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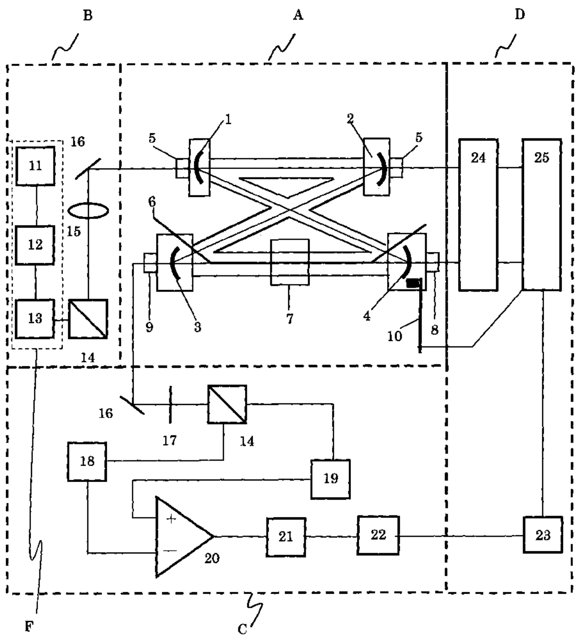
[Continued on next page]

(54) Title: TWO DIMENSIONAL (2-D)-4-MIRROR OPTICAL RESONATOR

FIG. 3



(57) Abstract: The present inventers provide an optical resonator which produces high strength of polarized laser beam so as to conduct laser Compton scattering, comprising: the 2-D-4-mirror optical resonator (A) includes the 2-D-4-mirror optic system which includes a pair of cylindrical concave mirrors (1, 2) and a pair of concave mirrors (3, 4) being arranged in the two-dimensional plane, the oscillation length controller device (10), the laser Compton scattering port (7) to conduct collisions laser beam and electron beam, the laser feed port (5) to guide an incident laser to the 2-D-4-mirror optic system, the electron feed port (6) to guide an incident laser to the laser Compton scattering port, the radiation output port (8) to output resultant laser Compton scattering radiation; the laser source unit (B) including the oscillation matching unit (F); the polarization controller unit (C); and the oscillation controller unit (D); wherein, laser beam supplied by the laser source unit (B) is the most strengthened in the laser Compton scattering port (7) in the 2-D-4-mirror optic system, selectively polarized through the intermediary of the polarization controller unit (C) and the oscillation controller unit (D).

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[Title of the Invention] Two Dimensional (2-D)-4-MIRROR OPTICAL RESONATOR

[Technical Field]

[0001]

The present invention relates to an optical resonator to conduct laser Compton scattering.

[Background Art]

[0002]

Recently, R&D of a small-sized X-ray generator utilizing laser Compton scattering has been watched. Here, laser Compton scattering is that radiation rays like X-rays are generated at collision of laser beam and electron beam. In order to perform laser Compton scattering, it is required to produce very high pulse-strength of laser and high luminance of electron beam. However, the production of high pulse-strength of laser beam has been very difficult as described below. On the other hand, it has been known that high-luminance of electron beam can be produced by circular-accelerators such as synchrotron and cyclotron. So that, it has been presented the conventional idea that laser oscillators are put in the electron beam loop-path of the circular-accelerators and laser Compton scattering is conducted in the oscillators. However, the circular-accelerators are very big, usually several kilometers in peripheral length, so that, the above method has been unsuitable for industrial uses.

[0003]

Circular-accelerators can generate high-luminance of coherent X-rays in the energy range from several keV to 100 keV. But, such accelerators will be never utilized for industrial usages due to their huge size. However, small-sized alternatives to produce X-rays as strong as synchrotron X-rays have been scarcely known.

[0004]

An optical resonator has been known as a tool to amplify laser beam. Laser beam is, in principle, amplified by laser-interference on the resonator mirror surfaces, so that, the amplification depends on reflectance of the resonator mirrors. As the optical resonators, Fabry-Perot ring resonator, Michelson interferometer-typed resonator and Fox-Smith interferometer-typed resonator, etc. have been known.

[0005]

Laser-amplification by optical resonators is only made under the condition that a resonator length is equal to an integral multiple of a half wave-length of laser. This is so-called a stationary wave standing. Because the resonance width of the stationary wave is determined by reflectance of resonator mirrors, the more the reflectance of mirrors becomes high, the more the resonance width becomes narrow, when intend to obtain high gains. For example, if supposing a resonator for obtaining 1000 times in gain using the mirrors with a reflectance of 99.9 %, the resonance width is to be 24 kHz or about 1 Å in resonance position. Consequently, the resonance state must be easily disappeared by environmental disturbance of mechanical vibrations and thermal expansion, etc. In order to maintain the resonance state, extremely precise feedback-regulations using piezoelectric driving of the resonator mirrors is required, so that, laser magnification of the conventional optical resonators is limited to about 1000 times due to limitations of mechanical regulations.

[0006]

Many laser-amplifiers using optical resonators have been presented (Patent Literatures 1-5 and Non Patent Literature 1). Patent Literature 1 discloses the simple-structured laser oscillators for encoding electrical signals onto optical beams in which the Fabry-Perot resonators having laser cavities are filled with rare-earth doped optical fibers for optical communication and the Fox-Smith interferometer-typed optical resonators having reflecting mirrors. The purpose of these laser oscillators is to provide fine optical conveying waves with longitudinal mode selections but not to generate lasers having high pulse strength. The pulse strength of this typed laser oscillators was at most in micro-joule levels due to declination in oscillation width by thermal vibrations, even if raising oscillation powers.

[0007]

Non-Patent Literature 1 discloses the optical resonator to generate single-frequency laser pulse using the Fox-Smith interferometer-typed optical resonators embedding concave mirrors and piezoelectric device for mechanically controlling resonant mirrors. The laser powers generated by this method have been reported to be at most 15 mW.

[0008]

Patent Literature 2 discloses the optical resonator to generate laser light by irradiating pumping-light (exciting laser) onto solid-state lasers, wherein the pumping light is generated by injecting currents into the laser diode or solid-state laser (induced emission medium) which is embedded in the inside of the resonator. This method is a convenient generation method using inexpensive and small-sized laser diodes, however, cannot generate laser light powerful enough to perform laser Compton scattering, because of low amplification as explained above.

[0009]

Patent Literature 3 discloses the laser amplifier to pump lasers using diodes. This amplifier is an apparatus to focalize laser beams into the medium by thermal lens which are put in the inside of the resonator, wherein the resonator is embedding a laser-active-solid-state medium. However, this method cannot generate laser beam powerful enough to perform laser Compton scattering, because of low amplification as explained above.

[0010]

Patent Literature 4 discloses the apparatus to generate laser light using a giant mode-locked laser oscillator and optical resonator. But the giant mode-locked laser oscillator is a very expensive huge apparatus, requires extremely high level of feedback regulations, and is limited to at most 1000 times in gain, therefore, the pulse strength of the laser light generable by this method is at most 100 μJ.

[0011]

Patent Literature 5 discloses the multistage amplification-typed laser system having multiple resonators placed in series for the purpose of semiconductor exposure. This apparatus uses reflection mirrors, but cannot accumulate laser light. This typed optical resonator is the one to raise gradually the amplification of laser light by subsequent transmission of laser light. The amplification of laser light is limited by mechanical regulative accuracies of resonance width. Even if the system is intended to raise the laser amplification up to gains enough to laser Compton scattering, the apparatus requires many resonators interconnected in series and each optical resonator requires extremely high level of regulation systems of resonance width. Therefore, it is in need impossible to use such a multistage laser system having multiple resonators placed in series for the purpose of laser source for laser Compton scattering.

