

DESCRIPTION

LASER RESONATOR, LASER, LASER APPLIED UNIT, LASER OSCILLATION METHOD

Technical Field

This invention relates to an optoelectronic field and, more specifically, to a laser resonator, a laser, a laser applied unit and a laser oscillation method for use in laser printers, optical shaping units, optical disk drives, DNA sequencers, particle counters and the like.

Background Art

With the progress of the advanced information communication age, demand for adaptation of computer peripheral laser applied units, such as optical disk drives and laser printers, to short wavelengths is arising to meet requirements for improved recording density and high-speed printing. However, as light sources capable of providing a blue color range (wavelength of 400 to 480 nm) which is in high demand for commercialization, only gas lasers such as He-Cd (helium-cadmium) and Ar (argon) lasers are available which are bulky and power consuming. Since lasers are bulky, laser applied units which incorporate a laser as a light source need to be larger than the laser and hence, become bulky. Therefore, there is the problem that such laser applied units cannot be fit in office environment and living environment in which desk top sized units are the

most fit.

Further, there is another problem that a laser applied unit becomes bulky because the conversion efficiency of a laser from input power to laser beams is small and a cooling means is required as most of consumption power turns into heat. There is still another problem that the dislocation of optics caused by the vibration of this cooling means deteriorates the reliability of a laser applied unit. A further problem is that the service life of a laser applied unit is short due to a short service life of a laser caused by gas deterioration or the like.

An attempt has been made to overcome the above problems of a gas laser by applying a wavelength conversion technology such as second harmonic generation (to be abbreviated as "SHG" hereinafter) which is caused by inserting a non-linear optical crystal into the resonator of a solid laser to convert a first laser beam (to be referred to as "fundamental wave" hereinafter in some cases), an oscillation wave of the solid laser, into a wave having half the wavelength of the first laser beam so as to generate a second laser beam. For instance, there has been proposed an SHG system for a solid laser in which $\text{Ti:Al}_2\text{O}_3$ (Ti-Sapphire; to be abbreviated as "Ti-Sap" hereinafter) or Cr:LiSrAlF_6 (chromium added lithium strontium aluminum fluoride; to be abbreviated as "LiSAF" hereinafter) are used as laser crystals capable of oscillating at a wavelength range of 800 to 900 nm. In the SHG light source, the service life of a

laser medium alone has been greatly improved by changing from gas to a solid crystal. However, the excitation light source of the latter LiSAF laser is a Kr (krypton) laser, that is, a gas laser, and hence, there still remain the problems of the prior art. As the excitation light source of a Ti-Sap laser, a green SHG laser which uses a Q switch Nd:YAG (neodymium added yttrium aluminum garnet) laser to generate a fundamental wave is used. Therefore, since the entire laser light source is solidified, its service life is improved. However, since two SHG lasers including the excitation light source are used, the unit becomes complex, bulky and power consuming and hence, does not greatly improve the problems of the prior art. Further, since SHG output is a pulse output in both cases, when it is used in laser applied units such as optical shaping units and optical disk drives, there is the problem that a disconnection point exists in a signal, for example.

It has already been disclosed in R. Scheps, J.F. Myers, H.B. Serreze, A. Rosenberg, R.C. Morris, and M. Long, "Diode-pumped Cr:LiSrAlF₆ laser", Opt. Lett., Vol.16 No.11, p.820 (1991) that excitation is possible with a red semiconductor laser having a wavelength of 670 nm as the excitation light source of the above LiSAF laser. Therefore, it is presumed that there is the possibility of greatly improving the size, power consumption and service life problems of the prior art gas lasers by replacing a Kr laser with a semiconductor laser as an excitation light

source in the SHG light source which uses the above LiSAF laser to generate a fundamental wave.

However, it is disclosed in Qi Zhang, G.J. Dixon, B.H. Chai and P.N. Ke an, "Electronically tuned diode-laser-pumped Cr:LiSrAlF₆ laser", Opt. Lett., Vol.17, No.1, p.43 (1992) that a loss in a resonator greatly reduces the efficiency of a LiSAF laser. For this reason, the possibility of implementation is extremely low unless the cause of reducing the efficiency is investigated and studied to find a solution.

Qi Zhang et al. as mentioned in the foregoing took from the resonator of a LiSAF laser a birefringence filter which is a wavelength tuning element for selecting the wavelength of the LiSAF laser. Generally speaking, a birefringence filter is arranged in a laser resonator of a laser capable of wavelength tuning, such as a LiSAF laser or the like, and has the function of selecting a laser beam having a desired wavelength by providing a loss such as a reflection loss to oscillation beams having wavelengths other than the desired wavelength out of all the oscillation beams. Then Qi Zhang et al. added a resonator dedicated for wavelength tuning including a birefringence filter after the resonator of a LiSAF laser. That is, they proposed means of tuning wavelength without providing a loss caused by the resonator of the LiSAF laser, by feeding back a laser beam having a desired wavelength to the resonator of the LiSAF laser and amplifying the laser beam (USP 5218610). The loss which Qi

Zhang et al. paid attention to is a reflection loss caused by the birefringence filter. Although this system can improve the above loss, it has the possibility that the apparatus may be complex and bulky.

Another attempt has been made to overcome the problems of the prior art, paying attention to the fact that nonuniform energy absorption of a LiSAF crystal as a laser crystal has an effect on a reduction in laser oscillation efficiency. That is, Cr which plays a part in absorption is distributed in different concentrations in an excitation direction to improve a reduction in the efficiency (USP 5287373). However, this system has not been commercially available yet and its effect of improving the problems indicated by Qi Zhang et al. is unknown.

In the optics shown by F. Balembois et al. as described above, an average pulse SHG laser output of 7.4 mW is obtained using a Kr laser as an excitation light source and an average pulse excitation power of 3.3 W. However, as described above, an SHG laser output should be a continuous wave. A required output is considered to be about 10 mW though it differs by each unit. Commercial semiconductor lasers capable of exciting LiSAF lasers have the maximum output of 500 mW in the case of a single stripe. Since output of a fundamental wave is generally in proportion to excitation input in the input/output characteristics of a solid laser, the power of the fundamental wave becomes about 1/6 by changing the excitation light source from a Kr laser

to a semiconductor laser. Further, since an SHG output is in proportion to the square of the power of the fundamental wave, an anticipated SHG output becomes about $1/36$, that is, a pulse output of 0.2 mW. Therefore, it is understood that a practically usable SHG output cannot be obtained without great improvement made on the efficiency. Since the shape, that is, transverse mode, of the output beam of a semiconductor laser is extremely flat, compared with that of a Kr laser, deterioration in excitation efficiency is expected even when a beam shaping technique is applied. Therefore, a further reduction in SHG output is anticipated.

