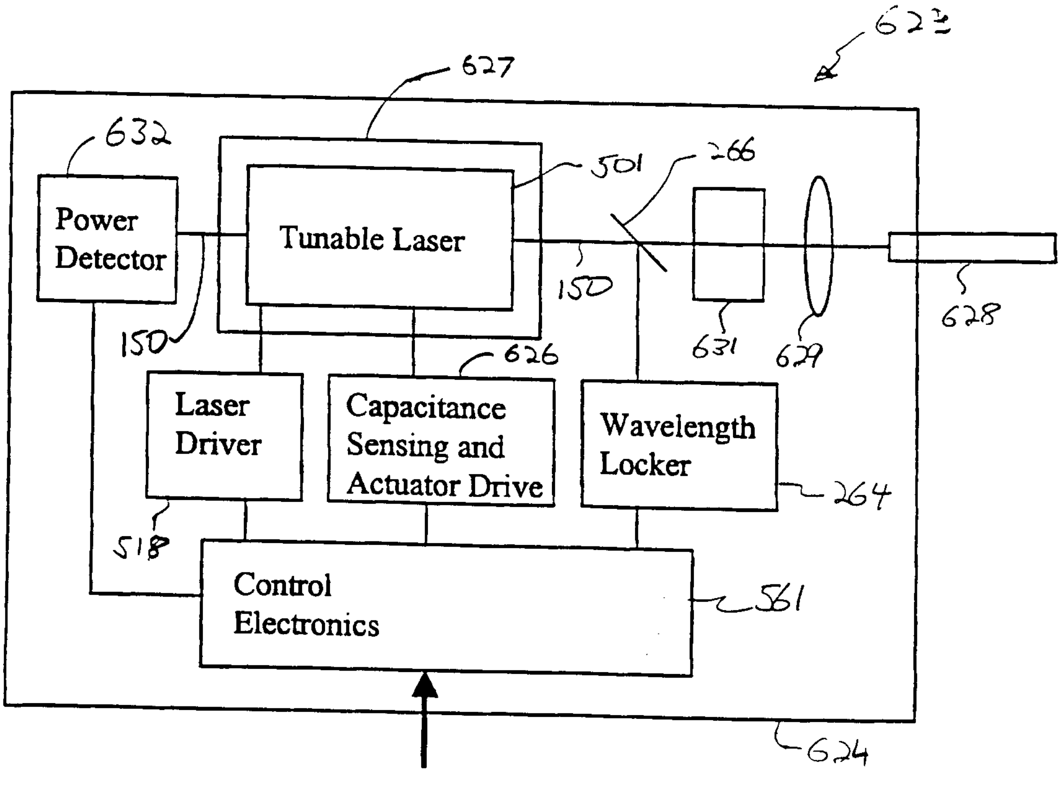
FIG. 9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627
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Tunable Laser
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266
150
150
