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(54) Title: CONFOCAL-TO-CONCENTRIC DIODE PUMPED LASER

(57) Abstract

A high power diode pumped, acousto-optically Q-switched Nd:YVO4 laser includes at least one resonator mirror and an output coupler defining a resonator cavity. At least one acousto-optic Q-switch device and at least one laser crystal, with strong thermal focussing properties, are positioned in the resonator. One or more diode pump sources supply a pump beam to the laser crystal or crystals to generate an output beam. A power source supplies power to the diode pump source.
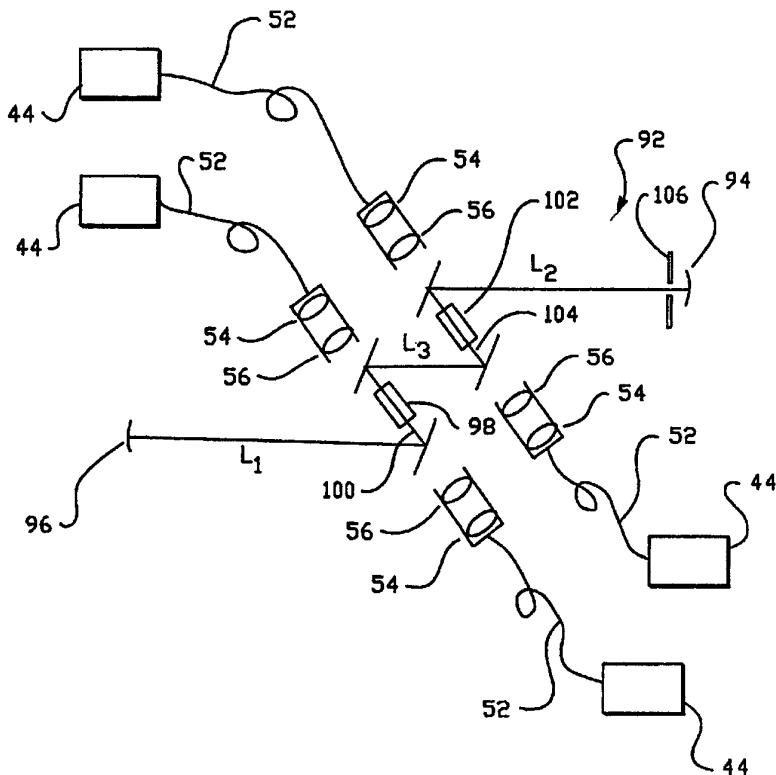
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CONFOCAL-TO-CONCENTRIC DIODE PUMPED LASER

Cross-Reference to Related Applications

This application is a continuation-in-part of U.S. Patent Application No.
08/432,301, (Attorney Reference No. SPEC 8053 CIP1), filed May 1, 1995 entitled
"Confocal-To-Concentric Diode Pumped Laser" having named inventors William l.
Nighan Jr., Marks S. Keirstead and David R. Dudley, which is a continuation-in-part
of U.S. Patent No. 5,412,683, (Attorney Reference No. SPEC 8053), issued May 2,
1995 entitled "Confocal Diode Pumped Laser", having named inventors William L.
Nighan Jr., and Mark S. Keirstead, both applications are assigned to the assignee of
the instant application and are herein incorporated by reference.

This application cross-references U.S. Patent Application No. 08/427,055,
(Attorney Reference No. SPEC 8052 CIP1), filed April 24, 1995 entitled "Diode
Pumped Laser Using Crystals with Strong Thermal Focussing", having named
inventors William L. Nighan Jr. and Mark S. Keirstead, which is a continuation-in-
part of U.S. Patent Application No. 08/191,655, (Attorney Reference No. SPEC
8052), filed February 4, 1994 entitled "Diode Pumped Laser with Strong Thermal
Lens Crystal" having named inventors William L. Nighan Jr. and Mark S. Keirstead,
both applications are assigned to the assignee of the instant application and are herein
incorporated by reference.

This application cross-references U.S. Patent Application No. 08/191,654,
(Attorney Reference No. SPEC 8051), filed February 4, 1994, entitled "Thermal lens
of Controlled Ellipticity", having named inventors Mark S. Keirstead, William L.
Nighan Jr., and Thomas M. Baer and is assigned to the assignee of the instant
application and is herein incorporated by reference.

This application cross-references U.S. Patent Application No. 08/516,586
(Attorney Reference No. SPEC 8181), filed August 18, 1995, entitled "Diode
Pumped, Fiber Coupled Laser with Depolarized Pump Beam", having named inventor
Alan B. Petersen and is assigned to the assignee of the instant application and is
herein incorporated by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

      This invention relates generally to highly efficient, high power, TEM_{00} lasers that have low sensitivity to misalignment with high beam pointing stability, and more

5   particularly to diode pumped lasers that are nearly confocal, or between confocal and concentric, and that utilize crystals with strong thermal focusing, and to lasers of this type that are Q-switched.

Description of Related Art

      There are many laser applications where insensitivity to misalignment and

10   beam pointing stability are critical. These characteristics are desirable in order that the laser power and mode do not degrade upon vibration, shock or thermal cycling. There are also applications where an insensitivity of a laser's output to changes in its thermal lens are highly desirable; for example, a Q-switched laser that is used in an application requiring dynamic variations in repetition rate.

15   Confocal or nearly confocal resonators are suitable candidates when misalignment sensitivity and beam pointing stability are important considerations. With confocal resonators, the mode diameter throughout the resonator does not vary by more than about the square root of two. Another description is that the laser resonator is about 2 times as long as the Rayleigh range of the intracavity mode. The

20   mode profile in a "concentric resonator" is somewhat different; it is analogous to the mode profile that would be found in a sphere. In fact, one type of perfectly concentric resonator is a simple two mirror resonator where the surfaces of the concave end mirrors define the surface of a sphere. In this type of concentric resonator, the mode diameter can be very small at one part of the resonator, but very

25   large in another part of the resonator. In this case, the laser resonator is much longer than two Rayleigh ranges of the intracavity mode. Of course, there are analogous resonators that are in between these descriptions, or between the confocal and concentric descriptions. For example, a resonator might be approximately four times longer than the Rayleigh range of an intracavity waist of the eigenmode of the

30   resonator.

A greater understanding of confocal or nearly confocal resonators can be ascertained with reference to Figure 1(a), a stability diagram with two axes, g_1 and g_2. The classic values of the stability parameters g_1 and g_2 are defined as:

$$g_1 = 1 - L/R_1$$

$$g_2 = 1 - L/R_2$$

where L is the length of the resonator and R_1, R_2 are the respective radii of curvature of mirrors M_1 and M_2 of the resonator, shown in Figure 1(b). A two mirror laser resonator is stable if $0 < (g_1)(g_2) < 1$. The TEM_{00} mode size of a resonator can be represented in terms of g_1 and g_2, and the stability parameters can also be used to judge misalignment sensitivity and other practical resonator characteristics. This classic discussion can be found in W. Koechner, *Solid State Laser Engineering*, 3rd edition, Springer-Verlag, NY, p. 204-205 (1992).

It should be noted that this stability analysis can be extended to a resonator with an intracavity lens or lenses, shown in Figure 1(c). The intracavity lens can be a conventional lens or a thermal lens. A thermal lens can be generated in a laser crystal by diode pump light, or by lamp pump light. In this case, the g parameters become:

$$g_1 = 1 - (L_2 / f) - (L_o / R_1)$$

$$g_2 = 1 - (L_1 / f) - (L_o / R_2)$$

where $L_o = L_1 + L_2 - (L_1 L_2 / f)$, and $L = L_1 + L_2$, as shown in Figure 1(c), R_1 and R_2 are defined as in the case of no lens, and with f as the focal length of the intracavity lens which can be a thermal lens. This background is also presented in W. Koechner, *Solid State Laser Engineering*, 3rd edition, Springer-Verlag, NY p. 204-205 (1992).

It should therefore be noted that the traditional two mirror stability analysis, with stability parameters g_1 and g_2, is still useful when more complicated, multiple mirror and lens resonators are being considered.

With reference now to Figure 1(a), in the upper right quadrant, a hyperbola 10 defines a region 12, bounded between hyperbola 10 and the g axes. For a resonator with values of g_1 and g_2 within region 12, a gaussian mode can exist. Hyperbola 10 has the characteristic that $(g_1)(g_2) = 1$. Region 12 represents a stable regime; a gaussian mode can exist between the two mirrors defining the resonator. In the lower quadrant 14, another stable regime is found; gaussian modes can also exist

for these g values. The ideal confocal resonator corresponds to point 16, the intersection of the g_1 and g_2 axis, where $g_1 = g_2 = 0$. A resonator can be called nearly confocal if g_1 and g_2 are not too large.

5   In Figure 2, an ideal confocal resonator 18 is defined by two opposing mirrors, 20 and 22, each having a radius of curvature R_1 and R_2, respectively. Mirrors 20 and 22 are separated by a distance L. For an ideal confocal resonator 18, $R_1 = R_2 = L$. If a lens is used at the center of the cavity and flat mirrors are used, a confocal resonator arises when $f = L/2$. A combination of lenses and curved mirrors can also produce a confocal resonator.

10   Referring again to Figure 1(a), a plane parallel resonator corresponds to points indicated at 24, where $g_1 = g_2 = 1$. The values of g_1 and g_2 place this resonator right on the edge of the stability diagram, and for applications requiring insensitivity to misalignment and pointing stability, the plane parallel resonator is typically not the best choice.

15   A large radius resonator exists when R_1 and R_2 are much larger than L, and corresponds to points 26 in Figure 1(a). Large radius resonators are useful for diode pumping. In one embodiment of a large radius resonator, a Nd:YLF crystal is used and the mode size of the TEM_{00} is large, which facilitates conventional mode-matching. This resonator is, however, sensitive to misalignment, and may have

20   reduced pointing stability. As an example, a large radius resonator of length L with $R = 10L$, is five times more sensitive to misalignment than the confocal resonator of length L. This is also shown by the Koechner reference.

A concentric or spherical resonator, where $R_1 = R_2 = L/2$, is represented at 24. In this case, $g_1 = g_2 = -1$. It has the properties that the mode can be very large at

25   one point of the resonator, and very small at the other. This is mainly because the mirrors are on the surface of a sphere. The TEM_{00} modes of such a resonator are very small at the center of the resonator, but very large at the ends. An equivalent resonator can be constructed using a lens or lenses and flat mirrors, or with a combination of lenses and curved mirrors.

30   A half symmetric resonator 30 is illustrated in Figure 3. It is defined by a curved mirror 32 and a flat mirror 34, separated by a distance L. In this instance, R_1

is the radius of curvature of mirror 32. Because mirror 34 is flat, it has an infinite radius of curvature. A half symmetric resonator can be made to have equivalent properties with that of a confocal resonator, if $g_2=1$ and $g_1 \sim 1/2$. In Figure 1(a), the half symmetric confocal resonator corresponds to point 36 on the stability diagram.

5   A half symmetric resonator can also be a large radius resonator, where one mirror is flat, and the other has a curvature $R_1 >> L$. Again, an equivalent resonator can be constructed using a lens or lenses and flat mirrors, or with a combination of lenses and curved mirrors.