In other words, it is easily anticipated that an SHG laser light source having a practically sufficient output cannot be realized simply by changing the excitation light source from a Kr laser to a semiconductor laser. Further, if a semiconductor laser having a high output is realized in the future, forced cooling means is required because the amount of heat generated from the semiconductor laser itself increases. As the result, there is the possibility that the apparatus will be bulky and power consuming.

As described above, it has been found difficult to realize an SHG laser which makes use of a LiSAF laser excited by a semiconductor laser to solve all the problems of a gas laser simply by combining what have been disclosed heretofore. Therefore, it is now necessary to realize a small-sized, power-saving SHG laser light source and a laser applied unit using such an SHG laser light source by finding

the cause of reducing the efficiency and taking countermeasures.

There is also proposed a method for obtaining a blue laser beam as a second oscillation wave, that is, an SH wave, from an SHG light source having the same output wavelength as that of the afore-mentioned gas laser, wherein the output of a near infrared semiconductor laser shown in Fig. 10 is taken as a first oscillation wave, that is, a fundamental wave, and resonated in an external resonator, and KN (KNbO_3 : potassium niobate) which is a nonlinear optical crystal (to be referred to as "SHG crystal" because wavelength conversions hereinafter are all for SHG) is arranged in the external resonator to obtain the blue laser beam (W.J. Kozlovsky and W. Lenth, "Generation of 41 mW of blue radiation by frequency doubling of a GaAlAs diode laser", Appl. Phys. Lett., Vol.56 No.23, p.2291, 1990).

However, the above SHG light source involves the following advanced technical problems. One of them is that it is necessary to insert an optical isolator 102 to protect the semiconductor laser from reflected light in order to always adjust the oscillation wavelength of the semiconductor laser which is easily affected by disturbance to a wavelength at which the conversion efficiency of KN becomes maximal. Another problem is that reflected light from the resonator should be received by an optical detector 105 to control the length of the external resonator including KN in the order of the wavelength of the

fundamental wave and the electrical output of the optical detector 105 is fed back to a feedback circuit 106 to stably oscillate the semiconductor laser. Therefore, it is expected to be difficult to find solutions to these technical problems for commercialization. In this SHG light source, it is expected to be difficult to solve the above two technical problems for commercialization that the oscillation wavelength of the semiconductor laser easily affected by disturbance is controlled to a wavelength at which the conversion efficiency of KN becomes maximal and that the length of the external resonator including KN is controlled in the order of the wavelength of the fundamental wave.

The inventors of the present invention have found that it is possible to use the above LiSAF laser as a broad-band wavelength variable laser by using a wavelength control element, studied a method for causing a nonlinear crystal to generate SHG light having a blue color range as a second oscillation wave, using this LiSAF laser to generate a first oscillation wave (fundamental wave), and found two problems.

The first problem is that the oscillation threshold value becomes high because wavelength ranges other than the transmission wavelength range of the wavelength control element become a loss in the laser resonator and the output of the excitation semiconductor laser becomes high to obtain a required SHG laser output. Fig. 11 shows the input/output characteristics of a semiconductor laser excited wavelength

variable solid laser (to be abbreviated as "LiSAF laser" hereinafter) which uses a LiSAF crystal. The solid line indicates the input/output characteristics of the LiSAF laser when there exists a wavelength control element and the dotted line indicates the input/output characteristics when there is no wavelength control element. The wavelength control element is formed of three quartz plates having different thicknesses as used in dye lasers and Ti sapphire lasers, can narrow the range of wavelength transmitting the quartz plates to 3 nm or less, and can control the laser oscillation wavelength width to 0.1 nm or less. It is understood from Fig. 11 that a loss in the resonator increases and the oscillation threshold value becomes 10 times or more by inserting a wavelength control element having a narrow transmission wavelength range, and hence, a large-sized semiconductor laser is necessary because an excitation input 10 times or more is required to obtain the same output as that when the wavelength control element is not inserted, resulting in a large apparatus for driving and cooling the semiconductor laser and large power consumption. When the wavelength control element is not inserted, the oscillation wavelength width is about 10 nm which is 100 times or more when the wavelength control element is inserted.

The second problem is that a loss in the resonator becomes large and the oscillation threshold value becomes high since a nonlinear KN crystal which has been used

heretofore to obtain blue SHG light has a narrow phase match wavelength half-value width, that is, phase wavelength width at which a SHG wave is generated, of 0.4 nm as shown in Fig. 12, and a high propagation loss of 0.5 %/cm, thereby making it impossible to obtain a sufficient SH output even when the KN crystal is inserted into the LiSAF laser.

There is still another problem that a stable SH output cannot be obtained unless the temperature of the KN crystal is controlled accurately because the wavelength of the KN crystal at which the conversion efficiency becomes maximal changes by 0.3 nm/°C, depending on temperature variations.

Disclosure of the Invention

The inventors have studied the loss in the resonator and found that the loss is connected with the size of the opening of an optical part somehow. The term "opening" means the effective cross section of the optical surface of the optical part in the resonator. That is, it is considered that there is no problem if the opening of the optical part in a regular laser is larger than the diameter of a laser beam. However, the inventors have found that a loss is generated in a LiSAF laser which is a new laser even when the opening of an optical part is normal in size and accomplish the present invention. That is, the present invention is a laser resonator including a laser crystal made of a fluoride containing Cr and at least one optical part, in which an opening in the resonator is substantially 5 times or more the diameter of a first laser beam which is

obtained by oscillating radiation from the laser crystal.

Fig. 13 is a diagram for explaining such a phenomenon that oscillation efficiency is reduced by openings in the resonators of an Nd:YVO₄ (neodymium-added vanadium yttrium oxide) laser as a typical solid laser and a LiSAF laser. The shape of the resonator used in experiments is shown on an upper part of Fig. 13.