[0012]

The generation of great strength of laser beam is conceptually possible by the combination of a giant exciting laser source and giant RF-oscillator to produce great powers, however, such a giant combination system is unsuitable for industrial usages.

[0013]

The conventional optical resonators as described above are able to produce laser beam with low amplification but cannot generate polarized laser beam.

[0014]

Several apparatuses to generate Compton scattering X-rays have been presented (Patent Literatures 6-8).

[0015]

Patent Literature 6 discloses the apparatus to generate X-rays by collision of laser beam and electron beam in the inside of the Fox-Smith interferometer-typed resonator having a laser oscillator between a pair of mirrors which is put in the electron beam loop-path of the circular-accelerators. Because laser beam is provided only by the laser oscillator, the amplification of the laser beam supplied from the laser oscillator is limited to at most 1000 times in gain as explained above, even if reflectance of the reflecting mirrors is much raised. Therefore, it is difficult to generate strong Compton scattering X-rays by this apparatus.

[0016]

Patent Literature 7 discloses the apparatus to generate short-wavelength light by collision between mode-locked laser beam and electron beam in the inside of the optical resonator providing a unit of multi concave mirrors arranged with a pair of concave mirrors in series, wherein the laser beam is in repetition reflected and focused between the concave mirrors and the collision of the laser beam and electron beam is carried out in the focused region of the laser beam. Because this apparatus in which the mode-locked laser is merely reflected between a pair of concave mirrors is, in structure, the same as the Fox-Smith interferometer-typed optical resonator, the amplification of the laser beam produced from this apparatus is limited to at most 1000 times in gain as above mentioned. Therefore, this apparatus may generate short-wavelength light for a photolithography usage as described in the Literature, but cannot generate strong laser Compton scattering X-rays.

[0017]

Patent Literature 8 discloses the apparatus to generate X-rays or γ-rays by collision between laser beam and electron beam in the inside of the Fox-Smith interferometer-typed optical resonator providing a pair of mirrors with super reflectance which is put in the electron beam loop-path of the circular-accelerators. Also, the invention discloses the apparatus providing a set of the resonators aligning in parallel on the electron beam orbit. However, the optical resonator used in this apparatus is the conventional resonator providing a pair of concave mirrors. Even if the mirrors with 99.99984 % in reflectance can be used, the amplification of laser beam is limited to at most 1000 times as explained above. Therefore, this apparatus cannot generate strong laser Compton scattering X-rays.

[0018]

For the purpose of the development of optical resonators to generate laser beam with 1 mJ or greater in pulse strength, the development of laser-resistant resonant mirrors might be challenged. There have been known the synthetic optical quartz glass for a semiconductor exposure usage (Patent Literature 9), the highly purified silica glass material with low refraction index (Patent Literature 10), the synthetic quartz glass (Patent Literature 11), the optical quartz glass for a excimer laser usage (Patent Literature 12), the laminated metal coat for a excimer laser usage (Patent Literature 13), the dielectric multi coat consisting of high-refraction tantalum oxide thin layers and low-refraction silica thin layers (Patent Literature 14) and the ceramic materials such as sapphire (Patent Literature 15), etc. In addition, it has been known that the reflecting mirrors deposited with multilayer structures containing diamond layers having high thermal conductivities can be used for optical devices such as semiconductor lasers (Patent Literature 16).

[0019]

However, the present inventers have noticed that most of the above mirrors were broken by exposure of laser beam with 300 μJ in pulse strength.

[0020]

In view of the above described circumstances, the present inventers have presented an outstanding three-dimensional-four-mirror (3-D-4-mirror) optical resonator which produces high strength of polarized laser beam and laser Compton scattering X-rays (Patent Literature 17). However, in order to narrow beam-sizes, the above 3-D-4-mirror resonator required very high-level oscillation matching techniques due to the 3-D arrangement of the mirrors.

[0021]

Most of laser-generators using the conventional optical resonators as described above have been used for optical communication laser-oscillators and material processing. However small-sized optical resonators to produce high strength of polarized laser beam so as to generate high-strength of laser Compton scattering X-rays have been scarcely known.

[Citation List]

[Non-Patent Literature]

[0022]

[Non-Patent Literature 1] P. W. Smith, Stabilized single-frequency output from a long laser cavity, IEEE Journal of Quantum Electronics, 1965, 11, Vol. QE-1, No. 8, pp. 343-348.

[Patent Literature]

[0023]

[Patent Literature 1] JP－A－1994－318751

[Patent Literature 2] JP－A－2002－141589

[Patent Literature 3] JP－A－1993－75189

[Patent Literature 4] JP－A－2009－16488

[Patent Literature 5] JP－A－2011－166169

[Patent Literature 6] USP4598415

[Patent Literature 7] JP−A−1995−110400

[Patent Literature 8] JP−A−1999−211899

[Patent Literature 9] JP−A−2010−150097

[Patent Literature 10] JP−A−2010−150097

[Patent Literature 11] JP−A−2009−190958

[Patent Literature 12] JP−A−2000−191329

[Patent Literature 13] JP−A−1998−160915

[Patent Literature 14] JP−A−2006−30288

[Patent Literature 15] JP−A−2004−356479

[Patent Literature 16] JP−A−1998−233558

[Patent Literature 17] JP−A−2011−34006

[Summary of the Invention]

[Technical Problem]

[0024]

As described above, the conventional laser Compton scattering apparatus has been presented based on the idea using large circular-accelerators as the electron beam source, so that, the conventional laser Compton scattering apparatus has not been utilized for industrial uses. The present inventers have changed tracks and now present the present invention on the bases of a new idea to conduct laser Compton scattering in an optical resonator using electron beam supplied by an extremely small-sized linear accelerator. Because electron beams produced by the linear accelerator are uncirculated, an optical resonator has to combine a vessel to conduct laser Compton scattering. The present invention is based on the idea to produce high strength of laser so as to conduct laser Compton scattering in an optical resonator.

[0025]

An object of the present invention is, in view of the above described circumstances, to provide an optical resonator which is capable of producing high luminance of polarized laser beam to conduct laser Compton scattering between the laser beam and supplied electron beams in the inside of the resonator.

[Solution to Problem]

[0026]

The present inventers are estimating that pulse strength of 100 μJ or less is required for generation of usual quasi-monochromatic X-rays through laser Compton scattering, however, pulse strength of 1 mJ or more is required for generation of high-luminance quasi-monochromatic X-rays which are useful for many industrial applications such as medical diagnostic, medical treatment, material structural analysis and material analysis. Also, the present inventers is estimating that high luminance of electron beam with small normalized-emittance of 10 μm-rad or less is required for the generation of high-luminance quasi-monochromatic X-rays useful for medical diagnostic and medical treatment.

[0027]

As the results of extensive studies to achieve the above described object, the present inventors have found that the 2-dimensional-4-mirror (2-D-4-mirror) optic system in which a pair of cylindrical concave mirrors and a pair of concave mirrors are arranged in the 2-dimensinal plane is possible to produce extremely high strength of laser beam and have achieved the present invention based on this finding.

[0028]

The present inventors have now found that the 2-D-4-mirror optic system in which a pair of cylindrical concave mirrors and a pair of concave mirrors are arranged in the two-dimensional plane are capable of producing very strong polarized laser beam with pulse-strength of 1 mJ or more and beam size of 5 μm. The pulse strength and beam size are 10^9 times as large as and hundredth as small as those of the conventional laser beam, respectively. Based on this finding, we present new small-sized optical resonator for laser Compton scattering that is capable of producing high-strength of quasi-monochromatic polarized laser beam as strong as synchrotron radiation X-rays.