Because a confocal resonator is relatively insensitive to misalignment, a

10   mirror can be tilted a certain amount and the laser output power does not drop as rapidly as with other types of lasers. The mode in the confocal resonator does not change or move very much as mirrors are tilted. Because the confocal's pointing stability and its misalignment sensitivity are very good, for example as a function of environmental changes, this type of resonator has some useful properties.

15   A major disadvantage of a confocal resonator is that it has the smallest average TEM_{00} mode diameter of any resonator of any length L. In essence, the TEM_{00} mode volume of the confocal resonator of length L is smaller than that of other resonators of length L. This makes conventional mode matching difficult.

This is taught in A.E. Siegman, *Lasers*, University Science Book, Mill Valley,

20   CA, p. 750-759, 1986. Because of its small average size, the TEM_{00} mode in a confocal resonator is not very effective in extracting power from a large diameter gain medium. Additionally, because of the small average size of the TEM_{00} mode, a confocal resonator is very likely to oscillate in a combination of the lowest and higher order modes. An important design goal for many diode pumped solid state lasers is

25   the generation of nearly diffraction limited TEM_{00} output at the highest possible efficiency and power. Because of the small TEM_{00} mode size of a confocal resonator, and its tendency to oscillate in a combination of the lowest and higher order modes, diode end pumping a confocal resonator has not been considered useful.

30   The effect of mode-matching is to maximize the coupling between the TEM_{00} mode and the excited volume in the crystal. In turn, the optical slope and the overall

optical efficiencies of the laser are both maximized. In a classic mode-matched geometry, the ratio of the TEM_{00} mode diameter to the diameter of the pump beam in an Nd:YAG pumped laser is about 1.3 or greater. Because of the small TEM_{00} size, this ratio is more difficult to achieve with a confocal resonator.

5   The thermal lens in a laser crystal can be used in combination with mirror curvatures or conventional lenses to design a nearly confocal resonator. Certain crystals exhibit strong thermal lens characteristics, these laser crystals have other important properties that make them suitable candidates for laser resonators. For example, in comparison to Nd:YLF, the strong thermal lens material $Nd:YVO_4$ has a

10   high gain and a short upper state lifetime. These properties provide important adjustable parameters when designing a Q-switched laser with high pulse energy or high repetition rate, or a laser that is insensitive to optical feedback. Additionally, $Nd:YVO_4$ has a high absorption coefficient at the diode pump wavelength of ~ 809 nm, permitting efficient coupling of diode pump light into the $Nd:YVO_4$ crystal.

15   Many laser crystals have strong thermal lenses, such as Nd:YAG and $Nd:YVO_4$. With a strong thermal lens, the focussing power of the pump induced lens is at least comparable to that of the other optics in the laser resonator. A strong thermal lens significantly changes the size and divergence of a laser resonator eigenmode within the resonator.

20   With a weak thermal lens, the focussing power of the pump induced lens is substantially lower than that of the other optics in the laser resonator such as mirrors and typical lenses. The other optics in the laser resonator dictate the size and divergence of the resonator eigenmode.

It is clear that a thermal lens can be used to build a nearly confocal resonator.

25   However, it has been thought that the large aberrations of strong thermal lens materials limit the efficiency of high power resonators. It has been generally believed that strong thermal lensing is a hindrance in the design and construction of an efficient laser with high TEM_{00} beam quality, high power and high efficiency. Therefore, successful use of strong thermal lens materials at higher pump powers has

30   been limited.

Additionally, classical mode-matching has taught that TEM_{00} mode diameter to pump beam diameter ratios less than unity are of little interest since laser threshold is high and the achievable conversion efficiency is poor. Ratios of less than unity result in lower gain while those approaching and exceeding unity can result in higher

5   loss due to aberration. It is more difficult to achieve a ratio greater than unity with a nearly confocal resonator since the TEM_{00} mode size is small. This feature goes against the teaching of conventional mode matching.

The use of diodes as pump sources for confocal resonators is desirable for reasons of cost, size and wall plug efficiency. Some strong thermal lens materials

10   have certain properties that would make them useful for diode pumped lasers.

Another useful resonator type can be described as "in between" confocal and concentric. This can be called a confocal-to-concentric resonator. In Koechner, *Solid State Laser Engineering*, Vol. 3, p. 206, a resonator sensitivity analysis shows that a resonator with $(g_1)(g_2) = 0.5$ features a mode size that is fairly insensitive to

15   changes in the g parameter values. This means that small changes in thermal lens focal powers are relatively well tolerated in this type of laser. A number of laser resonators can be built with $(g_1)(g_2) = 0.5$. This is represented by g values near point 25 in Figure 1(a).

It would be desirable to have a compact, efficient low cost diode pumped

20   laser that is sensitive to misalignment and has high pointing stability. It would also be desirable to provide a confocal-to-concentric resonator that has these properties, e.g. diode pumped, provides high output power, is highly efficient, and uses strong thermal lens materials. The laser may also have a TEM_{00} mode diameter in the laser crystal that is less than the diameter of the pump beam. It would also be useful to

25   provide a Q-switched laser with similar characteristics, especially for applications that demand dynamic variations in the repetition rate of the Q-switched laser. It would also be useful to provide a Q-switched, diode-pumped $Nd:YVO_4$ laser that provides high power and short pulses at a high repetition rate.

SUMMARY OF THE INVENTION

30   It is an object of the invention to provide a confocal-to-concentric resonator that is diode pumped and acousto-optically Q-switched.

Another object of the invention is to provide a high efficiency, high power, diode pumped, confocal-to-concentric or plane-parallel-to-confocal resonator.

Still another object of the invention is to provide a high efficiency, diode pumped, Q-switched, confocal-to-concentric resonator with nearly diffraction limited output.

Another object of the invention is to provide a Q-switched confocal-to-concentric resonator which uses laser crystals that exhibit strong thermal focussing.

It is an object of the invention to provide a confocal-to-concentric diode-pumped solid state laser that is repetitively Q-switched.

A further object of the invention is to provide a Q-switched confocal-to-concentric diode-pumped solid state laser that provides a polarized beam.

Still another object of the invention is to provide a diode-pumped solid state laser that utilizes laser crystals which exhibit strong thermal focussing, the laser resonator being on the order of one to several Rayleigh ranges in length.

It is an object of the invention to provide a high-repetition-rate, acousto-optically Q-switched, high power, diode-pumped $Nd:YVO_4$ laser.

These and other objects of the invention are achieved in a high power diode pumped, acousto-optically Q-switched $Nd:YVO_4$ laser that includes at least one resonator mirror and an output coupler defining a resonator cavity. At least one acousto-optic Q-switch device and at least one laser crystal, with strong thermal focussing properties, are positioned in the resonator cavity. One or more diode pump sources supply a pump beam to the laser crystal or crystals to generate an output beam. A power source supplies power to the diode pump source.

In another embodiment, the present invention is a high power, diode pumped laser. At least one resonator mirror and an output coupler are included. Also provided are at least one laser crystal with strong thermal focussing properties. At least one diode pump source supplies a pump beam to the laser crystal. At least one acousto-optic Q-switch is used to provide a pulsed output. This produces a thermal lens in the laser crystal. The combination of the laser crystal, thermal lens, resonator mirrors and output coupler create a resonator that is greater than 0.5 Rayleigh ranges in length.

Further, a nearly diffraction limited, high efficiency, diode pumped laser can include a confocal-to-concentric resonator. A strong thermal lens laser crystal is positioned in the resonator. A diode pump source supplies a pump beam to the laser crystal in the resonator to produce an output beam, and create a pump beam diameter

5   in the laser crystal that is greater than a TEM_{00} mode diameter. An acousto-optic Q-switch is used to provide a pulsed output.

In a further embodiment, the laser can be multi port, and can also include one or more fold arms.

The resonator can have a multiple Rayleigh range, and an optical slope

10   efficiency in a TEM_{00} mode of greater than about 40%. The laser may have an optical efficiency of greater than about 25%, and a ratio of a TEM_{00} mode diameter of the laser crystal to a pump beam diameter in the crystal is about less than 1.0 to 0.83. Thermal birefringence can be reduced because the output beam diameter is larger than the TEM_{00} mode diameter. In certain instances the laser includes a Q-

15   switch. An important embodiment is an acousto-optically Q-switched, high power diode-pumped $Nd:YVO_4$ laser. Another important embodiment is an acousto-optically Q-switched, end-pumped $Nd:YAG$ laser that is intended for resistor trimming. A variety of different laser crystal materials may be used including but not limited to $Nd:YVO_4$ and $Nd:YAG$.

20   BRIEF DESCRIPTION OF THE FIGURES

Figure 1 (a) is a stability diagram for a two mirror resonator. The diagram shows the stability parameter for different types of resonators, including those with lenses. An ideal confocal resonator is where g_1 and g_2 equal 0.

Figure 1 (b) illustrates a schematic diagram of a simple two mirror resonator

25   with mirrors M_1 and M_2, each having a radius of curvature of R_1, R_2, respectively, of length L, but the drawing does not include a laser crystal.

Figure 1 (c) illustrates a two mirror resonator with an intracavity lens.

Figure 2 is a schematic diagram of a simple two mirror confocal resonator. The mirrors each have a radius of curvature R1 and R2 respectively, and are

30   separated by a distance L.

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Figure 3 is a schematic diagram of a half symmetric confocal resonator with two mirrors. One of the mirrors is flat. The curved mirror has a radius of curvature, R1 equal to 2L, where L is the distance between the two mirrors. The flat mirror has a radius of curvature equal to infinity.

5   Figure 4 is a schematic diagram of a long radius mirror resonator using an Nd:YLF laser crystal, and for comparison shows the mode size of a laser using an Nd:YVO4 crystal.

Figure 5 is a schematic diagram of an asymmetric resonator.

Figure 6 is a schematic diagram of a symmetric resonator that is folded and

10   has a single port.

Figure 7 is a schematic diagram of a two port resonator.

Figure 8 is a schematic diagram of the resonator of Figure 7, pulled apart to eliminate the folds, in order to show the relationship between L1, L2 and L3.

Figure 9 is a schematic diagram of a double "Z" folded resonator.

15   Figure 10 is a schematic diagram of a confocal-to-concentric "Z" resonator, utilizing Nd:YAG or Nd:YVO$_4$. This resonator includes an optional Q-switch and an optional polarizing device.

Figure 11 is a schematic diagram of the TEM$_{00}$ mode size in a confocal-to-concentric resonator that contains a strong thermal lens or lenses.

20   DETAILED DESCRIPTION

The high efficiency, high power diode pumped laser, of the present invention, has a resonator mirror or mirrors and an output coupler defining a nearly confocal resonator. A laser crystal is positioned in the resonator along a resonator optical axis. A diode pump source supplies a pump beam to the laser crystal and produces

25   an output beam. A power source supplies power to the diode pump source. Aperture stops can be included for improved TEM$_{00}$ operation.

For purposes of the present invention, a nearly confocal resonator means exactly confocal and also includes:

a symmetric resonator where $g_1 = g_2$, and g_1, $g_2 < 0.5$, or the cavity

30   length L is about twice the Rayleigh range of a waist of the resonator eigenmode, where the Rayleigh range is

$$R = \frac{wo^2}{\lambda}$$

where wo = waist radius size and λ = wavelength.

A perfect symmetric confocal resonator is $g_1 = g_2 = 0$, or L = 2R exactly.

If the resonator is half-symmetric, then g_1 or $g_2 \sim 1$ and the other g parameter is near 0.5, or the cavity length L is about one Rayleigh range of a waist of the resonator eigenmode.