The resonator includes a plane mirror formed on an end surface of the laser crystal and a concave mirror. The diameter of an oscillation beam is determined by the curvature radii of these mirrors forming the resonator and the distance between the mirrors. In the plane-concave type resonator shown on an upper part of Fig. 13, the diameter of the beam is minimal at the plane mirror and maximal at the concave mirror. At this point, the curvature radius of the concave mirror is 150 mm, and the effective optical path between the resonator mirrors is slightly shorter than the curvature radius of the mirror. The axis of abscissas of Fig. 13 indicates the distance from the plane mirror and the axis of ordinates on right side indicates the diameter of a beam. The diameter of a beam in the resonator can be calculated from the minimum diameter of a beam obtained from the following expression 1 and the diameter of a beam at each location obtained from the following expression 2 when the transverse mode is TEM₀₀ mode, that is, a round beam.

$$w_0 = \left[\left(\frac{\lambda}{\pi} \right)^2 \frac{d(R_1 - d)(R_2 - d)(R_1 + R_2 - d)}{(R_1 + R_2 - 2d)^2} \right]^{\frac{1}{4}} \quad \text{expression 1}$$

$$w(z) = \left[w_0^2 \left[1 + \left(\frac{\lambda z}{\pi w_0^2} \right)^2 \right] \right]^{\frac{1}{2}} \quad \text{expression 2}$$

In the expression 1, w_0 is the minimum diameter of a beam, λ is the wavelength of a first beam, d is the length of the resonator, and R_1 and R_2 are the curvature radii of the mirrors. In the expression 2, $w(z)$ is the diameter of a beam at a distance z from a position where the diameter of the beam is minimal. The diameter of the beam calculated is about 0.2 mm at the minimum and about 0.8 mm at the maximum. When the diameter of the beam right after the output mirror was measured actually, the calculated value was almost equal to the actual value. An opening having a diameter of 2.5 mm was formed in the resonator and adjusted so that the strength of an oscillation beam became maximal and the actual strength of the oscillation beam was measured.

The axis of ordinates on left side indicates the ratio of oscillation beam strength when an opening is formed to oscillation beam strength when no opening is formed. It was found that, in an Nd:YVO₄ laser, oscillation is possible with an efficiency of 90 % or more when the opening in the resonator is 3 times the diameter of a beam, that is, when the diameter of a beam becomes the maximum of 0.8 mm,

whereas, in a LiSAF laser, the efficiency is reduced to 80 % by setting the opening in the resonator to 5 times or less the diameter of a beam.

The reduction rate of the efficiency of the LiSAF laser is larger than that of the Nd:YVO₄ laser. To obtain the same efficiency of 90 % or more as that of the Nd:YVO₄ laser, the opening is preferably 7 times or more the diameter of a beam. Further, since an efficiency reduction is not seen when the opening is 10 times or more the diameter of a beam, this range is particularly preferred.

Generally speaking, the diameter of a beam is defined as a diameter within the peak strength range of $1/e^2$ or more when the transverse mode is a round TEM₀₀ mode and light intensity shows a Gaussian distribution. Further, when the transverse mode of the beam is other than TEM₀₀, the diameter of a beam is defined as the maximum length connecting the most outer end of the boundary line where light intensity becomes $1/e^2$ or less of its peak. What has been described above defines the lower limit of the opening. The upper limit of the opening is specified by the maximum size of a possibly grown crystal, the size of a crystal processable stably, and the size of a crystal for securing the quality of coating. It is preferred that the upper limit is 1,000 times the diameter of a beam.

Then the inventors have found that a saturation phenomenon exists in the input/output characteristics of a LiSAF laser.

Fig. 14 is a diagram for explaining the comparison of input/output characteristics between a LiSAF laser and a Nd:YVO₄ laser, a typical solid laser. The solid line indicates the input/output characteristics of the LiSAF laser and the dotted line indicates the input/output characteristics of the general solid laser. In the Nd:YVO₄ laser, the input/output characteristics rise at an input value as shown by the dotted line and then excitation input and solid laser output are almost proportional to each other. On the other hand, in the LiSAF laser, as shown by the solid line, there is seen such a phenomenon that an output characteristic reaches saturation after a linear range and oscillation is finally lost even when excitation input increases. As the result, it is found that there is the problem that a stable solid laser output cannot be obtained. The inventors have conducted intensive studies and have found that the above saturation phenomenon and the above oscillation lost phenomenon that are seen in the input/output characteristics of the LiSAF laser as shown in Fig. 14 can be eliminated by controlling the temperature of a laser crystal made of LiSAF. The present invention has been predicated upon this finding.

Fig. 15 is a diagram for explaining the comparison of input/output characteristics of a LiSAF laser when the temperature of a LiSAF crystal is controlled and when the temperature is not controlled. The solid line indicates the input/output characteristics of the laser when the

temperature of the LiSAF crystal is controlled to $15 \pm 5^\circ\text{C}$ and the dotted line indicates the input/output characteristics when the temperature is not controlled. It is seen in Fig. 15 that the linear area is expended by controlling the temperature of the laser crystal and a stable solid laser output can be obtained. Fig. 15 shows the input/output characteristics when the temperature of the LiSAF crystal is set to 15°C . The input/output characteristics obtained by changing the crystal temperature to 10, 20, 30 and 40°C were measured. In either case, the linear area of the input/output characteristics was expanded and a stable solid laser output was obtained. In other words, the lower limit of the temperature control range is a temperature at which the laser crystal is free from dew condensation. The upper limit of the temperature control range is a temperature at which the above oscillation lost phenomenon is not observed under use conditions. It is desired that the temperature T of the laser crystal is controlled in a range of $0 \leq T \leq 50^\circ\text{C}$.

Preferably, at least one of a plurality of mirrors constituting the resonator is formed on one end surface of the laser crystal.

Preferably, at least one of the optical parts is a wavelength control element.

Preferably, a laser comprises a laser crystal made of Cr:LiSrAlF_6 , a resonator structure in which at least one resonator mirror is formed on one end surface of the laser

crystal, a semiconductor laser for exciting the laser crystal, a first laser beam having a wavelength λ_1 that satisfies $780 \leq \lambda_1 \leq 1,000$ nm, which is obtained by oscillating radiation from the laser crystal in the laser resonator, and an opening having a diameter 5 times or more that of the first laser beam which is formed into the resonator.

Further preferably, a laser comprises a laser crystal made of Cr:LiSrAlF_6 , a resonator structure in which at least one resonator mirror is formed on one end surface of the laser crystal, a semiconductor laser for exciting the laser crystal, means for controlling the temperature T of the laser crystal in a range of $0 \leq T \leq 50^\circ\text{C}$, a first laser beam having a wavelength λ_1 that satisfies $780 \leq \lambda_1 \leq 1,000$ nm, which is obtained by oscillating radiation from the laser crystal in the laser resonator, and a wavelength control element having an opening with a diameter 5 times or more that of the first laser beam and formed in the resonator.

Preferably, the optical parts include a wavelength control element and a nonlinear optical crystal.

Further, a birefringence crystal inclined at the Brewster angle may be used as a control element for controlling the oscillation wavelength of a solid laser crystal and any one of quartz (SiO_2), LiNbO_3 and LiTaO_3 may be used as the birefringence crystal.