[0029]

That is, the present invention is:

1. A 2-D-4-mirror optical resonator, comprising: a 2-D-4-mirror optic system which includes a pair of cylindrical concave mirrors and a pair of concave mirrors being arranged in the two-dimensional plane, a oscillation length controller device to adjust an optical path, a laser Compton scattering port to conduct collision of laser beam and electron beam; a laser feed port to guide laser beam in the 2-D-4-mirror optic system; an electron feed port to guide electron beam in the laser Compton scattering port; a radiation output port to output laser Compton scattering X-rays; wherein, laser beam is introduced in the 2-D-4-mirror optic system along the laser feed port and is the most strengthened in the laser Compton scattering port so as to conduct collision with electron beam introduced along the electron beam feed port and to output laser Compton Scattering X-rays through the radiation output port.

2. The 2-D-4-mirror optical resonator according to claim 1: further including a polarization controller unit to control polarization of the 2-D-4-mirror optic system and an oscillation controller unit to control oscillation of the 2-D-4-mirror optic system; wherein, laser beam is selectively polarized into right-circle polarized and/or left-circle polarized laser beam in accordance with the optical length through the intermediary of the polarization controller unit and oscillation controller unit.

3. The 2-D-4-mirror optical resonator according claim 2: further including a laser source unit which includes a mode-lock laser oscillator to supply mode-lock laser and an oscillation matching unit to match an oscillation state of the 2-D-4-mirror optical resonator and that of the mode-lock laser oscillator; wherein, laser beam supplied by the mode-lock laser oscillator is stably amplified.

[0030]

The present invention according to the description 1 is able to produce laser beam with pulse strength of 1 mJ or more and beam size of 30 μm or less.

[0031]

The present invention according to the description 2 is able to produce selectively polarized right-circle and/or left-circle laser beam with pulse strength of 1 mJ or more and beam size of 30 μm or less.

[0032]

The present invention according to the above description 3 is able to produce surprisingly high-strength of laser beam through automatically matching the oscillation state of the 2-D-4-mirror optical resonator with that of the mode-lock oscillator, whereby surprisingly stable and great laser-amplification exceeding 100,000 times is able to be performed.

[0033]

Also, the present invention is able to produce quasi-monochromatic polarized high-luminance of X-rays as strong as synchrotron radiation X-rays through collision of polarized laser beam with pulse strength of 1 mJ or more and beam size of 30 μm or less and electron beam with normalized emittance of 10 μm-rad or less with a collision angle in the range from 0 to 20 degrees in the laser Compton scattering port.

[Advantageous Effects of Invention]

[0034]

The present invention presents a new small-sized optical resonator, the 2-D-4-mirror-optical resonator, using a 2-D-4-mirror optic system which is able to produce high-luminance of laser beam and X-rays. The 2-D-4-mirror optic system is able to produce high-luminance of laser beam having an ideal circular narrow beam profile, selectively to produce high-luminance of right-circle polarized and/or left-circle polarized laser beam, easily to perform optical matching of incident and exiting laser beam, and to perform collisions of laser beam and electron beam (laser Compton scattering) in the inside of the optic system. Accordingly, the present optical resonator can selectively produce high-luminance of polarized X-rays as strong as synchrotron radiation X-rays.

[Brief Description of Drawings]

[0035]

Fig. 1 is a schematic structural view illustrating optical parameters of the 2-D-4-mirror optical resonator according to the present invention.

Fig. 2 is a schematic structural view illustrating a perspective structure example of the 2-D-4-mirror optical resonator according to the present invention.

Fig. 3 is a schematic structural view illustrating a block diagram example of the 2-D-4-mirror optical resonator equipped with the laser source unit which includes the optical matching unit, polarized controller unit and resonance controller unit according to the present invention.

Fig. 4 is a schematic structural view illustrating a block diagram example of the system as shown in Fig. 3 which is equipped with the electron beam source unit according to the present invention.

Fig. 5 is a view illustrating a relationship between laser beam-size and S-parameter for the 2-D-4-mirror optical resonator according to the present invention.

Fig. 6 is a view illustrating a relationship between observed pulse strength and currents of the exciting laser-source according to the present invention.

Fig. 7 is a view illustrating an oscillation state of laser beam according to the present invention.

[Description of Embodiments]

[0036]

The present invention is a 2-D-4-mirror optical resonator including the 2-D-4-mirror optic system which is able to produce high strength of laser beam so as to conduct collision of electron beam.

[0037]

The 2-D-4-mirror optical resonator comprises: in principle, a two-dimensional-four-mirror (2-D-4-mirror) optic system which includes a pair of cylindrical concave mirrors and a pair of concave mirrors being arranged in the 2-D plane, an oscillation length controller device to control an oscillation length of the 2-D-4-mirror optic system, and a laser Compton scattering port to conduct collisions between laser beam and electron beam; a laser feed port to guide incident laser beam into the 2-D-4-mirror optic system; an electron beam feed port to guide incident electron beam into the laser Compton scattering port; and radiation output port to output resultant radiation.

[0038]

The above cylindrical concave mirror is a mirror of which surface curve is a semi-cylindrical curve and the concave mirror is a mirror of which surface curve is a concave curve.

[0039]

Generally, in the conventional 2-D-4-mirror optic system comprising a pair of flat mirrors and a pair of concave mirrors, both incident and reflecting direction are not perpendicular to the respective mirror. Due to this gradient, vertical and horizontal focal length of the concave mirrors do not become equal and a beam profile at a laser convergent point between the concave mirrors turns to an ellipse. Because cross section areas of ellipses are larger than those of perfect circles, the conventional 2-D-4-mirror optic system produces weak laser beams in luminance.

[0040]

The present inventers have found that cylindrical concave mirrors in substitution for flat mirrors are capable of narrowing a beam profile at a laser convergent point between the concave mirrors into a perfect circle. For this reason, the 2-D-4-mirror optical resonator used for the present invention enables the luminance to rise much greatly in comparison to the conventional optical resonator.

[0041]

Due to perfectly collimated laser beam given by the cylindrical concave mirrors, the 2-D-4-mirror optic system in the present invention enables optical matching of incident, exiting and reflecting laser beam in the optic system to be handled with very easy in comparison to the conventional optic system. The 2-D-4-mirror optic system in the present invention has been scarcely known.

[0042]

Reflectance of all mirrors used for the 2-D-optic system is optimized to make resonant acuity (finesse) large. Finesse (F) is related with reflectance (R) in Eq. 1.

[0043]

$$F = \frac{\pi\sqrt{R}}{1-R} \qquad \text{Eq. 1}$$

[0044]

Other reason to use the mirrors of large R is to raise laser-resistance of the mirrors. Large reflectance of mirrors inhibits damages on mirror surfaces suffered by laser beams.

[0045]

Reflectance (R) of the above mirrors used for the present invention are preferably 99.9 %$\leqq$R$<$100 %, more preferably 99.99 %$\leqq$R$<$100 %. If R is below 99.9 %, finesse (F) is largely decreased and damages of the mirrors by laser beams become larger. R being more than 99.99 % makes F very large and decreases the damages. The reason why R is less than 100 % is to enter or exit laser beam through the mirrors. Usually, R is 99.999 % or more.

[0046]

The above mirrors used for the 2-D-4-mirror optic system are usually coated with dielectric multi-layers. The mirrors coated with dielectric multi-layers are relatively laser-resistant compared to the mirrors used for the conventional optical resonator. For example, the mirrors coated with dielectric multi-layers containing fluorides or single-crystalline diamond thin layers are preferable, but are not limited to them.

