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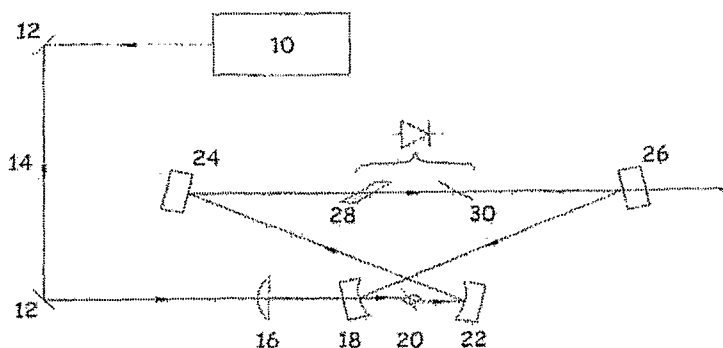
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Figure 1



(57) Abstract: According to the present invention there is provided a laser with compact planar ring cavity that produces unidirectional laser oscillation without using intracavity elements, and which can operate in single-frequency regime. A special prism is used as output coupler and the properties of internal reflection in this prism are used to select one of the two possible oscillation directions of the ring cavity. The compact design, without intracavity elements to enforce unidirectional oscillation, allows higher output powers to be achieved. Stable single-frequency operation is achieved by the combined use of frequency selective elements, such as volume Bragg gratings, etalons, or birefringent filters, with a compact design of

the cavity, which can include a monolithic structure, and the use of structural materials with low thermal expansion coefficient.

PRISM AND COMPACT UNIDIRECTIONAL SINGLE-FREQUENCY PLANAR RING CAVITY LASER WITHOUT INTRACAVITY ELEMENTS

5 BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to the field of ring cavity lasers, and particularly it relates to solid-state, single-frequency and tunable lasers, such as those based on Ti-sapphire, Cr:LISAF,
10 Alexandrite, Nd:YAG, or Nd:YVO₄ crystals.

2. Description of Previous Art Related to this Invention

Lasers are generally constructed with planar optical cavities in linear or ring configurations. It is well known that in the case of
15 continuous-wave (cw) lasers, ring cavities offer the advantage to achieve single-frequency operation with higher power because it avoids the effect of spatial hole-burning in the gain medium (A. E. Siegman, Lasers, univ. Sci. Books, Sausalito, CA, 1986). For linear cavities, the nodes of stationary-waves created by
20 counterpropagating beams leave regions of available gain which can be used by other modes of the laser cavity. Even when frequency selective elements are used, such as birefringent filters, etalons, etc, linear cavities may not provide single-frequency operation. However, single-frequency operation is
25 desired in many applications, especially when high spectral purity is required such as in precise, high-resolution spectroscopy, interferometry, analysis (trace gas detection) and inspection,

quantum optics, metrology, etc. Ring cavities avoid this problem, since the counterpropagating beams are traveling waves which do not cause spatial hole-burning. However laser oscillation in ring cavities occurs in both possible directions and is almost always
5 desirable that unidirectional oscillation is established.

Oscillation in a single direction of a ring cavity usually requires the use of an intracavity element such as an optical diode (C.E. Wagstaff and M. H. Dunn, J. Phys. D, 12 (1979) 355-368). The most common type employs the
10 discrimination provided by the Faraday effect, which causes a polarization rotation which depends on the propagation direction. This rotation is typically compensated by rotation by optical activity in another element such as a thin quartz plate, or by a half waveplate. The result is higher loss for one direction, since the
15 rotated polarization implies in higher reflection losses at other surfaces in the laser cavity. These devices however add complexity to the laser design and introduce optical insertion loss which reduces the laser output power.

Another scheme used to achieve unidirectional
20 single-frequency operation also uses the Faraday effect in a small monolithic ring cavity in nonplanar geometry (T. J. Kane, and R. L. Byer, Opt. Lett. 10 (1985) 65-67). This scheme has been employed with gain media with limited spectral bandwidth such as Nd:YAG, and others. However for gain media with large
25 spectral bandwidth, such as Ti:sapphire, Cr:LISAF, or Alexandrite, this design has limitations because intracavity

frequency selective elements can not be employed, and therefore wavelength tuning or control throughout the whole spectral band can not be obtained.

Yet another scheme to achieve unidirectional oscillation in planar ring cavities is based on retroreflection of one of the two output beams by an external mirror (H. W. Schröder, L. Stein, D. Frölich, B. Fugger, and H. Welling, Appl. Phys. B 14 (1977) 377-380; J.M. Green, J. P. Hohimer, F. K. Tittel, Opt. Commun., 7 (1973) 349-350). This scheme works well, but generally does not enforce single-frequency operation because thermal or vibration noise induces phase fluctuations in the retroreflected beam. A solution to this can be active stabilization by a servo-control system to, for example, hold stable the optical path between this external mirror and the laser cavity. This however adds complexity to the laser design. The present invention relates to this method, but introduces useful and non-obvious innovation.