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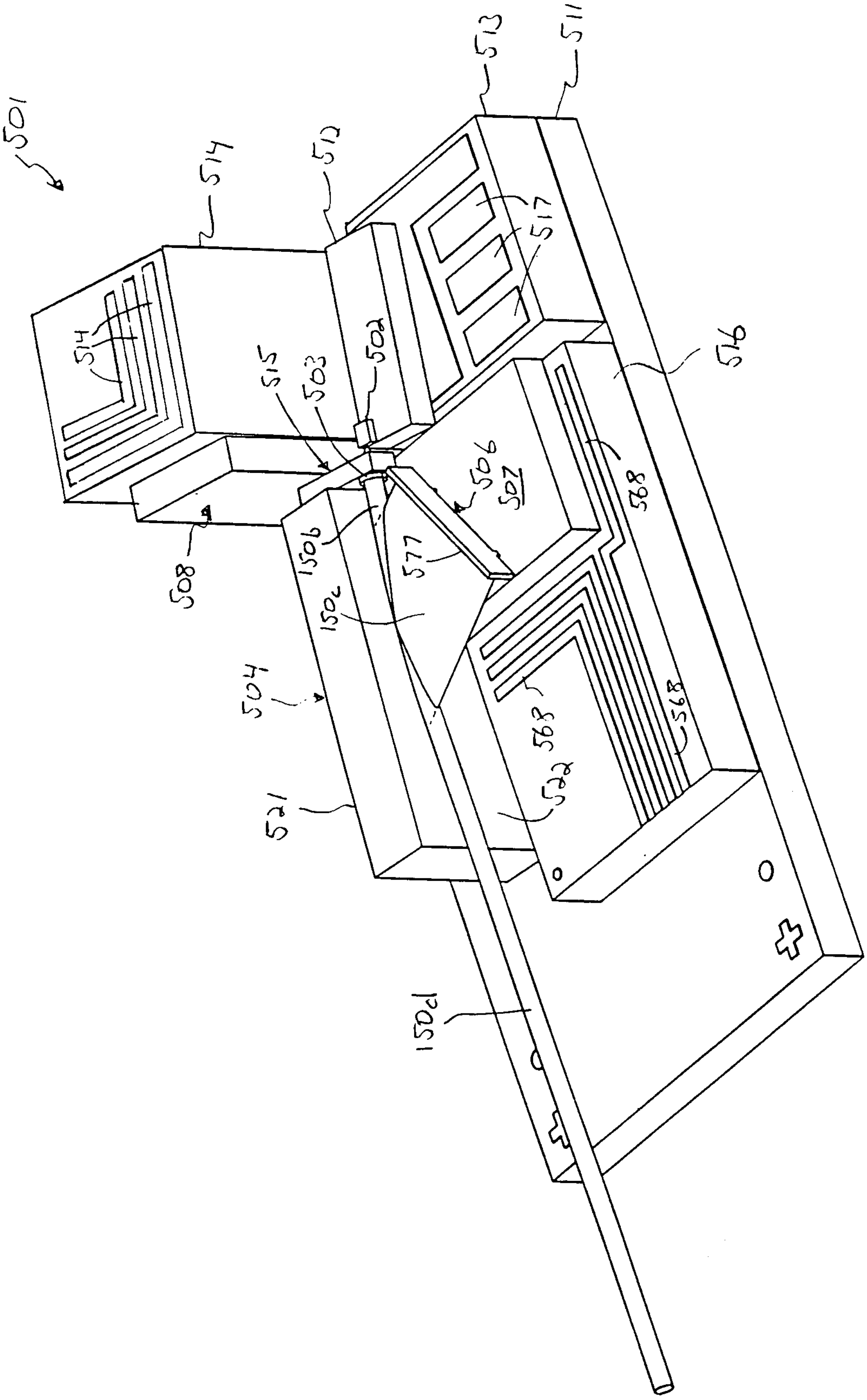
626
Laser Driver
Capacitance Sensing and Actuator Drive
Wavelength Locker
264
518
Control Electronics
561
624

FIG. 14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150b
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568