[0047]

The above oscillation length controller device is a device to control optical length between the concave mirrors. These devices are set in a holder respectively, and moved together with the holder by impressed voltages depending on oscillation states. Piezoelectric devices are preferable as the oscillation length controller device.

[0048]

The above laser Compton scattering port is a port to conduct collisions of laser beam and electron beam. The laser Compton scattering port is equipped with an electromagnet in front of and backside of the port, respectively. The collision is performable by controlling in precise an incident angle close to head-on collision of electron beam against facing laser beam with the electromagnet in front of the port. Electron beam after the collision is bent with the electromagnet in backside of the port. The port is usually set on an optical path in the 2-D-4-mirror optic system. The port is the most preferably set at the position of a half of oscillation length where a beam size of resonant laser becomes a minimum, and doing this, the laser beam in the optic system is the most strengthened in the laser Compton scattering port so as to conduct laser Compton scattering, as described latter.

[0049]

The above laser feed port is a port to guide laser beam into the above cylindrical concave mirrors. The port is attached to a side of an optical resonator body housing the above 2-D-4-mirror optic system so as to guide laser beam to the cylindrical concave mirror by an adequate incident angle.

[0050]

The above electron beam feed port is a port to guide electron beams into the laser Compton scattering port. The port is attached to a side of an optical resonator body housing the above 2-D-4-mirror optical system so as to guide electron beam in the laser Compton scattering port by an adequate incident angle.

[0051]

The above radiation output port is a port to output laser Compton scattering radiation. The port is attached to a side of an optical resonator body housing the 2-D-4-mirror optic system so as to output radiation by an adequate output angle. Usually, the port is attached to a side behind the resonant concave mirror.

[0052]

In order to generate high strength of laser Compton scattering X-rays in the laser Compton scattering port, pulse-strength of laser beam is preferably as strong as possible and beam size is preferably as small as possible. In the present invention, polarized laser beam with pulse-strength of 1 mJ or greater and beam size of 30 μm or smaller is preferable so as to collide with electron beam in the laser Compton scattering port. Further, polarized laser beam with pulse-strength of 1 mJ or greater and beam size of 20 μm or smaller is more preferable. Because, polarized laser beam having a beam size of 30 μm or smaller and pulse strength of 1 mJ or greater is able to generate high strength of polarized X-ray microbeams. Due to a theoretical minimum size of laser beams of the present 2-D-4-mirror optic system is 5 μm, the minimum beam size which can be produced by the present invention is 5 μm.

[0053]

Normalized emittance of electron beam to collide with laser beam in the laser Compton scattering port is preferably 10 μm-rad or less. Because, electron beam having a normalized emittance of 10 μm-rad or less is able to generate high luminance of X-rays.

[0054]

Collision angle between laser beam and electron beam in the laser Compton scattering port is preferably in the range from 0 to 20 degrees. Because, this range is preferable to raise probability of the collision and to generate quasi-monochromatic X-rays. The collision angle can be controlled with an electromagnet in front of the port.

[0055]

The 2-D-4-mirror optical resonator is preferably put under vacuum circumstance to prevent the oscillation state from laser-scattering due to microparticles and supernatant in the optical path. The vacuum is preferable to be 10^{-6} Pa or less.

[0056]

Further, the present invention is able to equip a polarization control unit to control selective right-circle or left-circle polarization of the laser beam in the 2-D-4-mirror optic system and an oscillation control unit to control the oscillation state of each polarized laser beam.

[0057]

The above polarization controller unit is a system to detect a polarization state of the resonant laser beam. The system includes plural reflecting mirrors to guide laser beam to a position being apart from the 2-D-4-mirror optic system by a predetermined distance, a half-wave plate to adjust a polarization face reflected by the final stage of reflecting mirror, a polarization beam splitter to sprit the laser the polarization face adjusted by the half-wave plate into P-polarized beam and S-polarized beam, a respective pin-photodiode to generate the respective beam strength signal indicating laser strength of the respective polarized beam, a differential amplifier to calculate differential between the respectively polarized beam strength signal output, a zero-cross determination circuit to determine the difference signal output from the differential amplifier, a zero-cross feedback signal generator to generate zero-cross feedback signal from the result of determination of the zero-cross determination circuit, and the like, and includes a calculation substrate mounting a microprocessor to perform a variety of calculations, a LSI with a calculating function assembled, and the like.

[0058]

The above oscillation controller unit is a system to control the piezoelectric device using signals from the above polarization controller unit. The system includes a polarization changeover-switch to output an indicating signal to indicate a selective right-polarization beam or left-polarization beam on the reception of zero-cross feedback signals supplied by the zero-cross feedback generator, an oscillation monitor to measure laser strength of resonant laser beam, an oscillation controller to control controlling-voltages of a piezoelectric device embedded in the above 2-D-4-mirror optic system on the basis of the outputs of the polarization changeover-switch and resonance monitor and zero-cross feedback generator, and the like, and includes a calculation substrate mounting a microprocessor to perform a variety of calculations, a LSI with a calculating function assembled, and the like. The present polarization and oscillation controlling technology is based on the measurement of slight difference in beam length between right-polarization and left-polarization beam.

[0059]

Further, the present invention is able to equip a laser source unit to supply laser into the 2-D-4-mirror optic system. The laser source unit includes a laser source, an oscillation matching unit, plural reflecting mirrors to guide laser beam, plural collimating lens to adjust beam diameters of laser beam, a polarized beam splitter (PBS) to change laser beam into linear polarized beam, and the like. The laser source is a mode-lock laser oscillator, pulse laser oscillator, CW-laser oscillator, and the like. As the laser source, a mode-lock laser oscillator which is able to amplify laser beam by self-oscillation amplification in the optical loop-orbit formed with an optical resonator and fiber laser amplifiers, is the most preferable.

[0060]

The oscillation matching unit is a method to attune amplification of the 2-D-4-mirror optical resonator and that of the above laser source. This unit is effective in the case of using the above mode-lock laser oscillator as a laser source. The oscillation matching unit enables the 2-D-4-mirror optical resonator to amplify mode-lock laser with ease, because the 2-D-4-mirror optical resonator is automatically attuned with the mode-lock laser oscillator. It has been confirmed that the control of resonance width is without any trouble performed with resonance width of 0.1 Å in accuracy.

[0061]

The oscillation matching unit includes a feedback system which detects the oscillation state of the resonant laser in the 2-D-4-mirror optical resonator, transforms the oscillation signals into driving voltage and a compensating board which monitors the oscillation state of the resonant laser and transmits the driving voltage to the oscillation controller device in the 2-D-4-mirror optical resonator. To perform them, the oscillation matching unit includes a calculation substrate on which a microprocessor to perform a variety of calculations, a LSI like FPGA (field-programmable gate array) and ASIC (application specific integrated circuit) with a calculating function is mounted.

[0062]

As the above feedback system, the system [λ/2 mirror 17－polarized beam splitter (PBS) 14－S-wave-polarizer-pin-photodiode 18－P-wave-polarizer-pin-photodiode 19－differentia-amplifier 20－zero-cross detector 21－zero-cross-feedback-signal-generator 22] which is similar to the polarization controller unit C in Fig. 3 can be used.

[0063]

As the above compensating board, the system [polarization-changeover-switch 23－ oscillation monitor 24－oscillation controller 25] which is similar to the oscillation controller unit D in Fig. 3, can be used.

[0064]

Further, the present invention is able to equip an electron beam generator unit to supply high-energy electron beam into the 2-D-4-mirror optical resonator.