Preferably, a single quartz plate having a thickness of 0.4 to 3 mm may be used as the birefringence crystal.

Further, LBO (LiB_3O_5) and/or BBO ($\beta\text{-BaB}_2\text{O}_4$) may be used as the nonlinear crystal.

The control element for controlling the oscillation wavelength of the solid laser crystal is preferably a resonator mirror for resonating the first radiation and the wavelength width of the first oscillation wave for which the resonator mirror has a reflectance of 99.9 % or more is preferably 10 nm or less with respect to the central wavelength.

Preferably, the resonator structure is constituted by at least two mirrors, or, at least one of the mirrors constituting the resonator structure has a second harmonic transmittance of 60 % or more.

The inventors have conducted studies on the transmission wavelength width of a birefringence crystal as a wavelength control element which causes a high oscillation threshold value when the birefringence crystal is used as a control element for controlling the oscillation wavelength of a solid laser crystal. Generally speaking, the oscillation characteristics of a laser resonator depend on a loss in the resonator. When the loss is high, the threshold value until oscillation is obtained becomes high. When the transmission wavelength width of the wavelength control element is narrow, there is a loss in the resonator, resulting in a high oscillation threshold value. Fig. 16 shows the calculation of a transmission wavelength width based on the number of quartz plates of the birefringence

crystal inclined at the Brewster angle. It is understood from Fig. 16 that the transmission wavelength width is narrowed by increasing the number of quartz plates of the birefringence crystal, that is, the thickness of the birefringence crystal. Thereby it is revealed that the wavelength control element has the effect that transmission wavelength width can be expanded and the oscillation threshold value can be lowered by reducing the number of quartz plates of the birefringence crystal, that is, the thickness of the birefringence crystal.

LiNbO_3 , LiTaO_3 or other birefringence crystal may be used as the birefringence crystal.

Further, Fig. 17 shows laser oscillation wavelength interval with respect to the thickness of the birefringence crystal when the birefringence crystal is formed of a single quartz plate. The term "laser oscillation wavelength interval" denotes the interval between the wavelengths of simultaneous laser oscillations, that depends on the gain characteristic of a laser medium for each wavelength. Since, when the gain characteristic is wide, the wavelength range of possible laser oscillations is wide, laser oscillations occur at the same time according to the transmission wavelength interval of the wavelength control element. It is seen from Fig. 17 that the interval between the wavelengths of laser oscillations is narrow when the thickness of the birefringence filter increases. This is because, when the thickness is large, the interval between

the adjacent wavelengths of possible laser oscillations is narrow and a laser which can oscillate at a broad bandwidth, such as a LiSAF laser, may oscillate at two or more oscillation wavelengths. Since a general laser mirror has a reflection bandwidth of 50 nm, an oscillation wavelength interval of 25 nm or more, about half the above reflection bandwidth is required to suppress two or more simultaneous oscillations. Therefore, the thickness of the birefringence crystal needs to be 3 mm or less according to Fig. 17. Since wavelength control becomes difficult when the thickness of the crystal is too small and the oscillation wavelength width of a LiSAF laser is about 20 nm, the thickness of the crystal needs to be 0.4 mm or more according to Fig. 17. Therefore, when the thickness of the birefringence crystal is in the range of 0.4 to 3 mm, the oscillation threshold value can be further reduced.

As described above, the oscillation threshold value can be reduced by using a birefringence crystal. However, since the oscillation wavelength width is broadened by expanding the transmission wavelength width, it is larger than the phase match half-value width of a SHG crystal, thereby making it difficult to cause SHG efficiently. The inventors have found it possible to further increase efficiency by using an LBO (LiB_3O_5), BBO ($\beta\text{-BaB}_2\text{O}_4$) or CLBO ($\text{CsLiB}_6\text{O}_{10}$) crystal having a relatively wide phase match half value width. Fig. 18 shows the phase match wavelength half value width of the LBO crystal. Since the crystal has a width

about 20 times that of a KN crystal, an SH output that satisfies the phase match width of the LBO crystal can be obtained by setting the transmission wavelength width of a wavelength control element which is formed of a single 0.5 mm thick quartz plate as a birefringence crystal to 10 nm and by inclining the wavelength control element at the Brewster angle to eliminate a loss in the resonator. Since a change in the phase match width of the LBO crystal by temperature variations is small at 0.1 nm/°C, it is not necessary to control the temperature of the LBO crystal. Further, since the propagation loss of the LBO crystal is small at 0.1 %/cm, it rarely becomes a loss in the resonator. The same effect as that of the LBO crystal can be obtained by using a BBO crystal or a CLBO crystal. However, it is obvious that a further stable output can also be obtained by controlling the temperature of an SH crystal.

Moreover, this is also possible by using what has a wavelength width of 10 nm or less with respect to the central wavelength, for which a resonator mirror has a reflectance of 99.9 % or more, without using a birefringence crystal as a control element for controlling the oscillation wavelength of a solid laser crystal. When the resonator structure constituting a laser resonator is constructed by at least two mirrors, SH light can be taken outside the resonator efficiently by setting a second oscillation wavelength, that is, SHG transmittance of at least one of the mirrors constituting the resonator structure to 60 % or

more.

Preferably, a laser comprises a laser crystal made of Cr:LiSrAlF_6 , a resonator structure in which at least one resonator mirror is formed on one end surface of the laser crystal, a semiconductor laser for exciting the laser crystal, a first laser beam having a wavelength λ_1 that satisfies $780 \leq \lambda_1 \leq 1,000 \text{ nm}$, which is obtained by oscillating radiation from the laser crystal in the laser resonator, a nonlinear optical crystal having an opening with a diameter 5 times or more that of the first laser beam and inserted into the resonator, a wavelength control element, means for controlling the temperature of the nonlinear optical crystal and the temperatures of the laser crystal and the nonlinear optical crystal simultaneously or individually, and means for taking out a second laser beam having a wavelength different from that of the first laser beam and converted from part of the first laser beam.

Preferably, the nonlinear optical crystal is selected from LiB_3O_5 (lithium triborate), $\text{CsLiB}_6\text{O}_{10}$ (caesium lithium borate), $\beta\text{-BaB}_2\text{O}_4$ (barium borate), KNbO_3 (potassium niobate), KTaO_3 (potassium tantalate), K-Li-Nb-O (lithium-potassium niobate), K-Ta-Nb-O (niobic acid, tantalic acid-potassium) and LiIO_3 (lithium iodate).