Additionally, nearly confocal also includes those asymmetric resonators of length L that share properties with nearly confocal symmetric and half-symmetric resonators. The g parameters may differ from the above definitions, but the length of the resonator is on the order of 1 to 2 Rayleigh ranges as defined above.

A confocal-to-concentric resonator is defined as one where $(g_1)(g_2)$ is approximately equal to 0.5. These resonator feature mode sizes that are relatively insensitive to small changes in the g parameters, as is well-known. This can be true even if the resonator is not completely symmetric. These resonator designs exhibit favorable behavior even if they are not perfectly symmetric. Additionally, these types of resonators work well with materials that exhibit strong thermal focussing, like Nd:YVO$_4$ or Nd:YAG, and that they work well when these lasers are used in a repetitively Q-switched manner. For example, when the repetition rate of a Q-switched Nd:YAG laser is varied from 20 kHz down to 1 kHz, the average power extraction from the laser is typically not constant, if pumping power is held constant. In a lamp-pumped system, there is typically so much heat dissipated in the Nd:YAG laser crystal that this change in power extraction has minimal effect upon the lamp-pump-induced thermal lens in the Nd:YAG crystal. However, in a diode-pumped system, this change in power extraction can have a significant and problematic effect upon the thermal lens in the diode-pumped Nd:YAG crystal. The effect can be severe enough to prevent stable 1 kHz Q-switched operation (for example, 1 - 2 W output) of a high power diode-pumped Nd:YAG laser when the laser is optimized for maximum output at 20 kHz (for example, 6 - 10 W output).

The reduction in repetition rate and power extraction can result in an excessive change in the effective focal length of the diode-pump-induced thermal lens. This problem is solved in the present invention by building a confocal-to-

concentric resonator, utilizing the thermal lenses in the Nd:YAG crystal as a variable

focussing element in the laser cavity. Dynamic variation in repetition rate is possible,

from 50 kHz to very low frequencies, with minimal change in the output spatial

characteristics of the diode-pumped Nd:YAG laser, and with very good pulse-to-

5   pulse stability. This laser is useful for resistor-trimming applications, where

repetition rates are varied according to the processing requirements for a particular

resistor material.

Resonators that are between plane-parallel and confocal can have $(g_1)(g_2) =$

0.5 and can have similar favorable properties to the confocal-to-concentric

10   resonators. The discussion of confocal-to-concentric resonators therefore extends to

plan-parallel to confocal resonators.

Resonator lengths that are a few Rayleigh ranges in length (1 to 5 Rayleigh

ranges, for example) are found to be relatively insensitive to thermal lens aberrations,

and are considered to be a part of this invention. The Rayleigh range is defined as

15      $W_o^2 /$, as is well known, where in this case the beam radius size W_o is the radius of an

intracavity waist, a nearby extracavity waist, or a nearby virtual or apparent waist of

the resonator. Resonators that have eigenmode beam propagations of this type are

less sensitive to loss due to aberrations in the thermal lens, even for mode size/pump

size ratios close to 1 or greater than 1, and even for resonators that are not

20   symmetric.

For purposes of the present invention, the following definitions apply:

Strong thermal lens: The focussing power of the pump

induced lens is at least comparable to that of the other

optics in the laser resonator. A strong thermal lens

25   significantly changes the size and divergence of a laser

resonator eigenmode within the resonator.

Weak thermal lens: The focussing power of the pump

induced lens is substantially lower than that of the

other optics in the laser resonator such as mirrors and

30   typical lenses. The other optics in the laser resonator

dictate the size and divergence of the resonator
eigenmode.

The laser of the present invention has an optical efficiency is greater than
25%. In a preferred embodiment, its optical efficiency is greater than 40%. High

5   power, polarized TEM_{00} operation of the laser is an output beam greater than 4 W in
a TEM_{00} mode. Its output is substantially TEM_{00}, or nearly diffraction limited, if at
least 95% of the power of output beam is measured to an M^2 value less than 1.2,
where M^2 is defined as the ratio of theoretical confocal parameter of a beam, as
predicted by an extracavity waist size, to the actual measured confocal parameter. In

10   a preferred embodiment, M^2 is <1.05. The output beam profile has a least squares
deviation from an ideal gaussian profile of less than 10%. In a preferred embodiment,
this deviation is less than 1%, and the output beam is substantially polarized.
Additionally, in certain embodiments, the laser may use a laser crystal where the
diode pump induced thermal lens in the crystal provides an optical path difference as

15   a function of radius that is not described by a parabolic profile.

In Figure 4, a long radius mirror resonator 38 includes a high reflector 40,
output coupler 42, laser crystal 43 and a diode pump source 44. If laser crystal 43 is
Nd:YLF, and with a pump beam 46 with a diameter of about 0.7 mm incident upon
crystal 43, the TEM_{00} mode diameter 48 is about 1 mm, and it remains fairly constant

20   in resonator 38. With a strong thermal lens material with strong thermal aberrations,
such as Nd:YAG or Nd:YVO$_4$, the same pump diameter can produce a TEM_{00} mode
diameter 50 of about 0.56 mm (this occurs because of the thermal lens that the pump
beam generates, in combination with other optics in the resonator). The TEM_{00}
mode size is slightly smaller than the pump diameter. The laser is highly efficient in

25   spite of this deviation from conventional mode matching. This configuration is
optimal because of the diffractive losses from aberrations at the edges of the pump
spot.

Diode pump source 44 can be a single diode, spatial emitter, diode bar or a
plurality of diodes, diode arrays, or diode bars. A suitable diode source 44 is model

30   No. OPC-A020-810-CS, available from OptoPower Corporation, City of Industry,
California. A similar model is denoted B020. Multiple diodes are typically used,

such as two, or more if needed. However, one can be used if the available power is sufficient. Preferred wavelengths of diode source 44 are in the range of 795 to 815 nm. Peak absorption wavelengths of specific crystals are approximately as follows: Tm:YAG - 785 nm; Nd:YLF - 797; and Nd:YAG, Nd:YVO4 - 809 nm.

5   Diode source 44 is coupled to one or more optical fibers 52. Preferably, a bundle of optical fibers 52 are utilized. Coupling can be accomplished as set forth in U.S. Patent No. 5,127,068. Suitable fibers 52 include but are not limited to those that have silica cores with silica cladding. The present invention can also utilize diodes that are not fiber-coupled.

10   A telescope arrangement provides for the focussing of the output beam from diode source 44 so that it is incident on laser crystal 43. In one embodiment, with Nd:YVO$_4$, the telescope arrangement includes first and second lenses, 54 and 56, that optimize the size of pump beam 46 to avoid fracture of crystal 43, but produce a pump beam such that the ratio of the TEM$_{00}$ mode diameter to pump beam diameter

15   is less than unity (for example, ~0.85). In another embodiment, with Nd:YAG in a Q-switched laser, this ratio can be less than one (such as~0.85) or close to one, but the resonator is a few Rayleigh ranges in length and also features $(g_1)(g_2)$ near 0.5.

          In a confocal resonator with no lens, two opposing mirrors are used which have radii of curvature R_1 and R_2, respectively, and the two mirrors are separated by

20   a distance L, where $R_1 = R_2 = L$. This is, again, a perfect confocal resonator. A strong thermal lens changes the ideal distances and curvatures, since the thermal lens has a strong effect on the mode propagation in the resonator.

          Strong thermal lens materials can be used for the laser crystal with the present invention. Suitable strong thermal lens materials include but are not limited to

25   Nd:YAG, Nd:YVO$_4$, Nd:GVO$_4$, Nd:YPO$_4$, Nd:BEL, Nd:YALO and Nd:LSB. A preferred material is Nd:YVO$_4$, available from Litton-Airtron, Charlotte, North Carolina. The atomic percentage of Nd is in the range of 0.5 to 3.0%, preferably about 0.6 to 0.9% and most preferably about 0.8%. An embodiment configured for high continuous wave power at 1.064 μm utilizes Nd:YVO$_4$ of dopant level

30   approximately 0.5%. This laser generates over 13 W in a TEM$_{00}$ mode for 26 W of pump power.

Nd:YVO$_4$ is an attractive material for certain applications because, compared to Nd:YLF, it exhibits high gain and a short upper state lifetime. Nd:YAG has an intermediate gain and an intermediate upper state lifetime. Nd:YVO$_4$ is also suitable for diode pumping because its absorption coefficient at the diode pump wavelength

5   of ~ 809 nm is extremely high, permitting efficient coupling of diode pump beam 46.

Optical, thermal and mechanical characteristics of Nd:YVO$_4$ are different along its "a" and "c" axes. The thermal expansion coefficient in a direction parallel to the "a" axis is about 2.5 times smaller than that parallel to the "c" axis. The variation of the index of refraction, as a function of temperature, is different by about a factor

10   of 2.8 along the "c" and "a" axes. Because Nd:YVO$_4$ is so strongly birefringent, there is more than a 10% difference between the indexes of refraction for the two crystallographic axes.

Nd:YVO$_4$, and other crystals that have strong thermal lens properties, can have a thermal lens of controlled ellipticity, such as circular, by proper control of heat

15   conduction in the crystal, as described in U.S. Serial No. 08/191,654, filed February 4, 1994.

In Figure 5, a half symmetric resonator 58 includes a laser crystal 60. Resonator mirror 62 and output coupler 64 define a resonator cavity of length L. In Figure 5, as with all Figures in this disclosure, like reference numerals denote the

20   same elements. The distance between resonator mirror 62 and laser crystal 60 is L1, and the distance between output coupler 64 and laser crystal 60 is L2. Resonator 58 can be made to become almost a perfect confocal resonator when L1 << L2, F = L, and R1, R2 >> L. R1 is the radius of curvature of resonator mirror 62, R2 is the radius of curvature of output coupler 64, and F is the focal length of laser crystal 60.

25   Additionally, a strong thermal lens material, such as Nd:YAG or Nd:YVO$_4$, can be used as the laser crystal 60 in order that its focussing power modifies the resonator and its stability. In essence, the positions of the g parameters of this laser on the stability diagram of Figure 1(a) are moved more towards that of a perfect confocal resonator. The effects of a strong thermal lens may be sufficient to create a

30   confocal resonator even with flat mirrors. However, it is preferred if curved mirrors are employed. This can improve the sensitivity of the laser to misalignment. Another

useful configuration is confocal-to-concentric, which is especially useful for a Q-switched Nd:YAG laser.

Figure 6 shows a symmetric nearly confocal resonator 66 with a folded geometry. The resonator is defined by an output coupler 68, with a radius of curvature R1, and a resonator mirror 70, with a radius of curvature R2. L1 is the distance between output coupler 68 and laser crystal 72, L2 is the distance between resonator mirror 70 and laser crystal 72. Fold mirror 74 is typically flat, and therefore has a radius of curvature R3 equal to infinity. For a symmetric resonator, L1 = L2, and R1 = R2. Laser crystal 72 is a strong thermal lens material such as Nd:YAG or Nd:YVO$_4$, with a thermal lens of controlled ellipticity.