[0065]

The above electron beam generator unit includes a RF signal generator and a high-energy electron beam generator which generates accelerated high-energy electron beam using RF voltages synchronized with the RF signal generator. As the high-energy electron beam generator, a RF linear accelerator is preferably used.

[0066]

Hereinafter, the present invention will be specially explained as an execution embodiment using the following drawings.

[0067]

An optical parameters of the present 2-D-4-mirror optic system as shown in Fig. 1 are a distance L_1 between a pair of cylindrical concave mirrors, a distance (resonator length) L_2 between a pair of concave mirrors, a resonator width d and an incident angle α. The parameters are optimized so as to minify as much as possible beam sizes (beam waists) ω_0 of laser light between the a pair of concave mirrors. The optimization raises flux of laser Compton scattering X-rays, because the more the beam size becomes small, the more the flux becomes large. In the present invention, a mode-lock laser of λ=1064 nm is used. L_2 is preferably 1075 mm in length according to the resonance-conditions. The value of ω_0 can be estimated from a relationship between ω_0 of perpendicular and horizontal laser beams and S-parameter which is obtained by envelop-calculation using a beam expander in the Gaussian beam optics. Here, the S-parameter is a position of laser beam lying in the line between the concave mirrors. As the result, the present inventors have found that each laser size ω_0 converges to a minimum of 5 μm at S=537.6 mm, as shown in Fig. 5. Also, the present inventors have found that the region (stabilized resonant area) formed by overlapping the respective relationship between ω_0 and S-parameter for the perpendicular and horizontal laser beams is enlarged as an optics. The obtained ω_0(=5 μm) is one-tenths the ω_0(=50 μm) for the conventional mode-lock laser oscillator (50 W power, 10 ps/pulse pulse time width, 1064 nm wavelength, 150 MHz repetition). Accordingly, the present invention enables the luminance to rise by 100 times compared to the conventional mode-lock laser oscillator. Therefore, the laser Compton scattering port is the most preferably set at a midpoint of the resonator where a beam size of resonant laser becomes a minimum, and doing this, the laser beam in the optic system is the most strengthened in the laser Compton scattering port.

[0068]

The above resonator width d and incident angle α is optimized so as to make convergences of perpendicular and horizontal laser at the concave mirrors maximum. In the present invention, d is preferably 240 mm and α is preferably 0.20 radian (11.4°).

[0069]

The present invention as shown Fig. 2 is the optical resonator comprising the 2-D-4-mirror optic system which includes a pair of cylindrical concave mirrors 1-2 and a pair of concave mirrors 3-4, wherein both mirrors are arranged in the 2-D plane, the oscillation length controller device 10 to control of an optical path length in the optic system, the laser Compton scattering port 7 to conduct collisions of laser beam and electron beam, the laser feed port 5 to guide laser beam of the laser source 11, the electron beam feed port 6 to guide electron beam, and the radiation output port 8 to output radiation, and is able to introduce a part of resonant laser beam into a polarization controller unit C through behind the concave mirror 3.

[0070]

The present invention as shown in Fig. 3 is the optical resonator which includes the 2-D-4-mirror optical resonator A, the laser source unit B, the polarization controller unit C and the oscillation controller unit D.

[0071]

The present invention as shown in Fig. 4 is the optical resonator which includes the 2-D-4-mirror optical resonator A, the laser source unit B, the polarization controller unit C, the oscillation controller unit D and the electron beam generator unit E.

[0072]

Operation of the present invention will be explained with reference to the schematic structural view of Figs. 2 and 4.

[0073]

The 2-D-4-mirror optical resonator in the present invention is set under vacuum less than 10^{-6} Pa. When a start switch is turned on, laser from the laser source 11 is emitted, enters in the feedback system 12 and the compensating board 13, thereby is synchronized with the laser of 2-D-4-mirror optic system, enters in the polarized beam splitter 14 and the collimate lens 15, whereby is adjusted a polarization face and beam diameter of the laser, enters in the flat mirror 16, enters behind the cylindrical concave mirror 1 of the 2-D-4-mirror optical system, is transmitted through the cylindrical concave mirror 1, is confined in the route in the order of the cylindrical concave mirror 2, the concave mirror 3, concave mirror 4, cylindrical concave mirror 1 and cylindrical concave mirror 2.

[0074]

Further, in parallel to the above operation, the strength of laser transmitted through the cylindrical concave mirror 2 is measured by the oscillation monitor signal is generated by the oscillation monitor 24, and supplied to the oscillation controller 25. The oscillation monitor 24 includes a pin-photodiode which measures laser strength and generates monitor signals (large signals when laser is resonant in the resonator).

[0075]

Further, in parallel to the above operation, the zero-cross feedback signal generator 22 in the polarization controller unit C includes the flat mirror 16 which reflect laser transmitted through the concave mirror 3 out of resonating laser in the 2-D-4-mirror optic system and guides the laser to a position being apart from the 2-D-4-mirror optic system by a predetermined distance, the half-wave plate 17 which adjusts a polarization face of the laser reflected by the flat mirror 16 of the final stage as being adjusted to form an attaching angle corresponding to a distance from the 2-D-4-mirror optic system, the polarization beam splitter 14 which splits the laser with polarization face adjusted by the half-wave plate 17 into P-polarized light and S-polarized light, the flat mirror 16 which reflects laser of the S-polarized light side split by the polarization beam splitter 14, the pin photodiode 18 which receive the laser of the S-polarized light side reflected by the flat mirror 16 and generates an S-polarized light strength signal indicating laser strength of the S-polarized light side, the flat mirror 16 which reflects laser of the P-polarized light side split by the polarization beam splitter 14, the pin-photodiode 19 which receives the laser of the P-polarized light side reflected by the flat mirror 16 and generates a P-polarized light strength signal indicating laser strength of the P-polarized light side, the differential amplifier 20 which calculates difference between the S-polarized light strength signal output from the pin-photodiode 18 and the P-polarized light strength signal output from the pin-photodiode 19 and generates a difference signal, and the zero-cross feedback signal generator 22 which generates a zero-cross feedback signal indicating a result of determination whether or not zero-crossing occurs at the difference signal output from the zero-cross detector 21, whether zero-crossing occurs from the plus side to the minus side or from the minus side to the plus side when zero-crossing occurs, and the like. The polarization controller unit C performs introducing of the laser transmitted through the concave mirror 3 out of the resonant laser in the 2-D-4-mirror optic system, splitting of the laser into P-polarized light and S-polarized light, measuring of strength thereof, obtaining of the difference value between there, generating the zero-cross feedback signal indicating whether or not zero-crossing occurs at the difference signal output from the differential amplifier 21, whether zero-crossing occurs from the plus side to the minus side or from the minus side to the plus side when zero-crossing occurs, and the like, and supplying the signal to the oscillation controller 25. The polarization change-over switch 23 generates, based on setting, an instruction signal to alternately assign right circular polarization or left circular polarization in accordance with an instruction signal assigning right circular polarization (or left circular polarization) or a high frequency signal output from the high frequency signal generating unit and supplies the signal to the oscillation controller 25.

[0076]

Further, in parallel to the above operation, drive voltage with a voltage value increased like a ram-shape is generated by the oscillation controller 25 and is supplied to the piezoelectric device 10 in the 2-D-4-mirror optical resonator A, so that the optical path length of the 2-D-4-mirror optic system is adjusted.

[0077]

Here, either right circular polarization or left circular polarization (e. g., right circular polarization) is assigned with an instruction signal output from the polarization change-over switch 23. Under the above conditions, when a zero-cross feedback signal indicating detection of right circular polarization is generated by the zero-cross feedback signal generator 23 in the polarization controller unit C and a monitor signal indicating that laser is oscillating in the 2-D-4-mirror optic system is output from the oscillation monitor 24, the oscillation controller 25 fixes the voltage value of the drive voltage as detecting the above.