When a laser resonator or a laser according to the present invention is used in a laser printer, an optical shaping unit, an optical disk drive, a particle counter, a DNA sequencer and the like, a small-sized apparatus having

excellent stability can be provided.

Other objects and advantages of the present invention will become more apparent from the following description with reference to the accompanying drawings.

Brief Description of Drawings

Fig. 1 is a diagram for explaining an embodiment of the present invention.

Fig. 2 is a diagram for explaining another embodiment of the present invention in which control of the temperature of a laser crystal is applied as another means for improving efficiency.

Fig. 3 is a diagram for explaining an SHG laser according to another embodiment of the present invention.

Fig. 4 is a diagram for explaining an application example in which an embodiment of the present invention is applied in a laser printer.

Fig. 5 is a diagram for explaining an application example in which an embodiment of the present invention is applied in an optical shaping unit.

Fig. 6 is a diagram for explaining an application example in which an embodiment of the present invention is applied in an optical disk drive.

Fig. 7 is a diagram for explaining another embodiment of the present invention.

Fig. 8 is a diagram for explaining still another embodiment of the present invention.

Fig. 9 is a diagram for explaining still another

embodiment of the present invention.

Fig. 10 is a diagram for explaining an embodiment of the prior art.

Fig. 11 is a diagram for explaining the comparison of the input/output characteristics of a semiconductor laser excited solid laser in the presence and the absence of a wavelength control element.

Fig. 12 is a diagram for explaining the phase match wavelength width of an KN crystal.

Fig. 13 is a diagram for explaining the oscillation efficiency reduction phenomenon caused by an opening in the resonators of an Nd:YVO₄ laser as a typical solid laser and a LiSAF laser.

Fig. 14 is a diagram for explaining the comparison of the input/output characteristics of a semiconductor laser excited solid laser using a LiSAF crystal and an Nd:YVO₄ laser as a typical solid laser.

Fig. 15 is a diagram for explaining the comparison of the input/output characteristics of a LiSAF laser when the temperature of the LiSAF crystal is controlled and when the temperature is not controlled.

Fig. 16 is a diagram for explaining the comparison of transmission wavelength width which differs according to the number of quartz crystals of a birefringence crystal.

Fig. 17 is a diagram for explaining the oscillation wavelength interval with respect to the thickness of a birefringence crystal.

Fig. 18 is a diagram for explaining the phase match wavelength width of an LBO crystal.

Best Mode for Carrying out the Invention

The most preferred embodiments of the present invention are described in detail. However, it is to be understood that the present invention is not limited to the embodiments.

(Embodiment 1)

Fig. 1 is a diagram for explaining an embodiment of the present invention. An excitation beam 31 radiated from a semiconductor laser 11 is converged by converging optics 12 and excites a laser crystal 21. An AlGaInP semiconductor laser manufactured by Spectra Diode Laboratory Co. which has an output of 50 mW and an oscillation wavelength of 670 nm is used as the semiconductor laser 11. A semiconductor laser collimator (focusing distance of 8 mm), an anamorphic prism pair (magnification of 6X) and a single lens (focusing distance of 30 mm) are used as the converging optics 12.

The excited laser crystal 21 oscillates a first laser beam 32 in a solid laser resonator 20 which comprises an input-side resonator mirror 24 formed on an end surface of the laser crystal and an output mirror 25. In the solid laser resonator 20, the laser crystal 21 and a wavelength tuning element 23 as a wavelength control element are arranged. The wavelength of the first laser beam 32 oscillated in the resonator is tuned by the wavelength tuning element 23. In this embodiment, the resonator

structure 20 is a plane-concave type resonator, the output mirror 25 has a curvature radius of 150 mm, and the effective optical path is slightly shorter than the curvature radius.

A LiSAF crystal ($\phi 3 \times 5$ mm) containing 1.5 mol% of Cr is used as the laser crystal 21. To the front end surface 24 of the crystal are applied an anti-reflection (to be abbreviated as AR hereinafter) coating having a reflectance of 2 % or less for an excitation wavelength and a high reflection (to be abbreviated as HR hereinafter) coating having a reflectance of 99 % or more for the wavelength of the first laser beam. In this respect, any reflectance of the HR coating is acceptable if it can reflect the first laser beam efficiently and the reflectance does not need to be 99 % or more. To the rear end surface is applied an AR coating having a reflectance of 2 % or less for the wavelength of the first laser beam. To the output mirror 25 is applied an HR coating having a reflectance of 99 % or more for the first laser beam. In this respect, any reflectance of the output mirror 25 is acceptable if it can take out the first laser beam with a high efficiency, and the reflectance does not need to be 99 % or more.

In the present invention, as shown in Fig. 13, it has been verified that the loss can be greatly improved by setting the openings in the resonator of the LiSAF laser to 5 times or more the diameter of the first laser beam. Based on this fact, the diameter of the opening of the laser

crystal has been set to 3 mm, the diameter of the opening in the wavelength tuning element 23 to 5 mm and the diameter of the opening in the output mirror to 10 mm.

A single birefringence filter made of a quartz plate is used as the wavelength tuning element 23 and inclined at the Brewster angle so that the reflection loss of the first laser beam becomes minimal. The wavelength of the first laser beam 32 can be tuned by turning the birefringence filter around the optical axis. The wavelength tuning range is set to about 860 ± 50 nm and the wavelength selection width is set to about 0.5 nm. Any wavelength selection width is acceptable if the output of the first laser beam is not reduced considerably. Further, besides a birefringence filter, a prism, etalon, external injection synchronism or a combination thereof may be used as the wavelength tuning element.

The absorption wavelength allowable width of the LiSAF crystal 21 is wide at about 100 nm, and no temperature control element is used to tune the wavelength of the excitation beam radiated from the semiconductor laser. However, wavelength tuning may be carried out by matching the wavelength of the excitation beam with the maximum absorption wavelength.

An optical part having a beam shaping function such as a cylindrical lens or an optical fiber may be used in place of the converging optics of the semiconductor laser.

(Embodiment 2)

Fig. 2 is a diagram for explaining another embodiment of the present invention in which laser crystal temperature control is applied as another means for improving efficiency. The excitation light source 11, the converging optics 12, the laser crystal 21, the wavelength tuning element 23 and the resonator structure 20 are the same as those of Embodiment 1. The openings in the resonator and the wavelength tuning range are also the same as in Embodiment 1.