A "two port" resonator 76, shown in Figure 7, is defined by an output coupler 78 with radius of curvature of R1, a resonator mirror 80 with radius of curvature R2, and two fold mirrors 82 and 84 that define a fold arm of resonator 76. The term "port" refers to a point where diode pump light is input. Two laser crystals 86 and 88 are positioned along a fold arm optical axis 90. Although two crystals are shown, it is possible to use one. Two diode pump sources 44, two sets of optical fibers 52 and two sets of telescope arrangements of lenses 54 and 56 are included. It is possible to use one diode pump source and a bifurcated fiber bundle. Two pump sources are used to increase the output power of resonator 76. In order to minimize damage to the laser crystals, two crystals 86 and 88 are used. Crystals 86 and 88 can be made of a strong thermal lens material including but not limited to Nd:YVO$_4$. It is also possible to use only one crystal when a single Nd:YVO$_4$ crystal is used, it is possible to generate over 13 W of TEM$_{00}$ output for 26W of incident pump light.

Fold mirrors 82 and 84 are dichroic. The optics are HR at the laser wavelength, and HE at the pump wavelength. They can be called "pump windows". Two pump beams, each coming from a diode pump source 44, each provide half of the total pump power. Again, this provides a margin against exceeding the fracture limit of the incident face of the laser crystal. The two pump beams are configured in such a way as to insure their antiparallelism in the laser crystal and their coaxial propagation with respect to the TEM$_{00}$ mode of resonator 76. This produces a

cylindrically shaped pump volume, and a normally radially symmetric composite thermal lens.

Optimal transverse alignment of the two telescope devices that image the pump light into crystals 86 and 88, through lenses 54 and 56, can be achieved by insuring that the pump light from diode sources 44, through one fiber 52, or bundle of fibers, is optimally coupled into the other fiber 52, or bundle of fibers, in the absence of laser crystals 86 and 88. Upon insertion of crystals 86 and 88 it is not necessary to make significant further adjustments to the transverse alignment of the telescopes, but some adjustment may be desired as the entire telescope system is locked in place. A simple optimization of the longitudinal positions of the two telescopes may be necessary after the insertion of crystals 86 and 88. Output coupler 78 and resonator mirror 80 may also be adjusted to ensure the concentricity of the pumped cylindrical volume and the TEM_{00} mode of resonator 76. An aperture 92 may be included to ensure oscillation in the lowest order mode. This is typically required.

When a strong thermal lens crystal is used, such as Nd:YAG or $Nd:YVO_4$, the magnitude of the thermal lenses in crystals 86 and 88 is such that resonator 76 cavity can be nearly confocal. Resonator 76 is geometrically symmetric about its center, ensuring that the mode size in both crystals 86 and 88 is nearly identical, and that losses due to the aberrated parts of the thermal lenses are minimized. The TEM_{00} mode sizes in the two highly aberrated pumped volumes are nearly identical. Additionally, the two pumped volumes in crystals 86 and 88 are nearly identical. The close proximity of crystals 86 and 88 allows them to act nearly as a single composite lens and minimizes undesirable dynamic behavior between them and the spatial mode of resonator 76. The close proximity of crystals 86 and 88 to the midpoint of resonator 76 ensures its symmetry. A single crystal can also be used. It should be noted that good results can also be obtained with somewhat asymmetric resonators, especially when the properties of the resonators are similar to those described for a confocal-to-concentric or a plane-parallel-to-confocal resonator. For example, asymmetric resonators can still have the product $(g_1)(g_2) = 0.5$, as is well-known.

In one embodiment, the resonator has an overall length of approximately 20 cm, and the composite thermal lens crystals 86 and 88 are at the center of the cavity of approximate composite focal length F equal to about 9 cm. A single crystal can also be used. This is achieved for 13 W incident power per port. An aperture 92 is

5 used to ensure TEM_{00} operation. In this embodiment, dichroic fold mirrors 82 and 84 are flat. Additionally, in this embodiment output coupler 78 and resonator mirror 80 are flat, or are of long radius curvature. In another embodiment, resonator 76 has a length of about 23 cm, with the same thermal lens power, and includes flat fold mirrors 82 and 84. However, output coupler 78 and resonator mirror 80 are of 60

10 cm curvature. The resonator of this embodiment is easier to align at low power due to the mirror curvatures, and exhibits excellent pointing stability and insensitivity to misalignment. When $Nd:YVO_4$ is used, over 13 W of output power can be generated in a round, TEM_{00} mode, for 26 W of incident diode pump power, which is therefore >50% optical-to-optical efficiency. In both embodiments, the resonators

15 are nearly confocal; the mode size from one end of the resonator to the other varies by not much more than a factor of the square root of 2. In some cases, these resonators are confocal-to-concentric. In this case, the mode size varies by about a factor of two from one end of the resonator to the other, which is similar to the case of the confocal resonator. With regard to the stability diagram of Figure 1(a), both

20 resonators are in the lower half of the diagram, between confocal and concentric, as compared to the upper half, which is between confocal and plane parallel.

The ratio of TEM_{00} mode diameter in crystals 86 and 88 to pump beam diameter is from 1.2 to as low as 0.6. In one embodiment it is 0.83.

The ratio of the TEM_{00} mode diameter in crystals 86 and 88 is less than unity

25 in one embodiment. When a fiber bundle is utilized, the ratio of the TEM_{00} mode diameter of each crystal 86 and 88, to the diameter of a nearly top hat shaped pump beam, is less than unity to about 0.83. This is in contrast to prior teachings that a ratio of less than unity is inefficient. The TEM_{00} mode diameter in crystals 86 and 88 is defined traditionally as the diameter at which the mode intensity is 1/e2 (~13.5%)

30 of its peak intensity. The pump beam diameter in the crystal is defined as the

diameter of the image of the pump beam in the crystal. The intensity distribution of the pump beam is close to a top hat profile.

Although prior investigators have indicated that ratios less than unity should result in lasers that are not efficient, for either strong or weak thermal lens materials, the present invention produces a different result. In one embodiment, the combination of strong thermal lens laser crystals 86, 88, such as $Nd:YVO_4$, management of heat conduction through the "c" crystal faces, and the use of a fiber-coupled diode pump source results in a highly efficient laser that operates in the TEM_{00} mode over a wide range of pump powers.

Nd:YAG can be used with similar results. An intracavity polarizer, such as a Brewster plate, is required to insure well-polarized output. In Nd:YAG, not only are thermal lensing and thermal aberrations problematic, but thermal birefringence is as well. With the present invention, it is found that the losses due to both effects are reduced significantly when the TEM_{00} mode diameter in the crystal is slightly smaller than the pump beam diameter in the crystal. The areas of the Nd:YAG crystal that provide the greatest birefringence are at the edges of the pump beam diameter in the Nd:YAG crystal. The strongest depolarization effects are therefore seen when mode sizes typical for conventional mode matching are used. If the TEM_{00} mode size is larger than the high power pump beam, then parts of the TEM_{00} beam pass through the thermally birefringent areas, experience rotation, and then rejection or loss by an intracavity polarizer. With the present invention a pump beam size slightly larger than the TEM_{00} mode diameter in the crystal minimizes losses due to birefringence.

Figure 8 illustrates a schematic of resonator 76 in an unfolded geometry. It is intended to show the respective lengths of components in resonator 76. For a symmetric resonator, L1 = L2, F1 = F2, R1 = R2, and L3 << L1, L2.

A double "Z" folded confocal resonator 92 is illustrated in Figure 9. Resonator 92 is defined by an output coupler 94 and a resonator mirror 96. A single laser crystal 98, or two crystals, is positioned along a first fold arm optical axis 100. A single laser crystal 102, or two crystals, is positioned along a second fold arm optical axis 102. An aperture 106 is used. Resonator 92 is symmetric if L1 ~ L2, and L3 << L1, L2.

One embodiment of a 2 port laser has the following characteristics, (i) output powers in the range of about 1-12 W, (ii) an overall optical efficiency greater than about 25% and preferably greater than 40%, (iii) an optical slope efficiency in a TEM_{00} mode of greater than 40%, (iv) a ratio of the TEM_{00} mode diameter to the

5   pump beam diameter in the crystal in the range of about 1.2 to 0.8, preferably less than 1.0 to 0.83; an M^2 of less than 1.2, and preferably less than about 1.05 and (v) a least squares deviation of a beam profile from a gaussian of less than about 10%, and preferably about 1%. When $Nd:YVO_4$ is used, the output beam is naturally polarized, parallel to the "c" axis of the $Nd:YVO_4$ crystal. When Nd:YAG is used,

10   the system can either be optimized as an unpolarized laser, or it can be polarized by the insertion of an intracavity polarizing element, such as one or more Brewster plates.

Figure 10 depicts a "Z" configuration resonator that includes an optional Q-switch 104 and a polarizing element 106. Suitable Q-switch devices are available

15   from NEOS, in Melbourne, Florida. Either acousto-optic or electro-optic devices can be used. A preferred embodiment includes an acousto-optic Q-switch. Polarizing element 106 can be one or more Brewster plates, as are used when Nd:YAG is the laser crystal and a polarized output beam is required. When $Nd:YVO_4$ is used, the resonator dimensions are similar to those described for

20   Resonator 76 of Figure 7. When Nd:YAG is used, similar dimensions can be used, but a preferred embodiment is larger in overall length. The overall cavity length of a preferred embodiment with Nd:YAG is approximately 65 to 70 cm, with correspondingly larger mode sizes and pump beam sizes (for example 0.85 mm and 1.05 mm, respectively). The Nd:YAG system is approximately confocal-to-

25   concentric, and is nearly symmetric. Figure 11 depicts the mode size as a function of position in the resonator of Figure 10. This mode size plot is very similar to the plot for Resonator 76 of Figure 7. The TEM_{00} mode size varies by just about a factor of two from one end to the other. The laser is about four Rayleigh ranges in length. It can be Q-switched from 0 to 50 kHz, with dynamically changing repetition rate, with

30   minimal change to the mode sizes and very high Q-switched stability over this range.

In contrast, resonator designs other than the confocal-to-concentric design can exhibit instabilities when Q-switched repetition rates are varied.

Thermal birefringence can be problematic when Nd:YAG is use. Additionally, strong thermal birefringence is seen in YAG. This is primarily because

5   the index of refraction in these materials is a strong function of temperature (dn/dT is large), and the deposition of heat by the pump beam induces large thermal gradients. These gradients also induce stress, which also results in non-uniform changes in the index of refraction. It has been generally believed that strong thermal focussing and thermal birefringence is a hindrance in the design and construction of an efficient

10   laser with high beam quality, and therefore, there has not been great success in the use of materials with strong thermal focussing and thermal birefringence in highly efficient, high power diode-bar-pumped lasers.

When Nd:YAG is used as the laser medium, an additional problem thermal birefringence in a high-power, end-pumped geometry. The effect of thermal

15   birefringence is well-known in lamp-pumped Nd:YAG lasers (see for example Koechner, *Solid-State Laser Engineering*, vol. 3, p. 393). Many laser applications require a polarized beam; thermal birefringence results in spatially-dependent polarization rotation of parts of the cavity eigenmode within the laser crystal and thus loss when the eigenmode passes through an intracavity polarizer. This loss can be

20   significant, and can severely limit the output power of a polarized laser. In the present invention, it is found that a TEM_{00} mode size slightly smaller than the pump beam size minimizes loss due to thermal birefringence, especially when Nd:YAG is used. Fore example, a mode-size-to-pump-beam size-ratio of ~0.85 is found to be optimal in a high power, diode-end-pumped, polarized, Nd:YAG laser.