[0078]

Accordingly, the optical path length in the 2-D-4-mirror optic system is fixed at that time and resonance against the laser of right circular polarization is maintained in the 2-D-4-mirror optic system for a specified period.

[0079]

The oscillation controller 25 includes a calculation substrate on which a microprocessor to perform a variety of calculations, a LSI with a calculating function assembled or the like is mounted. The oscillation controller 25 generates drive voltage having a ramp-shaped voltage value or a voltage value required for selecting laser of right circular polarization or left polarization in the 2-D-4-mirror optical resonator A based on the instruction signal output from the polarization change-over switch 23, a monitor signal output from the oscillation monitor 24 and a zero-cross feedback signal output from the polarization controller unit C, and supplies the drive voltage to the piezoelectric device 10 of the 2-D-4-mirror optical resonator A. Thus, the oscillation controller 25 controls the optical path length of the 2-D-4-mirror optical resonator A and selectively accumulates laser of right circular polarization or left circular polarization into the 2-D-4-mirror optical resonator A.

[0080]

Here, a line width of the pulse laser is determined by a mode-locking oscillation frequency and a time width of the pulse laser. Further, a beam size of the pulse laser at the collision point is 30 μm or smaller in the 2-D-4-mirror optical resonator A. Accordingly, as long as the time width of the pulse laser is 30 psec or shorter, it is possible to set pulse strength at the collision point in the 2-D-4-mirror optical resonator A to be 1mJ or higher. Here, using the concave mirrors 1-4 which are coated with laser-resistant dielectric multi-layers, it is possible to set pulse strength to be 10 mJ or greater.

[0081]

Similar control is performed as well as in the case that an instruction signal assigning right circular polarization and left circular polarization alternately is output from the polarization change-over switch 23, so that pulse laser of right circular polarization (high-strength pulse laser) and pulse laser of left circular polarization (high-strength pulse laser) alternately resonate and are amplified in the 2-D-4-mirror optical resonator A.

[0082]

Operation of the present invention will be explained with reference to the schematic structural view of Fig. 4.

[0083]

Electron beam are accelerated by the high-energy electron beam generator 27 using voltages synchronized with RF signals from the RF signal generator 26, both generators are in the electron beam generator unit E, and supplied to the 2-D-4-mirror optical resonator A. Further, in parallel to the above operation, mode-lock laser is generated by the laser source unit B, supplied to the 2-D-4-mirror optical resonator A, the polarization is adjusted by the polarization controller unit C, and the oscillation state is adjusted by the oscillation controller unit D.

[0084]

Representative results of the present invention will be explained with reference to Figs. 5 and 6.

[0085]

The present inventors observed pulse strength and oscillation state of the resonant laser in the 2-D-4-mirror optical resonator using the optical resonator as shown in Fig.3. As the laser source, was used the mode-lock laser oscillator which was equipped with an optical loop path which was formed by connection of the same 2-D-4-mirror optical resonator as above and fiber laser amplifiers. As the mirrors used in the 2-D-4-mirror optical resonator, the cylindrical concave mirrors and concave mirrors having 99.99 % in reflectance were used. Pulse strength of the seed laser supplied into the above mode-lock laser oscillator was set to about 0.1 μJ (10^{-7} J). The results are shown in Figs. 5 and 6. Fig. 5 shows the result of the relationship between pulse strength and currents of the exciting laser supplied in the mode-lock laser oscillator, which was measured using a photodiode. From the result, it has been confirmed that pulse strength of 1mJ and amplification of 10,000 times can be achieved. The result also shows that resonant width of 0.1 Å is achieved. Fig. 6 shows the result of the oscillation state of resonant laser which was observed with an oscilloscope. From the result, it has been confirmed that resonant laser can be split into right polarization and left polarization laser.

[0086]

A summary is, the present invention as shown in Figs. 1-4 is able to produce parallel laser beams having a perfect circle narrow beam profile and enables laser beam optics to be handled very easily. Accordingly, it is possible to generate high-strength of polarized laser beam having 30 μm or smaller in laser size and 1 mJ or greater in pulse strength which is very useful for wide variety of industrial usages.

[Industrial Applicability]

[0087]

The present invention has industrial applicability as relating to a polarized laser oscillation method, a polarized radiation generation method, and a device and a system thereof for a X-ray source to generate X-ray microbeam using laser Compton scattering and the like, and in particular, relating to a polarized laser oscillation method, a polarized radiation generation method, and a device and a system thereof being capable of freely selecting right or left circular polarization. The present invention is useful for a variety of industrial usages such as medical instrument, diagnostic instrument, material analyzer, structural analyzer, material processing, and the like.

[Reference Signs List]

[0088]

A: 2-D-4-mirror optical resonator

B: laser source unit

C: polarization controller unit

D: oscillation controller unit

E: electron beam generator unit

F: oscillation matching unit

1: cylindrical concave mirror

2: cylindrical concave mirror

3: concave mirror

4: concave mirror

5: laser feed port

6: electron beam feed port

7: laser Compton scattering port

8: radiation output port

9: laser exit port

10: oscillation length controller device (piezoelectric device)

11: laser source

12: feedback controller

13: compensating board

14: polarized beam splitter

15: collimate lens

16: flat mirror

17: λ/2 plate

18: pin-photodiode

19: pin-photodiode

20: differential amplifier

21: zero-cross detector

22: zero-cross feedback signal generator

23: polarized change-over switch

24: oscillation monitor

25: oscillation controller

26: RF signal generator

27: high-energy electron beam generator

[Kind of Document] CLAIMS

[Claim 1]

A Two dimensional (2-D)-4-mirror optical resonator, comprising:

a 2-D-4-mirror optic system which includes a pair of cylindrical concave mirrors and a pair of concave mirrors being arranged in the two-dimensional plane,

a oscillation length controller device to adjust an optical path,

a laser Compton scattering port to conduct collision of laser beam and electron beam;

a laser feed port to guide laser beam in the 2-D-4-mirror optic system;

an electron feed port to guide electron beam in the laser Compton scattering port; and

a radiation output port to output laser Compton scattering X-rays; wherein,

laser beam is introduced in the 2-D-4-mirror optic system along the laser feed port and is the most strengthened in the laser Compton scattering port so as to conduct collision with electron beam introduced along the electron beam feed port and to output laser Compton Scattering X-rays through the radiation output port.

[Claim 2]

The 2-D-4-mirror optical resonator according to claim 1: further including a polarization controller unit to control polarization of the 2-D-4-mirror optic system and

an oscillation controller unit to control oscillation of the 2-D-4-mirror optic system; wherein,

laser beam is selectively polarized into right-circle polarized and/or left-circle polarized laser beam in accordance with the optical length through the intermediary of the polarization controller unit and oscillation controller unit.

[Claim 3]

The 2-D-4-mirror optical resonator according claim 2: further including a laser source unit which includes a mode-lock laser oscillator to supply mode-lock laser and

an oscillation matching unit to match an oscillation state of the 2-D-4-mirror optical resonator and that of the mode-lock laser oscillator; wherein, laser beam supplied by the mode-lock laser oscillator is stably amplified.