As shown in Fig. 15, it is known that a stable laser output can be obtained by controlling the temperature of a LiSAF crystal. In Fig. 2, the temperature of the LiSAF crystal is controlled to 15°C by using an electronic cooling element and a thermistor. The lower limit of the control temperature is a temperature at which the laser crystal starts dew condensation and which can be set freely if saturation is not seen in laser output under use conditions. (Embodiment 3)

Fig. 3 is a diagram for explaining an SHG laser according to another embodiment of the present invention. The same excitation optics including the semiconductor laser 11 as those of Embodiment 1 are used.

The excited laser crystal 21 generates a fundamental wave 32 which is a solid laser oscillation wave in the solid laser resonator 20 which comprises the input-side resonator mirror 24 formed on an end surface of the laser crystal and the output mirror 25. The laser crystal 21, a nonlinear

optical crystal 22 for converting part of the fundamental wave of the laser crystal 21 into an SHG wave and a wavelength tuning element 23 are arranged in the solid laser resonator 20. LiB_3O_5 (lithium borate which is abbreviated as LBO hereinafter) is used as the nonlinear optical crystal 22 which measures 3 x 3 x 5 mm and is coated with an AR coating having a reflectance of 2 % or less for the wavelengths of the fundamental wave and the SHG wave.

The temperatures of the LiSAF crystal 21 and the LBO crystal 22 are controlled to $25 \pm 0.1^\circ\text{C}$ by using a temperature control element. To the output mirror 25 are applied an HR coating having a reflectance of 99 % or more for the fundamental wave and an AR coating for the SHG wave, and the diameter of an opening in the mirror is set to 10 mm as in Embodiment 1. The other optical parts are the same as those of Embodiment 1. The wavelength of the fundamental wave 32 oscillated in the resonator is tuned by the wavelength tuning element 23 to a wavelength at which the wavelength conversion efficiency of the nonlinear optical crystal 22 becomes maximal, and part of the fundamental wave 32 is converted into an SHG wave 33 by the nonlinear optical crystal 22 and radiated from the output mirror 25. According to the present invention, an SHG output of 10 mW was obtained at a semiconductor laser input of 455 mW.

The wavelength tuning range is set to about 860 ± 70 nm and the wavelength selection width is set to 0.5 nm. In this respect, any wavelength tuning range and any wavelength

selection width are acceptable if the wavelength is near a wavelength at which the conversion efficiency of the LBO crystal becomes maximal and if the SHG laser output does not decrease significantly, respectively.

Further, a nonlinear optical crystal capable of phase matching in the wavelength tuning range of the fundamental wave, such as β -BaB₂O₄ (barium borate), CsLiB₆O₁₀ (caesium lithium borate), KNbO₃ (potassium niobate), K-Li-Nb-O (lithium potassium niobate) or LiIO₃ (lithium iodate), may be used as a wavelength conversion element.

Using a gas laser of the prior art which achieved the same output as that of the above embodiment, comparison of characteristic properties was made. The gas laser had a service life of 2,000 to 5,000 hours and experienced a 50 % reduction in output whereas the SHG laser experienced no reduction in output after 1,000 hours or more of operation. Therefore, the service life of the SHG laser was extended to 2 to 5 times that of the prior art according to the embodiment of the present invention. The gas laser had a volume of 10 to 15 liters whereas the SHG laser had a volume of 0.3 liter. Therefore, the volume of the SHG laser was reduced to 1/50 to 1/30 that of the prior art according to the embodiment of the present invention. The gas laser had a power consumption of 1,000 to 2,000 W whereas the SHG laser had a power consumption of 5 W. Therefore, the power consumption of the SHG laser was reduced to 1/400 to 1/200 that of the prior art according to the embodiment of the

present invention. Comparison between the characteristic properties of the gas laser and the SHG laser of the embodiment of the present invention is shown in Table 1.

Table 1

Comparison results of specifications between gas laser and SHG laser of the present invention

laser light source	output (mW)	service life (hours)	volume (liter)	power consumption (W)
Ar laser	15	5000	10	2000
He-Cd laser	10	2000	15	1000
SHG laser	10	>10000	0.3	5

(Example 4)

Fig. 4 is a diagram for explaining an application example in which an embodiment of the present invention is applied in a laser printer. The SHG laser output 33 radiated from an SHG laser light source 100 illustrated in Fig. 3 passes through an acousto-optical (to be abbreviated as AO hereinafter) modulator 51, a beam expander 52, a rotary polygon mirror 53 and an f θ lens 54 and is converged on a photosensitive drum 55. The AO modulator 51 modulates the SHG output 43 according to image information, and the rotary polygon mirror 53 scans in a horizontal direction (of the paper of the drawing). With this combination, secondary information is recorded on the photosensitive drum 55 as

partial potential differences. The photosensitive drum 55 turns, adhered by toner according to the potential differences, and reproduces information on recording paper.

At this point, a photosensitive material applied to the photosensitive drum 55 is selenium (Se) and the output wavelength of the SHG laser light source 100 is set to 420 nm to which the photosensitive material is relatively highly sensitive and its output is set to 10 mW. In this respect, a photosensitive material other than Se may be used.

(Embodiment 5)

Fig. 5 is a diagram for explaining an application example in which an embodiment of the present invention is applied in an optical shaping unit. The SHG laser light source 100 illustrated in Fig. 3 is used as a light source. A blue cured resin 61 is charged into a container and a laser beam is caused to scan the surface of the liquid two-dimensionally. At this point, only a surface portion 61-a of the blue curing resin 61 that absorbs light cures. After the formation of one layer is completed, an elevator 62 falls to form the next layer continuously. With this operation, a solid model 63 having a desired shape can be formed. At this point, the SHG laser light source has a wavelength of 430 nm and an output of 10 mW.

(Embodiment 6)

Fig. 6 is a diagram for explaining an application example in which an embodiment of the present invention is applied in an optical disk drive. The SHG laser light

source 100 illustrated in Fig. 3 is used as a light source. An optical disk drive of opto-magneto recording system is used. An SHG laser output 33 radiated from the SHG laser light source 100 is expanded by a beam expander 52 and then becomes parallel beams. Part of the beams reflected by the beam splitter 72 are received by a front monitor 73. The beams passing through the beam splitter 72 are converged on a medium 75 by a converging optic 74. Reflected light partially reflected by the beam splitter 72 and separated into two beams to be received by two detectors 76. The front monitor 73 monitors the SHG laser output 33 to control it. Each of the two detectors 76 after the beam splitter 72 performs autofocusing and signal detection. A fixed magnetic field is applied to the medium 75 so that the SHG laser output 33 is modulated and the focusing temperature is raised to a Curie temperature of the medium 75 to reverse magnetization for recording. When the output is on, the magnetic field of the medium is reversed, and when the output is off, the magnetic field is not reversed and signal recording is enabled. The recording frequency is set to 10 MHz. At the time of signal reproduction, the same SHG laser light source 100 as that for recording is used to obtain a well reproduced signal.