150c
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568
522
521
150d

FIG. 10

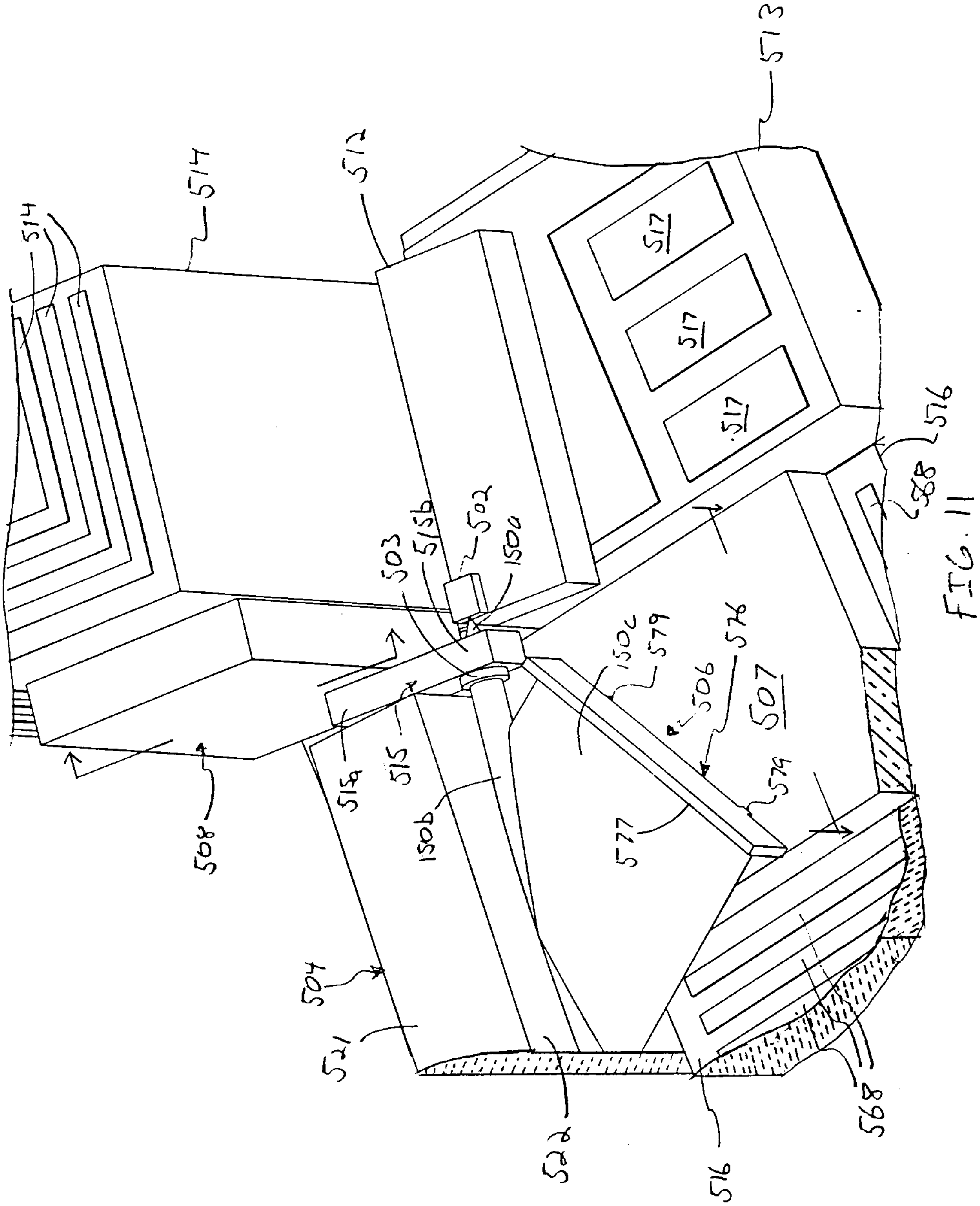
514
514
514
512
513
517
517
517
576
568
508
503
515b
502
150a
150c
579
576
506
507
515a
515
150b
577
579
504
521
522
516
568

FIG. 11