FIG. 1

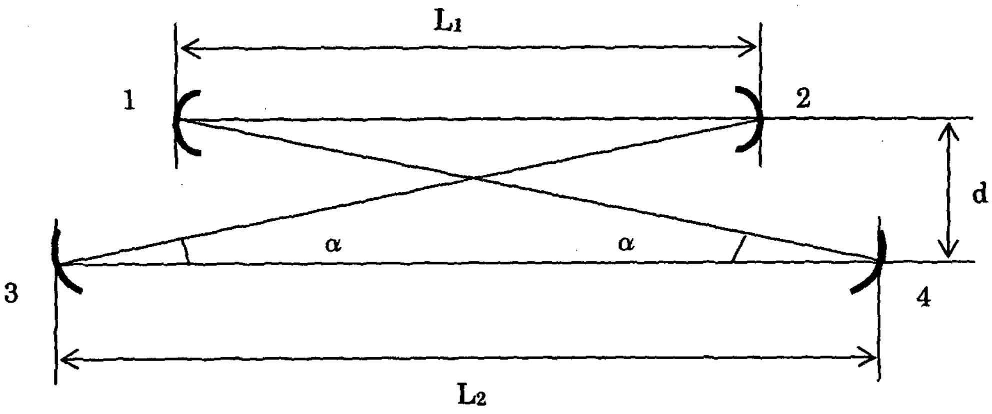


FIG. 2

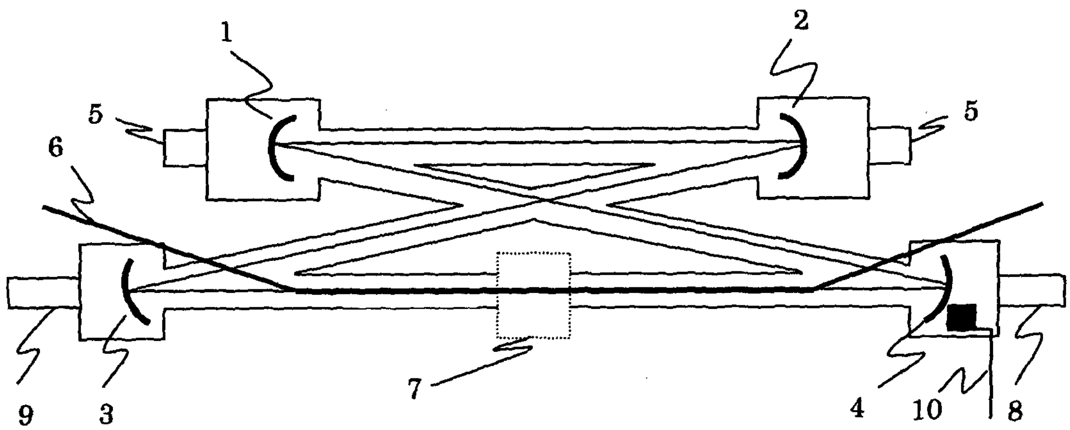
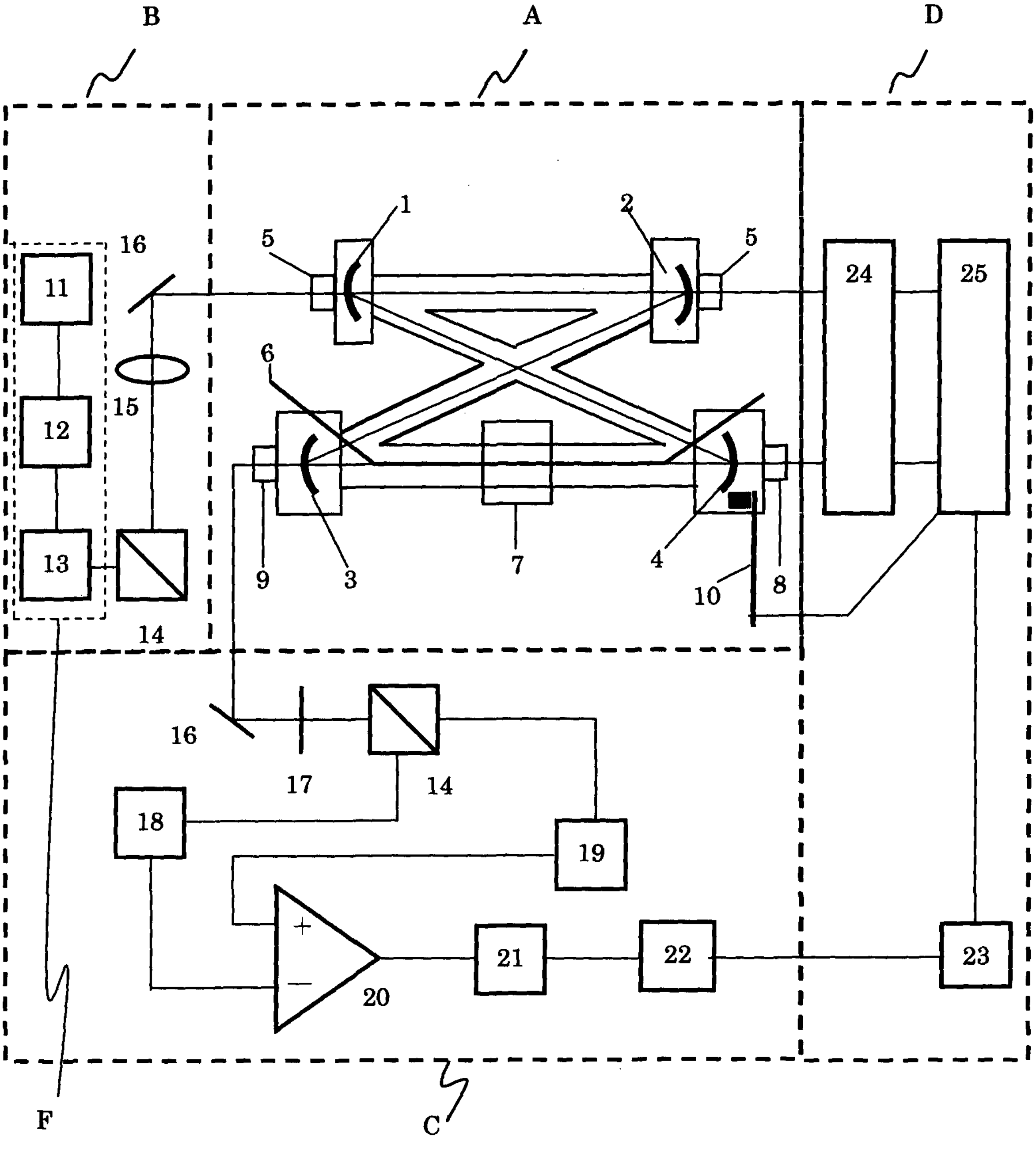


FIG. 3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A
D
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2
5
5
16
11
12
13
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3
7
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25
16
17
14
18
19
20
21
22
23
+
−
F
C