(Embodiment 7)

Fig. 7 is a diagram for explaining another embodiment of the present invention. Excitation beams 141 radiated from a semiconductor laser 111 are converged by converging

optics 112 to excite a laser crystal 121. An AlGaInP semiconductor laser manufactured by Spectra Diode Laboratory Co. and having an output of 500 mW and an oscillation wavelength of 670 nm is used as the semiconductor laser 111. A semiconductor laser collimator ($f = 8$ mm), an anamorphic prism pair (magnification: 6X) and a single lens ($f = 30$ mm) are used as the converging optics 112.

The excited laser crystal 121 generates a fundamental wave 142 in a solid laser resonator 120 which includes an input-side resonator mirror 122 formed on an end surface of the laser crystal and an output mirror 124. In the solid laser resonator 120, the laser crystal 121, an SHG crystal 131 and a wavelength control element 125 are arranged. At this point, the solid laser resonator 120 is a plane-concave resonator having a length of 145 mm, and the output mirror 124 has a curvature radius of 150 mm. A LiSAF crystal ($\phi 3 \times 5$ mm) containing 1.5 mol% of Cr is used as the laser crystal 121. To a front end surface of the crystal are applied an AR coating having a reflectance of 2 % or less for an excitation wavelength and an HR coating having a reflectance of 99 % or more for the wavelength of the fundamental wave. To a rear end surface of the crystal is applied an AR coating having a reflectance of 0.2 % or less for the wavelength of the fundamental wave to make it the input-side resonator mirror 122.

The SHG crystal 131 formed of a $3 \times 3 \times 5$ mm LBO crystal is arranged right after the LiSAF crystal 121. To

both end surfaces of the LBO crystal is applied an AR coating having a reflectance of 0.2 % or less for the wavelength of the fundamental wave and 1 % or less for SH wavelength. A birefringence crystal formed of a single 0.5 mm thick quartz plate is used as the wavelength control element 125, inclined at the Brewster angle with respect to the optical axis and turned around the optical axis to control the wavelength of the fundamental wave to a wavelength at which the conversion efficiency of the LBO crystal as the SHG crystal 131 becomes maximal. In the resonator, part of the fundamental wave is converted into an SH wave 143 by the SHG crystal 131 and taken out from the output mirror 124 to the outside of the resonator as an SH output. In this structure, the oscillation threshold value was twice that when the wavelength control element shown in Fig. 12 did not exist and an SH output of 10 mW was obtained.

The locations of the SHG crystal 131 and the wavelength control element 125 inserted into the resonator shown in Fig. 7 in the present invention can be exchanged. The absorption wavelength allowable width of the LiSAF crystal 121 is wide at about 100 nm and the wavelength of the excitation semiconductor laser is not controlled using the temperature control element. However, the wavelength may be controlled to the maximum absorption wavelength.

(Comparative Embodiment 1)

In the same laser resonator as that of Fig. 7, a single

5 mm thick quartz plate was used as the wavelength control element 125 and a KN crystal was used as the SHG crystal 131. Since the interval between laser oscillation wavelengths controlled by the wavelength control element formed of this single 5 mm thick quartz plate was narrow at 12 nm, 4 to 5 fundamental waves were oscillated simultaneously at a wavelength interval of 12 nm by the LiSAF crystal as the laser crystal 121. An SH output of several nWs only was obtained as KN which was the SHG crystal had a narrow phase match wavelength half value width of 0.4 nm and the power of the fundamental wave was diverged because laser beams were oscillated at other wavelengths even if one of the wavelengths of the fundamental waves was converted by the KN crystal.

(Embodiment 8)

Fig. 8 is a diagram for explaining another embodiment of the present invention. Excitation optics consisting of the semiconductor laser 111 and the converging optics 112 are the same as those of Embodiment 7. The excited laser crystal 121 generates a fundamental wave 142 in a solid laser resonator 120 which is formed of three resonator mirrors consisting of an input-side resonator mirror 122 formed on an end surface of the laser crystal, a concave mirror 126 and a plane output mirror 123. In the solid laser resonator 120, the laser crystal 121 and the SHG crystal 131 are arranged between the input-side resonator mirror 122 and the plane output mirror 123 and a wavelength

control element 125 is arranged between the plane output mirror 123 and the concave mirror 126. The materials, shapes and coatings of the laser crystal 121 and the SHG crystal 131 used at this time are the same as those of Embodiment 7. The same wavelength control element 125 as that of Embodiment 7 was used.

To the concave mirror 126 was applied an HR coating having a reflectance of 99 % or more for the wavelength of the fundamental wave. To the plane output mirror 123 were applied an HR coating having a reflectance of 99 % or more for the wavelength of the fundamental wave and an AR coating having a transmittance of 85 % or more for an SH wavelength. The wavelength control element 125 was turned around the optical axis to control the wavelength of the fundamental wave to a wavelength at which the conversion efficiency of the LBO crystal as the SHG crystal 131 became maximal. In the resonator, part of the fundamental wave is converted into an SH wave 143 by the SHG crystal 131 and taken out from the plane output mirror 123 to the outside of the resonator as an SH output 143. In this structure, an SH output of 15 mW was obtained since there was no loss in the SH light at the wavelength control element 125 shown in Fig. 7.

(Embodiment 9)

Fig. 9 is a diagram for explaining still another embodiment of the present invention. Excitation optics consisting of the semiconductor laser 111 and the converging

optics 112 are the same as those of Embodiment 7. The excited laser crystal 121 generates a fundamental wave 142 in a solid laser resonator 120 which includes an input-side resonator mirror 122 formed on an end surface of the laser crystal and an output mirror 124. The materials, shapes and coatings of the laser crystal 121 and the SHG crystal 131 used at this time are the same as those of Embodiment 7. Since the output mirror 124 is coated with an HR coating having a reflectance of 99.9 % or more for the wavelength of the fundamental wave with a central wavelength of 860 ± 5 nm, control of an oscillation wavelength can be carried out without a wavelength control element. The output mirror 124 is also coated with an AR coating having a transmittance of 85 % or more for an SH wavelength. As shown in Fig. 18, since the phase match wavelength half value width of the LBO crystal as the SHG crystal 131 is wide at 8 nm, SH light can be obtained efficiently without controlling wavelength.