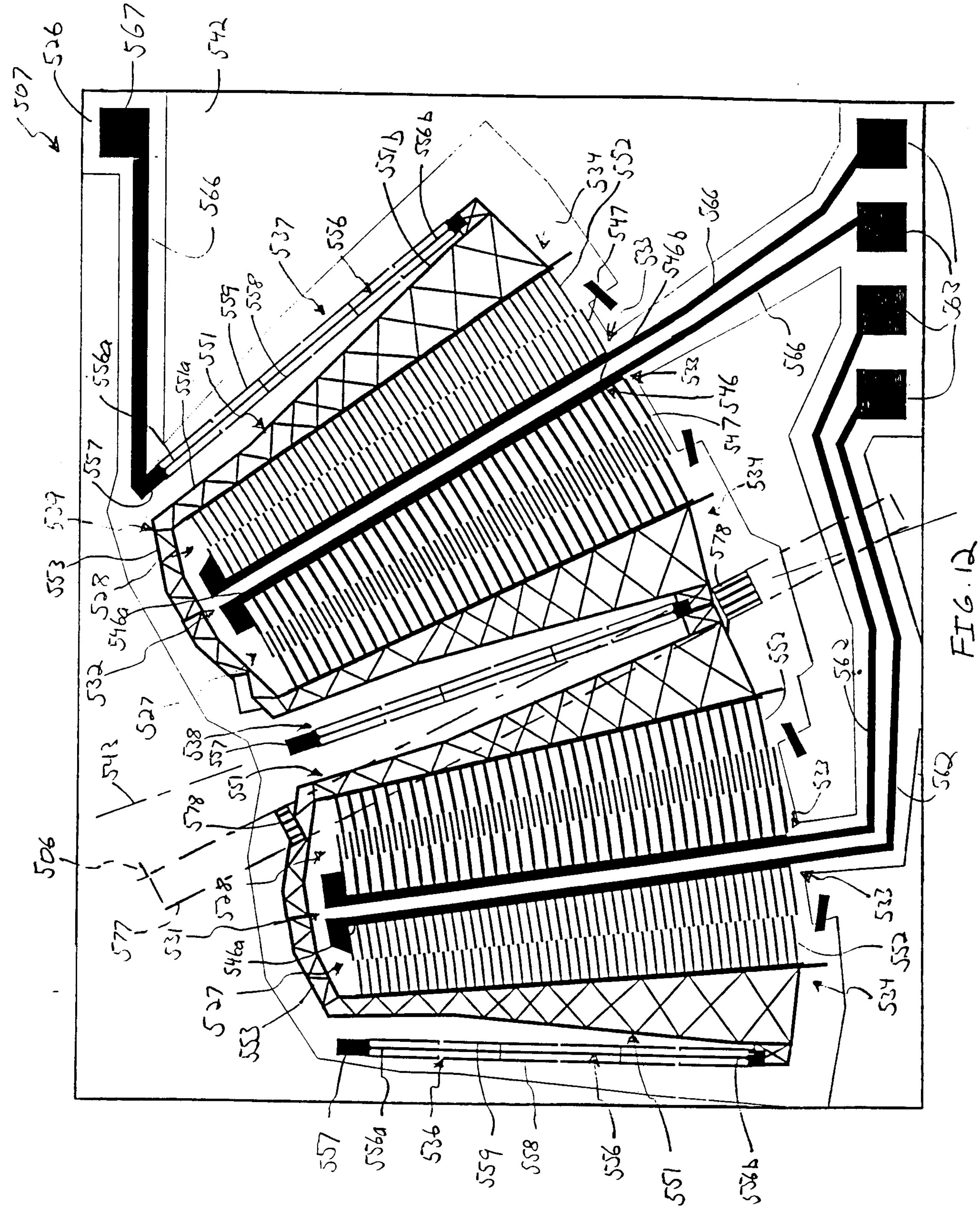
507
526
567
542
566
551b
556b
534
552
537
556
559
558
547
533
546b
566
556a
551a
551
532
546
547
534
557
539
553
528
546a
532
578
527
563
562
562
543
538
557
551
578
528
506
577
531
546a
527
553
533
532
552
534
557
556a
536
559