25   When $Nd:YVO_4$ is used, the gains can be much high than those with Nd:YAG. This is due to a stimulated emission cross section that is many times that of YAG. As an example, in a confocal-to-concentric resonator with one $Nd:YVO_4$ crystal pumped by 13 W at each end (a total of 26 W), a round trip small signal gain of over 30 is achieved. While the high gain allows short pulse generation, it is so

30   high that one skilled in the art would typically chose an electro-optic Q-switch, which can typically provide greater loss and faster turn-off times than can an acousto-optic

Q-switch. For example, in the TFR product, available from Spectra-Physics Lasers, Mountain View, CA, an electro-optic Q-switch is used in a very high gain diode-pumped laser. However, there are drawbacks to using electro-optic devices. It is more difficult to drive these devices at high repetition rates, like 20 to 50 kHz, while

5   maintaining adequate performance of the Q-switch device. Additionally, these devices typically require high voltage pulses, which is sometimes inconvenient to provide. On the contrary, it is straightforward to modulate an acousto-optic Q-switch at high repetition rates.

It has been reported that end-pumped $Nd:YVO_4$ lasers can be acousto-

10   optically Q-switched at output power levels of 2.5 W and beam qualities of $M^2 \sim 1.5$ as in M.S. Keirstead et al, paper CFM4, in CLEO Technical Digest, 1993, Vol. 11, Optical Society of America. Based upon this report, it is not obvious that this beam quality can be improved to closer to $M^2 = 1.1$, or if the power can be scaled, still with an end-pumped, Q-switched design. Thermal aberrations have been reported to limit

15   scaling of TEM_{00} mode lasers, and the higher gain can result from some high power end-pumped configurations, which can render acousto-optic Q-switching difficult. It has also been reported that beam qualities of $M^2 \sim 1.1$ and powers of ~ 4 W could be generated with similar Q-switched $Nd:YVO_4$ lasers (Nighan et al, OE/LASER 1995, SPIE 2380). It has been reported that higher power (> 4 W) continuous wave (CW)

20   end-pumped $Nd:YVO_4$ lasers can be built (by the inventors of this patent, in Nighan, Jr. et al, paper CMD5, CLEO Technical Digest, 1995, Vol. 15, Optical Society of America), but no Q-switched results were reported by the inventors at that time. The prior art does not indicate that a high-power (> 4 W average output power), diode-pumped, high-repetition rate (> 10 kHz), acousto-optically Q-switched, good beam

25   quality ($M^2 \sim 1.5$) $Nd:YVO_4$ laser end-pumped can be constructed.

A preferred embodiment of a confocal-to-concentric, high power $Nd:YVO_4$ laser can include an acousto-optic Q-switch and provide up to 10 W of average output power at a repetition rate of 50 kHz, with a pulse duration of approximately 20 nsec, and a beam quality of $M^2 \sim 1.1$. This laser can also provide 8 W of output

30   at 20 kHz, with pulse durations of ~ 14 nsec. A total pump power of 26 W is used, as with the CW version of this laser. The output coupler reflectance is about 65%.

The laser resonator path length is about 25 cm. The resulting thermal focussing power results in a laser that is confocal-to-concentric in a preferred embodiment. A perfectly symmetric cavity is not required, but a preferred embodiment is nearly symmetric.

5   The Q-switch must provide adequate loss modulation to suppress laser oscillation when RF power is applied. While complete suppression is preferred, some low level CW laser oscillation or leakage can be acceptable (for example, 500 mW leakage from a laser that would provide 10 W when Q-switched at 50 kHz). Some low level of leakage does not adversely affect high repetition rate Q-switching,

10   at repetition rates above 10 kHz, for example. An SF10 device, available from NEOS of Melbourne, Florida, is adequate, when approximately 5 W of RF power is applied. The single pass loss modulation is greater than 70%, i.e. the throughput is <30%. Higher loss modulation is preferred in order to insure complete suppression of laser oscillation. Other acousto-optic Q-switch devices are also suitable, provided

15   that sufficient loss is provided.

Another important parameter of any Q-switch is its opening time, or rise time. The implications of this effect on laser performance are well-known, and are described in Lasers, by Siegman, 1986, Chapter 26. Typically, for an acousto-optic Q-switch, this time is approximately 100 nsec for a 1 mm aperture, and therefore ~

20   50 nsec for a 0.5 mm aperture. The Q-switch acts like a fast shutter in the cavity; this time refers to its opening time. It is typically limited by the acoustic velocity in the acousto-optic material. For a very high gain laser, like a high energy flash-lamp-pumped Nd:YAG laser, this rise time would be very slow relative to the build-up time of a laser pulse in the cavity, and therefore would be a very lossy Q-switch,

25   leading to inefficient operation. A high-power (over 4 W output) diode-end-pumped Nd:YVO$_4$ laser is also a high gain laser, but acousto-optic Q-switching can be used under certain conditions in this invention. First, the device must provide adequate loss, and second, it must have an opening time that is acceptably fast with respect to the build-up time of a laser pulse in the Q-switched laser cavity. The embodiment of

30   a high power (>4 W), diode-pumped, acousto-optically Q-switched Nd:YVO$_4$ laser meets these requirements when loss modulation is approximately 70% or greater and

the repetition rate of the laser is higher than 10 kHz. The high repetition rate requirement limits the build-up time of the laser pulse in the laser cavity. It is well-known that this build-up time increases as the repetition rate of the laser is increased. In this embodiment, operation above 10 kHz ensures a sufficiently long build-up

5   time. In order to increase the loss modulation provided by the acousto-optic Q-switching, multiple Q-switch devices can be used within a single diode-pumped Nd:YVO$_4$ laser. Additionally, multiple laser crystals can be used within a single diode-pumped Nd:YVO$_4$ laser. Each crystal can be placed in a separate arm of the laser resonator, if necessary, as is shown in Figure 9.

10   An embodiment of the high-power, diode-pumped, high-repetition rate, acousto-optically Q-switched Nd:YVO$_4$ laser is as shown in Figure 10. It is end-pumped in a preferred embodiment, but side-pumping could be employed if appropriate care were taken. The dopant density of the Nd:YVO$_4$ crystal is about 0.5% in a preferred embodiment. Further included, but not shown, can be

15   depolarizing elements between the output of the fiber bundles and the laser crystal. This insures a uniform absorption of the pump light in the laser crystal as a function of fiber conditions. The embodiment provides over 4 W of output power, and up to 10 W. It also provides short pulses at repetition rates over   10 kHz. At high repetition rate, the pulses generated are significantly shorter than those generated

20   with other media. This is due to the high stimulated emission cross section and the resulting high gain The cavity design is nominally symmetric, although perfect symmetry is not required. Any thermal lens generation in the Q-switch device must be taken into account when the cavity is optimized. A preferred embodiment also includes a pump beam size that is somewhat larger than the TEM$_{00}$ mode size in the

25   Nd:YVO$_4$ crystal. A mode control aperture is typically required to ensure TEM$_{00}$ operation.

Changes and modifications in the specifically described embodiments can be carried out without departing from the scope of the invention which is intended to be limited only by the scope of the appended claims.

30   The foregoing description of a preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be

exhaustive or to limit the invention to the precise forms disclosed. Obviously, many

modifications and variations will be apparent to practitioners skilled in this art. It is

intended that the scope of the invention be defined by the following claims and their

equivalents.

5   What is claimed is:

CLAIMS

1.   A high power diode pumped, acousto-optically Q-switched Nd:YVO$_4$ laser, comprising:

at least one resonator mirror and an output coupler defining a resonator;

at least one acousto-optic Q-switch device;

5   at least one laser crystal with strong thermal focussing properties positioned in the resonator;

at least one diode pump source supplying a pump beam to the laser crystal or crystals, generating an output beam; and

a power source supplying power to the diode pump source.

10   2. A high power diode pumped, acousto-optically Q-switched Nd:YVO$_4$ laser, comprising:

at least one resonator mirror and an output coupler defining a resonator cavity;

at least one acousto-optic Q-switch device;

15   at least one laser crystal with strong thermal focussing properties positioned in the resonator cavity;

at least one diode pump source supplying a pump beam to the laser crystal or crystals, the pump beam producing a thermal lens or lenses in the laser crystal or crystals, the combination of the laser crystal or crystals, thermal lens or lenses,

20   resonator mirrors and output coupler creating a confocal-to-concentric resonator generating an output beam; and

a power source supplying power to the diode pump source.

3.   A high power diode pumped, acousto-optically Q-switched Nd:YVO$_4$ laser, comprising:

25   at least one resonator mirror and an output coupler defining a resonator cavity;

at least one acousto-optic Q-switch device;

at least one laser crystal with strong thermal focussing properties positioned in the resonator cavity;

30   at least one diode pump source supplying a pump beam to the laser crystal, the pump beam end-pumping the crystal or crystals, generating an output beam; and a power source supplying power to the diode pump source.

4. The laser of claim 2, where the pump beam end-pumps the laser crystal.

5. The laser of claim 1, wherein the Nd:YVO$_4$ laser crystal has a 0.5%

35   doping.

6. The laser of claim 2, wherein the Nd:YVO$_4$ laser crystal has a 0.5% doping.

7. The laser of claim 3, wherein the Nd:YVO$_4$ laser crystal has a 0.5% doping.

40   8. The laser of claim 2, wherein a ratio of a TEM$_{00}$ mode diameter of the laser crystal to a pump beam diameter in the crystal is about less than about 1.0, to about 0.83.

9. The laser of claim 3, wherein a ratio of a TEM$_{00}$ mode diameter of the laser crystal to a pump beam diameter in the crystal is about less than about 1.0, to

45   about 0.83.

10.   The laser of claim 1, wherein the laser has an optical slope efficiency in a TEM$_{00}$ mode of greater than about 40%.

11.   The laser of claim 2, wherein the laser has an optical slope efficiency in a TEM$_{00}$ mode of greater than about 40%

-27-

50

12.   The laser of claim 3, wherein the laser has an optical slope efficiency in a TEM_{00} mode of greater than about 40%

13.   The laser of claim 1, wherein the laser has an optical efficiency of greater than about 20%.

14.   The laser of claim 2, wherein the laser has an optical efficiency of

55   greater than about 20%.

15.   The laser of claim 3, wherein the laser has an optical efficiency of greater than about 20%.

16.   The laser of claim 1, wherein the output beam has a power greater than about 4 W.

60   17.   The laser of claim 2, wherein the output beam has a power greater than about 4 W.

18.   The laser of claim 3, wherein the output beam has a power greater than about 4 W.

19.   The laser of claim 1, wherein the diode pump sources are diode bars.

65   20.   The laser of claim 2, wherein the diode pump sources are diode bars.

21.   The laser of claim 3, wherein the diode pump sources are diode bars.

22.   The laser of claim 1, wherein the diode pump sources are fiber-coupled diode bars.

23. The laser of claim 2, wherein the diode pump sources are fiber-
coupled diode bars

24. The laser of claim 3, wherein the diode pump sources are fiber-
coupled diode bars.

25. The laser of claim 1, further including an aperture.

26. The laser of claim 2, further including an aperture.

27. The laser of claim 3, further including an aperture.

28. The laser of claim 1, further providing an output beam of
$M^2 < 1.5$.

29. The laser of claim 2, further providing an output beam of
$M^2 < 1.5$.

30. The laser of claim 3, further providing an output beam of
$M^2 < 1.5$.

31. The laser of claim 1, with the Q-switch device modulated so as to
provide an output beam that is comprised of a train of Q-switched pulses at a
repetition rate greater than 10 kHz.