FIG. 4

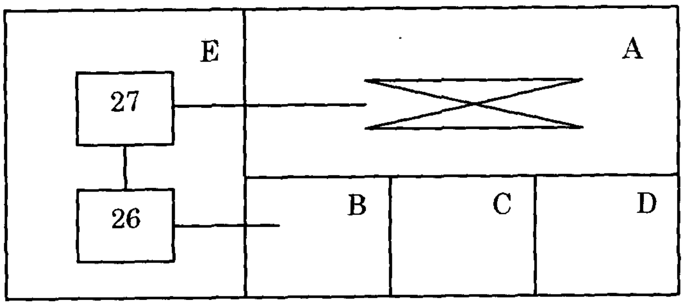
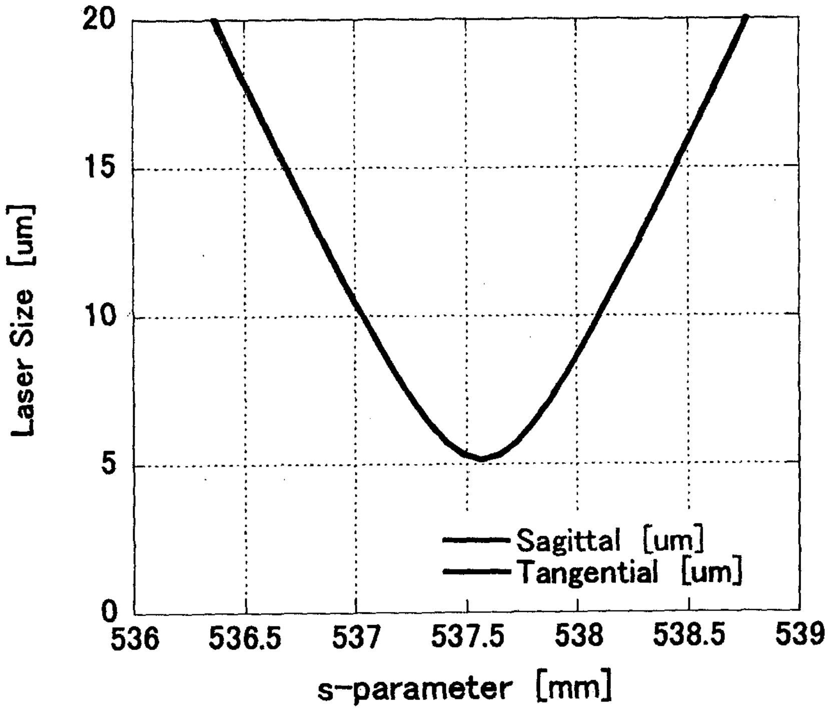

E
A
27
26
B
C
D

FIG. 5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10
5
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Laser Size [um]
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536.5
537
537.5
538
538.5
539
s-parameter [mm]
Sagittal [um]
Tangential [um]

FIG. 6

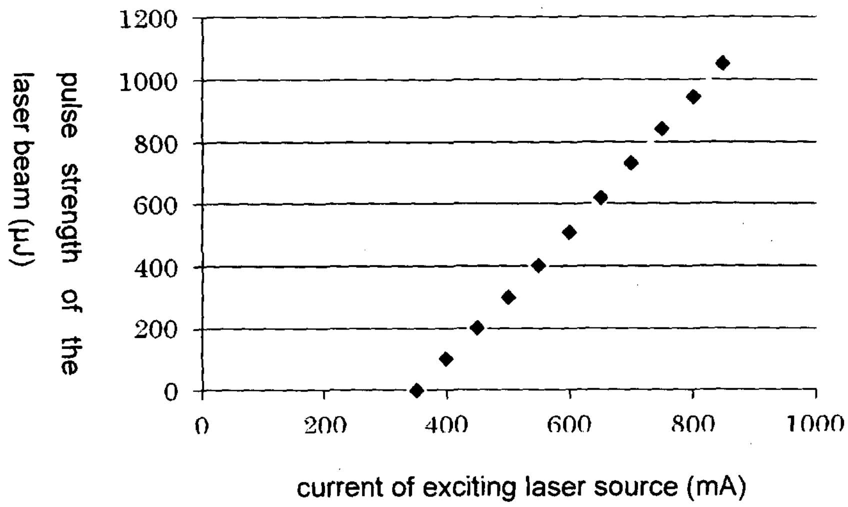
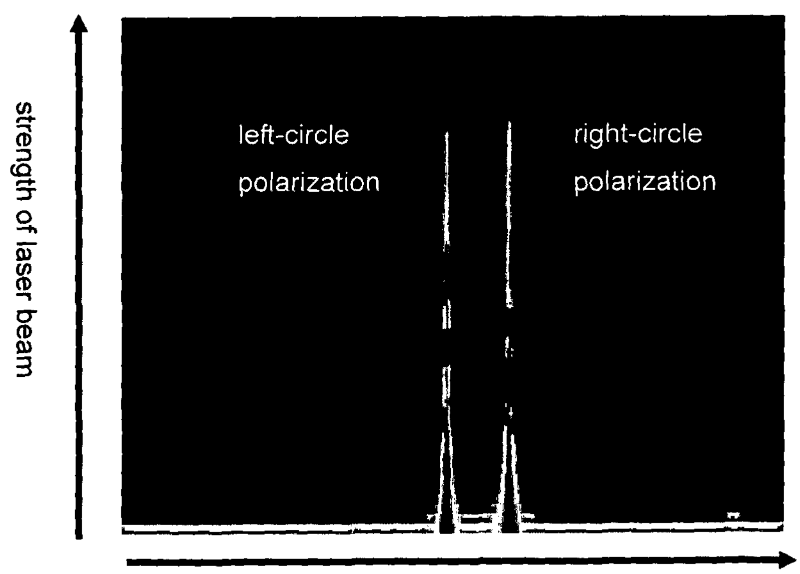


FIG. 7



circular length of the laser beam as circulation on the optic system

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2013/052958

A. CLASSIFICATION OF SUBJECT MATTER

Int.Cl. H01S3/30(2006.01)i, H01S3/10(2006.01)i, H05G2/00(2006.01)i

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)

Int.Cl. H01S3/00-3/30, H05G2/00

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

Published examined utility model applications of Japan 1922-1996
Published unexamined utility model applications of Japan 1971-2013
Registered utility model specifications of Japan 1996-2013
Published registered utility model applications of Japan 1994-2013

Electronic data base consulted during the international search (name of data base and, where practicable, 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 Y	Masafumi FUKUDA et al., Development Status and Future Plan of Laser Undulator Compact X-ray Source (LUCX) in KEK, Journal of Accelerator Society of Japan, 2012.10.31, Vol.9, No.3, pp.156-164	1 2-3
X Y	WO 2012/031607 A1 (Max-Planck-Gesellschaft zur Forderung der Wissenschaften e. V.) 2012.03.15, the whole document (Family: none)	1 2-3
Y	WO 2011/016378 A1 (High Energy Accelerator Research Organization) 2011.02.10, the whole document & JP 2011-35328 A & JP 2011-34006 A	2-3

☑ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21.05.2013	04.06.2013

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2011/041493 A2 (Massachusetts Institute of Technology) 2011.04.07, abstract, all figures & US 2011/0073784 A1	1-3
A	WO 2006/104956 A2 (Massachusetts Institute of Technology) 2006.10.05, abstract, all figures & US 2006/0251217 A1	1-3
A	US 2006/0222147 A1 (Robert John Filkins et al.) 2006.10.05, abstract, all figures (Family: none)	1-3
A	WO 2005/101925 A2 (Lyncean Technologies, Inc.) 2005.10.27, abstract, all figures & JP 2007-533081 A & JP 5030772 B & US 2005/0226383 A1 & US 2005/0243966 A1 & US 2005/0254534 A1 & US 2005/0254535 A1 & US 2005/0271185 A1 & US 2008/0002813 A1 & US 2008/0031420 A1 & EP 1745682 A & WO 2005/101926 A2 & WO 2005/112525 A2	1-3
A	WO 2011/060805 A1 (Max-Planck-Gesellschaft zur Forderung der Wissenschaften e. V.) 2011.05.26, abstract, figure 1 (Family: none)	1-3
A	WO 2012/018034 A1 (High Energy Accelerator Research Organization) 2012.02.09, abstract, figure 2 & JP 2012-38866 A	1-3
A	WO 2011/016379 A1 (High Energy Accelerator Research Organization) 2011.02.10, abstract, figure 2 & JP 2011-35331 A	1-3