558
556
551
536b

FIG. 12

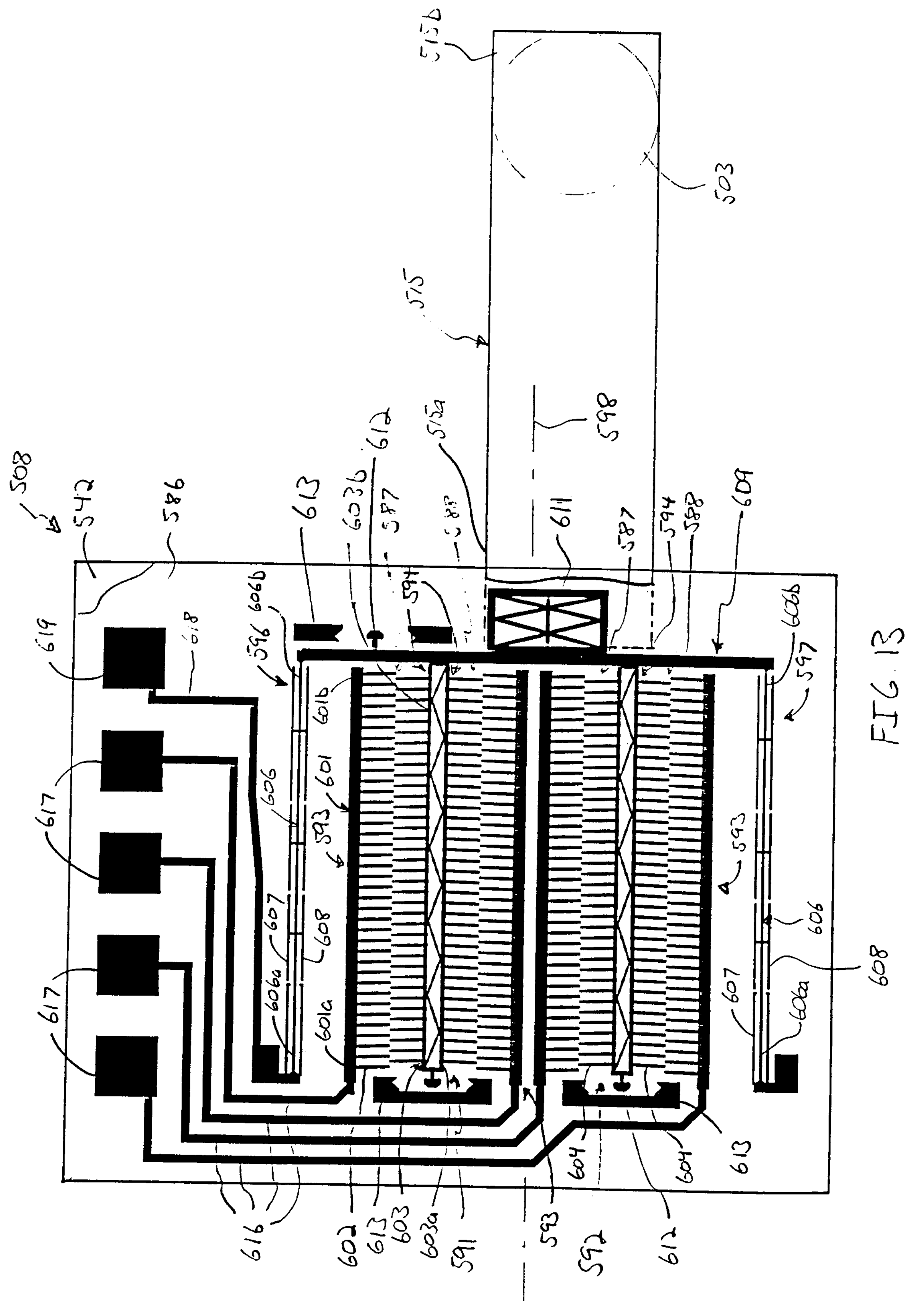
508
542
586
619
618
617
617
617
616
596
606b
606
606a
607
608
601
601a
601b
593
602
613
603
603a
603b
612
587
588
594
591
592
575
575a
575b
503
598
611
609
604
604
613
612
606b
597
606
606a
607
608

FIG 13