32. The laser of claim 2, with the Q-switch device modulated so as to
provide an output beam that is comprised of a train of Q-switched pulses at a
repetition rate greater than 10 kHz.

33.   The laser of claim 3, with the Q-switch device modulated so as to
provide an output beam that is comprised of a train of Q-switched pulses at a
90   repetition rate greater than 10 kHz.

34.   The laser of claim 1, further including at least one depolarizing device
between at least one diode pump source and at least one laser crystal.

35.   The laser of claim 2, further including at least one depolarizing device
between at least one diode pump source and at least one laser crystal.

95   36.   The laser of claim 3, further including at least one depolarizing device
between at least one diode pump source and at least one laser crystal.

FIG.1(a)

FIG.1(b)

FIG.1(c)

L

20   22

R1 = R2 = L

18

FIG.2

R1   L   R2

34

32

30

FIG.3

FIG.4

4 / 9

FIG.5

5 / 9

FIG.6

6 / 9

FIG.7

FIG.8

8 / 9

FIG.9

9/9

Q-SWITCH
DEVICE

106   104

APERTURE

POLARIZING
DEVICE

FIG.10

1   3 6 9 11   13

0   69.2

MODE SIZE AS A FUNCTION OF POSITION IN A
CONFOCAL – TO – CONCENTRIC RESONATOR
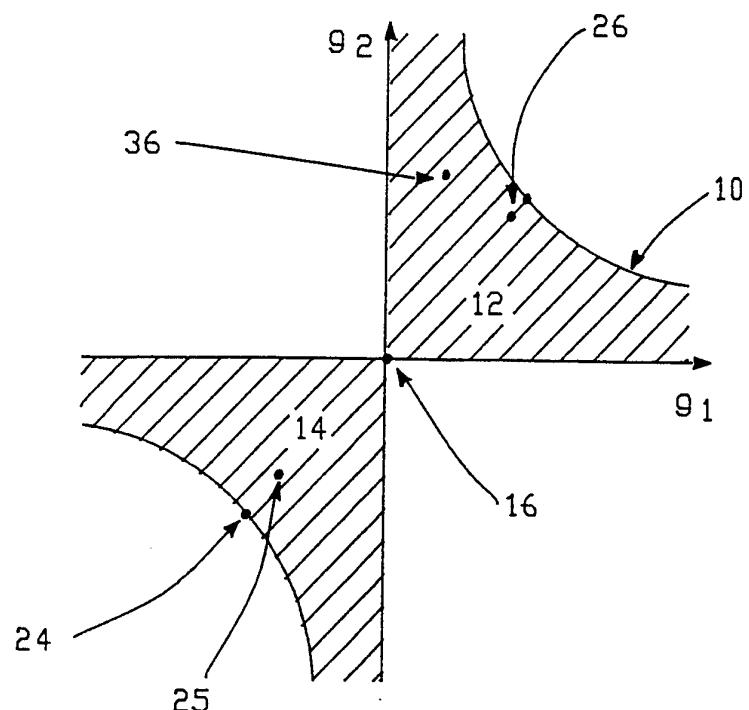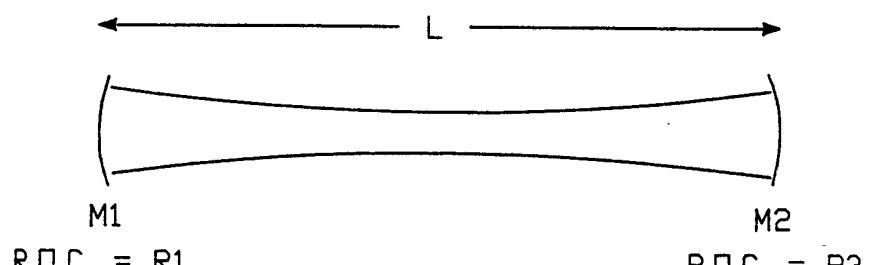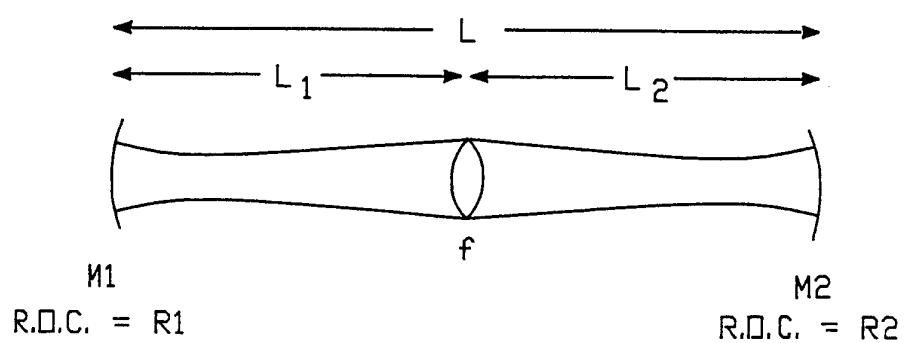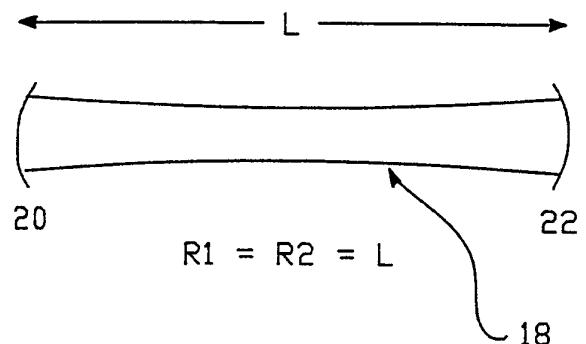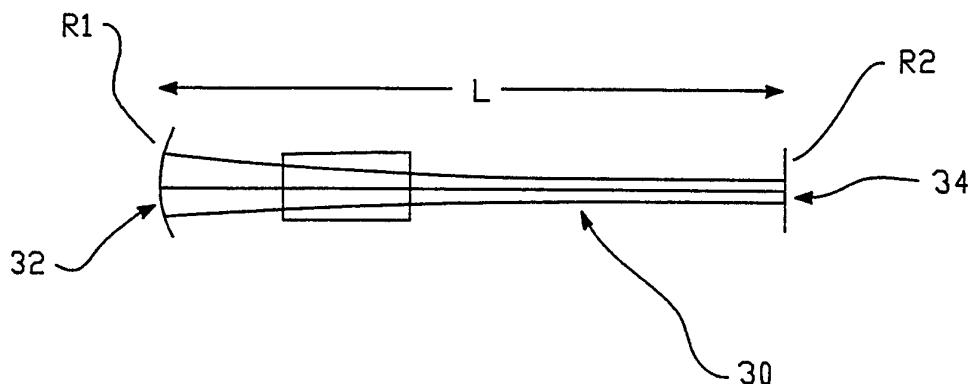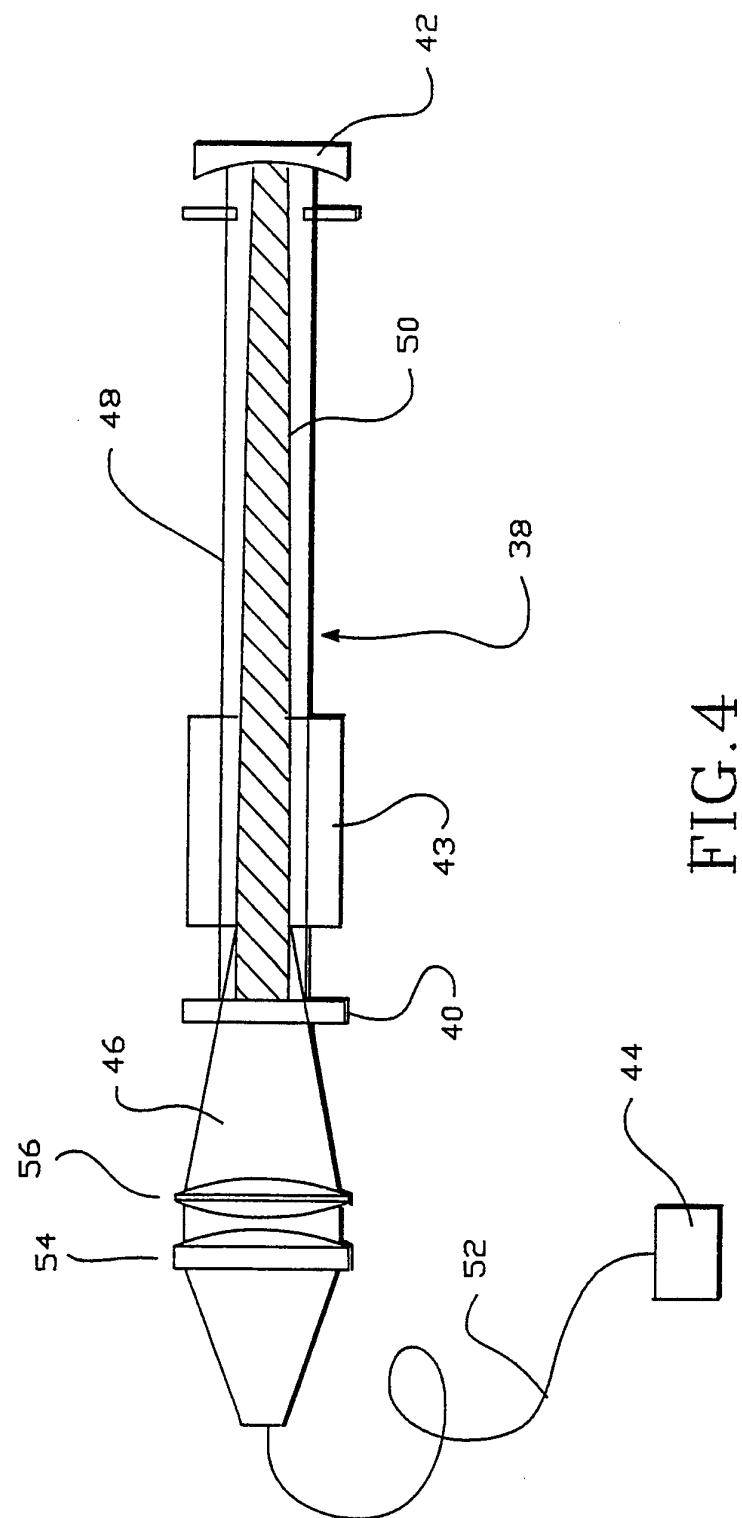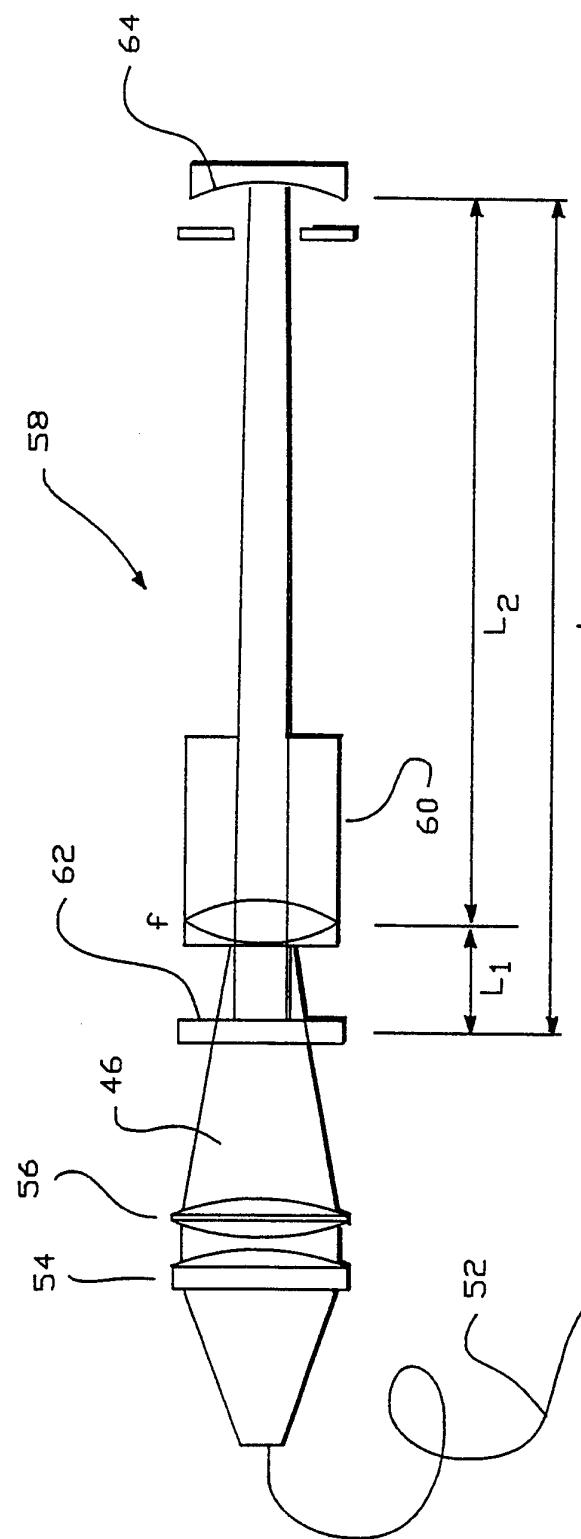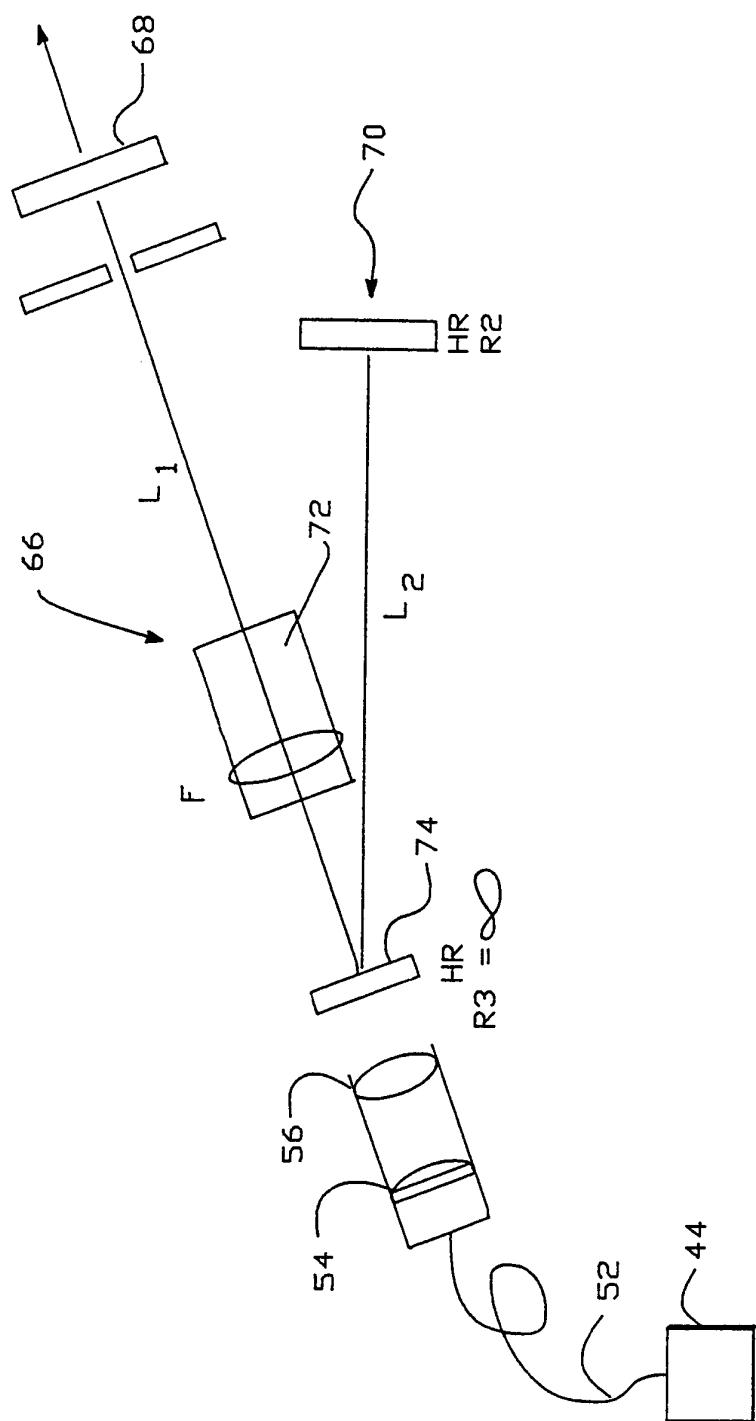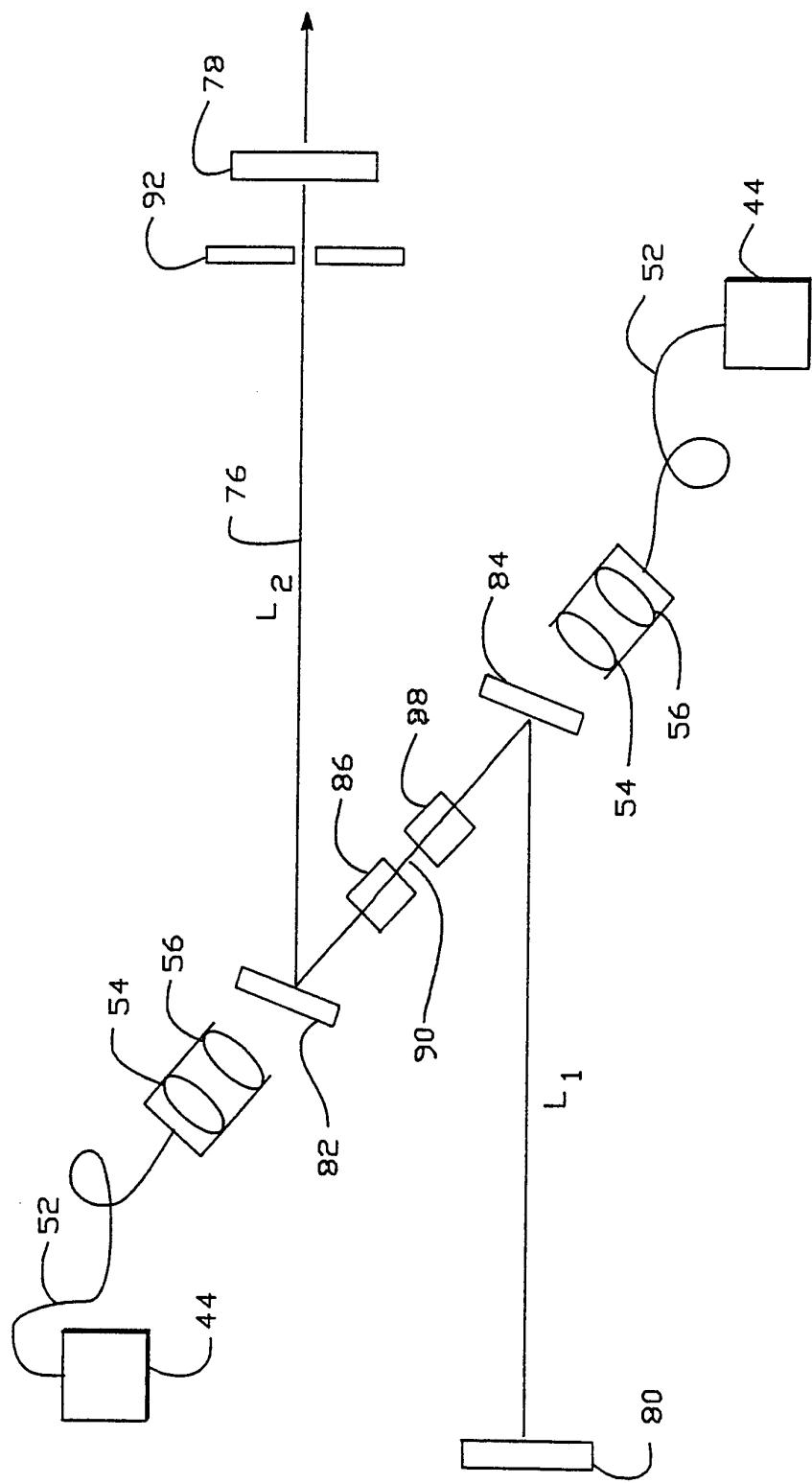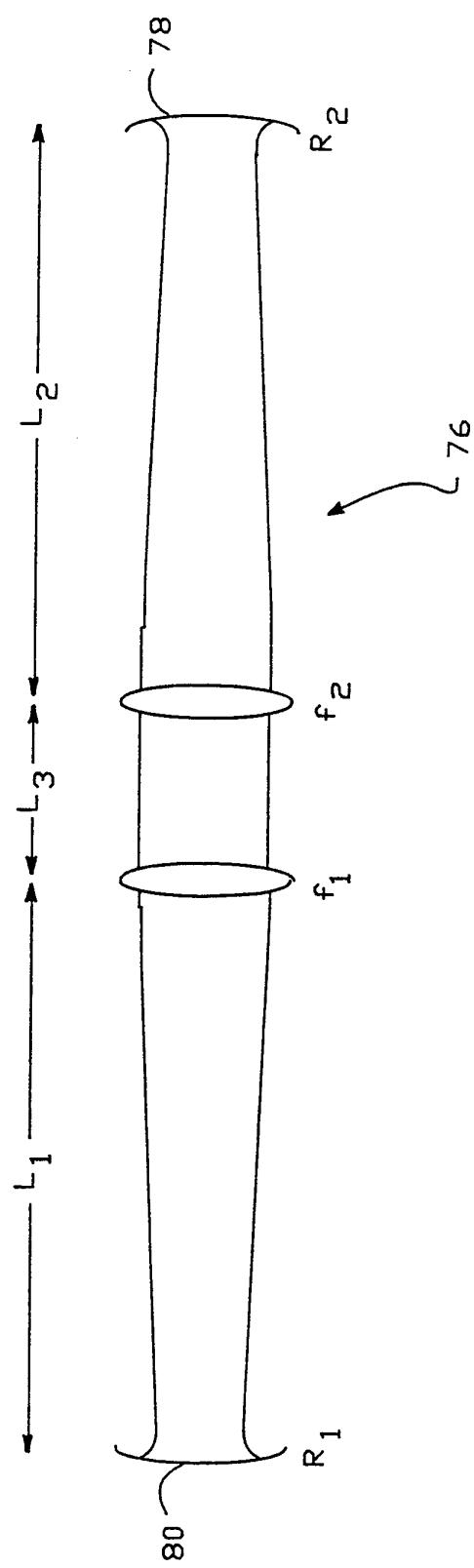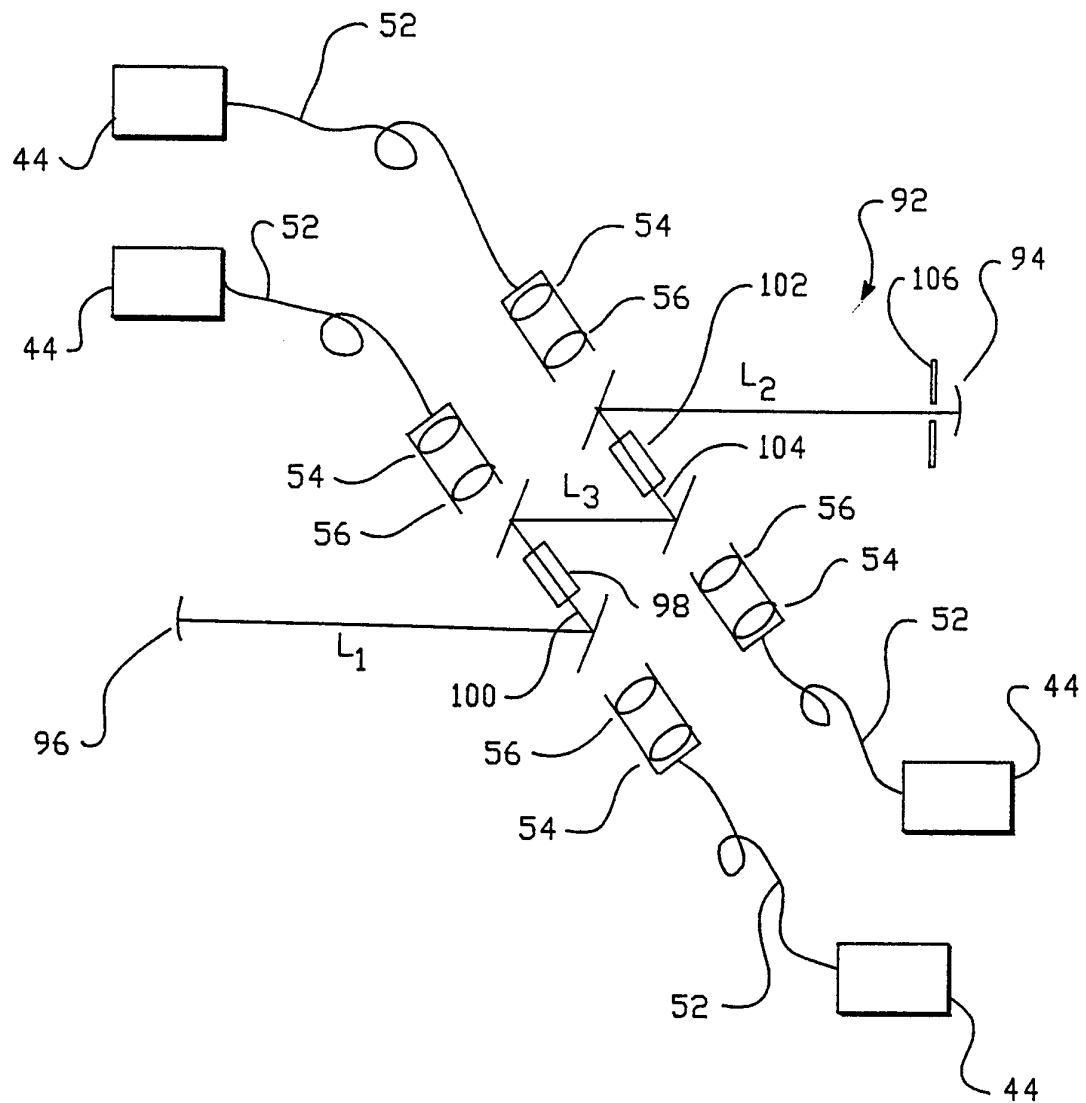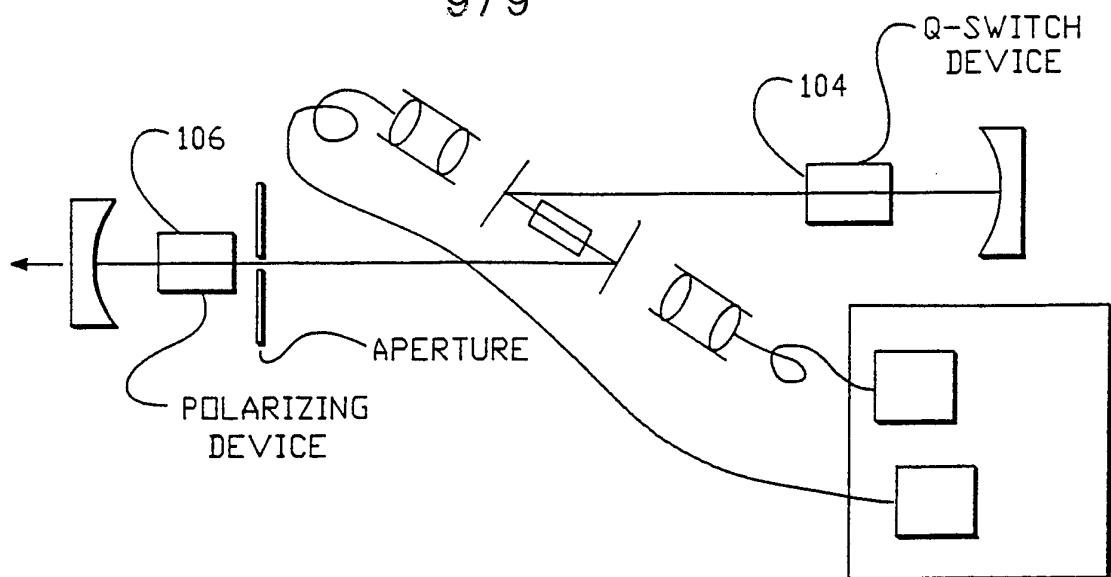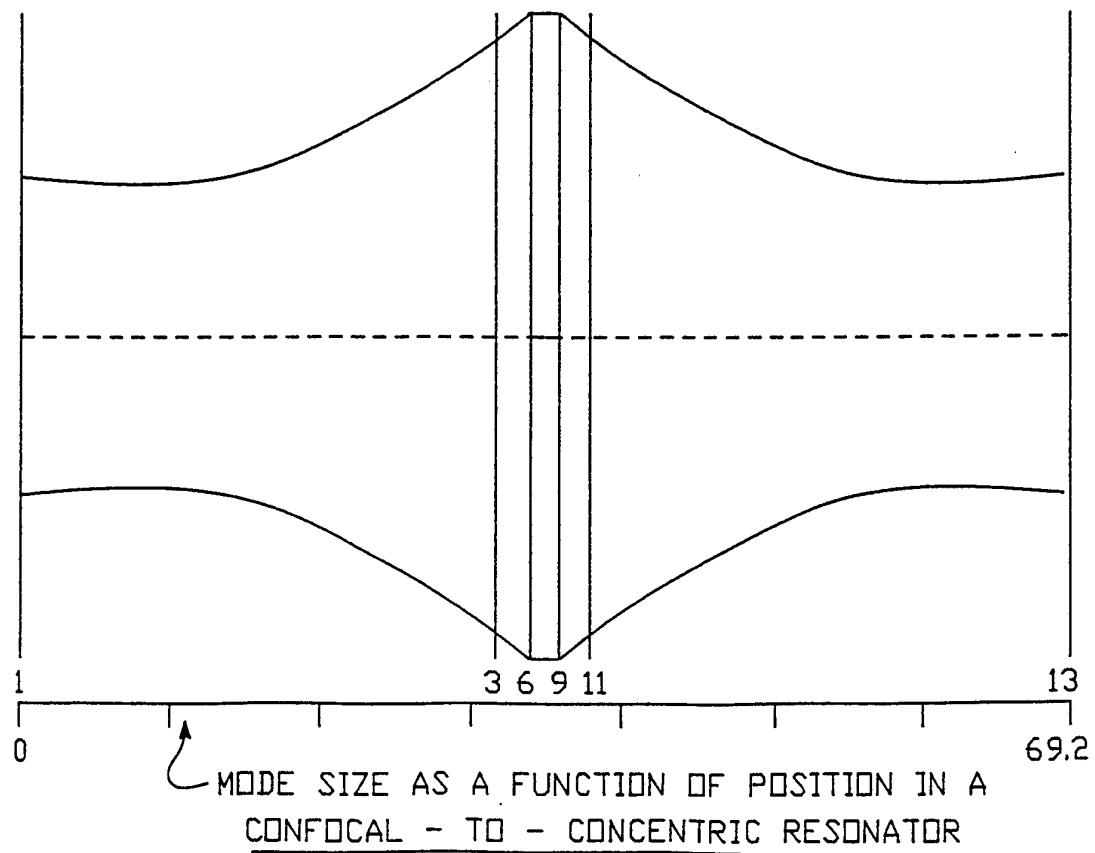
FIG.11