In the present invention, by designing a LiSAG laser resonator, taking into consideration openings in the resonator, the efficiency of the semiconductor laser excited LiSAF laser is greatly improved. Further, by controlling the temperature of the LiSAF crystal, the oscillation lost phenomenon of the laser is avoided and means for obtaining a stable laser output is proposed. Using this LiSAF laser, an SHG laser having an output of 10 mW is implemented. The present invention makes it possible to extend service life to 2 to 5 times and reduce volume and power consumption to

1/50 to 1/30 and 1/400 to 1/200 those of the prior art, respectively. In addition, the present invention makes it possible to reduce the size and power consumption, extend the service life and improve the reliability of laser applied units.

According to the present invention, in a wavelength variable laser, particularly an internal resonator SHG system using a LiSAF laser, the oscillation threshold value is reduced by expanding the transmission wavelength width of the wavelength control element and the efficiency and reliability of a second harmonic generator as a laser are improved by using an LBO crystal as an SHG crystal having a wide phase match width. Moreover, using this second harmonic generator as a light source, the reliability of a laser applied product such as a laser printer is improved.

Industrial Applicability

As described on the foregoing pages, according to the present invention, a small-sized laser resonator, laser and laser applied unit such as a laser printer having excellent stability can be provided.



CLAIMS

1. A laser resonator comprising a laser crystal made of a fluoride containing Cr and at least one optical part, characterized in that an opening in the resonator has substantially a diameter 5 times or more that of a first laser beam, which is obtained by oscillating radiation from the laser crystal in the resonator.
2. The laser resonator of claim 1, wherein the laser crystal is made of Cr:LiSrAlF₆ (chromium added lithium strontium aluminum fluoride).
3. The laser resonator of claim 1 or 2 which has means for controlling the temperature of the laser crystal.
4. The laser resonator of claim 3 which has means for controlling the temperature of the laser crystal in a range where input/output characteristics thereof do not reach saturation.
5. The laser resonator of claim 3 or 4 which has means for controlling the temperature T of the laser crystal in a range of $0 \leq T \leq 50^{\circ}\text{C}$.
6. The laser resonator of any one of claims 1 to 5, wherein at least one of a plurality of mirrors constituting the resonator is formed on one end surface of the laser crystal.
7. The laser resonator of any one of claims 1 to 6, wherein at least one of the optical parts is a wavelength control element.
8. The laser resonator of claim 7, wherein a birefringence



crystal inclined at the Brewster angle is used as the wavelength control element for controlling the oscillation wavelength of the solid laser crystal.

9. The laser resonator of claim 8, wherein at least one selected from quartz (SiO_2), LiNbO_3 , LiTaO_3 and a liquid crystal plate is used as the birefringence crystal.

10. The laser resonator of claim 9, wherein a single quartz plate having a thickness of 0.5 mm or less is used as the birefringence crystal.

11. The laser resonator of any one of claims 1 to 10, wherein the optical parts include a wavelength control element and a nonlinear optical crystal.

12. The laser resonator of claim 11, wherein at least part of the first laser beam is converted into a second laser beam having a wavelength different from that of the first laser beam when it passes through the nonlinear optical crystal.

13. The laser resonator of claim 11 or 12, wherein the nonlinear optical crystal is made of at least one selected from LiB_3O_5 (lithium triborate), CsLiB_3O_5 (caesium lithium borate), $\beta\text{-BaB}_2\text{O}_4$ (barium borate) KNbO_3 (potassium niobate), KTaO_3 (potassium tantalate), K-Li-Nb-O (lithium-potassium niobate), K-Ta-Nb-O (niobic acid, tantalic acid-potassium) and LiIO_3 (lithium iodate).

14. The laser resonator of any one of claims 11 to 13 which has means for controlling the temperatures of the laser crystal and the nonlinear optical crystal simultaneously or



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individually.

15. A laser comprising the laser resonator according to any one of claims 1 to 14 and a laser crystal.

16. The laser of claim 15, wherein means for exciting the laser crystal is a semiconductor laser.

17. The laser of claim 15 or 16 comprising a laser crystal made of Cr:LiSrAlF_6 , a resonator structure in which at least one resonator mirror is formed on one end surface of the laser crystal, a semiconductor laser for exciting the laser crystal, a first laser beam having a wavelength λ_1 that satisfies $780 \leq \lambda_1 \leq 1,000 \text{ nm}$, which is obtained by oscillating radiation from the laser crystal in the laser resonator, and a wavelength control element having an opening with a diameter 5 times or more the diameter of the first laser beam and inserted into the resonator.

18. The laser of claim 15 or 16 comprising a laser crystal made of Cr:LiSrAlF_6 , a resonator structure in which at least one resonator mirror is formed on one end surface of the laser crystal, a semiconductor laser for exciting the laser crystal, means for controlling the temperature T of the laser crystal in a range of $0 \leq T \leq 50^\circ\text{C}$, a first laser beam having a wavelength λ_1 that satisfies $780 \leq \lambda_1 \leq 1,000 \text{ nm}$, which is obtained by oscillating radiation from the laser crystal in the laser resonator, and a wavelength control element having an opening with a diameter 5 times or more the diameter of the first laser beam and inserted into the resonator.





19. The laser of claim 15 or 16 comprising a laser crystal made of Cr:LiSrAlF_6 , a resonator structure in which at least one resonator mirror is formed on one end surface of the laser crystal, a semiconductor laser for exciting the laser crystal, a first laser beam having a wavelength λ_1 that satisfies $780 \leq \lambda_1 \leq 1,000 \text{ nm}$, which is obtained by oscillating radiation from the laser crystal in the laser resonator, a nonlinear optical crystal having an opening with a diameter 5 times or more the diameter of the first laser beam and inserted into the resonator, a wavelength control element, means for controlling temperature of the nonlinear optical crystal and the temperatures of the laser crystal and the nonlinear optical crystal simultaneously or individually, and means for taking out a second laser beam converted from part of the first laser beam and having a wavelength different from that of the first laser beam.
20. A laser applied unit which uses the laser of any one of claims 15 to 19.
21. The laser applied unit of claim 20 which is a laser printer.
22. The laser applied unit of claim 20 which is an optical shaping unit.
23. The laser applied unit of claim 20 which is an optical disk drive.
24. The laser applied unit of claim 20 which is a particle counter.
25. The laser applied unit of claim 20 which is a DNA



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sequencer.

26. A laser oscillation method for oscillating radiation from a laser crystal made of a fluoride containing chromium in a laser resonator to obtain a first laser beam, wherein resonance is carried out in the resonator having an opening with a diameter which is substantially 5 times or more the diameter of the first laser beam.

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