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   H01S3/0941   H01S3/08   H01S3/117

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   H01S

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US,A,5 410 559 (NIGHAN JR WILLIAM L ET AL) 25 April 1995 cited in the application see abstract see column 5, line 55 - column 6, line 40 see column 7, line 55 - column 9, line 11 see claims; figure 1 --- -/--	1,3,5,7, 9,10,12, 13,15, 16,18, 19,21, 22,24, 25,27, 28,30

[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 December 1996	08.01.97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Iasevoli, R

INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SPIE PROCEEDINGS VOL 2380 - UV AND VISIBLE LASERS AND LASER CRYSTAL GROWTH, SAN JOSE, CA, USA, 7-9 FEB. 1995, vol. 2380, ISSN 0277-786X, pages 138-143, XP000579455 NIGHAN W L JR ET AL: "Harmonic generation at high repetition rate with Q-switched Nd:YVO/sub 4/ lasers" cited in the application see abstract; sections 1-3; figure 1 ---	1,3,16, 18,19, 21,22, 24,25, 27,28, 30,31
X	SPIE PROCEEDINGS VOL 1865 - DIODE PUMPING OF AVERAGE-POWER SOLID STATE LASERS, LOS ANGELES, CA, USA, 21-22 JAN. 1993, vol. 1865, ISSN 0277-786X, pages 61-72, XP000534134 HUTCHISON S B ET AL: "Advances of 3-10 Watt average power diode pumped lasers" see page 68; figures 10,11 ---	1,3,19, 21,22, 24,25, 27,28, 30,31
A	KOECHNER W: "Solid-state laser engineering - (2nd edition)" , SPRINGER-VERLAG , BERLIN, GERMANY XP002011993 cited in the application see page 174 - page 191 particularly sections 5.1.4,5.1.7; page 191, paragraph 2; figures 5.7,5.12,5.20 -----	

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
US-A-5410559	25-04-95	EP-A-	0742963	20-11-96
		WO-A-	9521477	10-08-95
		US-A-	5577060	19-11-96