Yet another scheme to achieve unidirectional oscillation has been explored in which a wedge with unequal-reflectivity mirror coatings on both sides is introduced inside the laser cavity (E. Stoykova, M. Nenchev, Opt. Lett., 19 (1994) 1925-1927). This technique has the disadvantage of introducing significant losses in the cavity, and thus has been demonstrated for pulsed lasers, in which the high gain and amplification overcomes these losses.

The easy achievement of unidirectional oscillation by retroreflection from the “output-coupler-prism”, allows for a very compact and efficient laser operating in single-frequency. In previous publications (C. Zimmermann, V. Vuletic, A. Hemmerich, L. Ricci, and T. W. Hänsch, Opt. Lett, 20 (1995) 297-299) a compact Ti:sapphire laser is demonstrated by using only two etalons as the only intracavity elements, besides the gain medium. This cavity however was a stationary-wave linear cavity, and as a result of this, laser oscillation was restricted to two longitudinal modes. No single-frequency operation was achieved.

More recently a volume Bragg grating has been employed as a frequency selective element in a Ti:sapphire laser (Te-Yuan Chung, A. Rapaport, V. I. Smirnov, L. B. Glebov, M.C. Richardson, and M. Bass, Opt. Lett., 31 (2006); M. Hemmer, T. Chung, Y. Chen, V. Smirnov, L. Glebov, M. C. Richardson, and M. Bass, 27th Annual Conference on Lasers and Electro-Optics CLEO/QELS and PAHST Technical Digest, paper code CThE5, Baltimore, MD, 2007). However, the cavity employed was again a stationary-wave ring cavity and as a result of this, laser oscillation was restricted to two longitudinal modes. No single-frequency operation was achieved.

As described in the prior art, unidirectional laser oscillation in planar ring cavities can be achieved through the use of one or more intracavity optical components. Such intracavity devices are unappealing because they add complexity to the laser design and also add losses to the laser cavity that reduce the laser output

power.

OBJECT OF THE INVENTION

It is therefore an object of the present invention to provide a planar ring cavity laser that has a small physical size, and operates in only one direction without recurring to intracavity elements for this purpose.

Another object of the present invention is to provide a special prism used both as the laser output coupler and as an optical component which enforces unidirectional oscillation. Because no intracavity elements are used to achieve unidirectional oscillation, it is thus possible to achieve higher useful output power, lower cost and very small physical size.

In one embodiment of the present invention, this output-coupler-prism has a partially reflecting coating in one of its face that is part of the laser cavity. This coating reflectivity is such that maximizes the output power, as a regular output coupler mirror. The two beams, circulating in opposite directions in the laser ring cavity, inside in this face and refract in the prism according to Snell's law. The prism angles are such that one of those beams (called the first beam) is totally transmitted by the second face at Brewster's angle, and constitutes the laser output beam. The other beam (called the second beam) is totally reflected at this same face by total internal reflection. In this embodiment, it is explored the small angular difference that exists in total internal reflection between the Brewster angle and the critical angle. This second beam then insides in the third

remaining prism face, which has a high reflecting coating, and is retroreflected along its optical path. This beam is therefore reinjected into the laser cavity, and is responsible to eliminating the laser oscillation in that direction. Laser oscillation then occurs
5 only in the direction of the first beam.

In another embodiment of the present invention, this output-coupler-prism also has a partially reflecting coating in its face that is part of the laser cavity. However the second face has a coating such that strongly transmits one of the beams, that
10 insides at a given incidence angle, and strongly reflects the other beam that insides at another incidence angle. This second beam then insides the third prism face, that has a high reflecting coating, at normal incidence (zero degree) and is retroreflected along the same direction. This beam is then reinjected into the
15 laser cavity, and is responsible for eliminating the laser oscillation in that direction. Laser oscillation then occurs only in the direction of the first beam.

A further object of the present invention is to provide a compact ring laser whose cavity is constructed with
20 materials of low thermal expansion coefficient, such as fused silica, INVAR, carbon fiber, Zerodur and ULE.

A further object of the present invention is to provide a compact ring laser whose cavity has a monolithic design in order to provide high mechanical stability, with reduced
25 sensitivity to acoustic and vibrational noise.

A further object of the present invention is to provide a compact ring laser which combines a small physical size with the use of low thermal expansion materials, to achieve cavity length fluctuations, induced by vibrational and thermal noise, smaller than or on the order of the wavelength. For visible
5 or near infrared lasers, this can be a few hundred nanometers.

Another object of the present invention is to provide a compact planar ring cavity laser system which, in addition to achieving unidirectional oscillation as described
10 above, also oscillates in a single longitudinal mode (single-frequency). This is accomplished by constructing the laser cavity with small physical size using low thermal expansion materials. With these two features, the cavity passive length fluctuations, induced by thermal and vibrational (acoustic, seismic) noise, are
15 on the order of or smaller than the laser wavelength. In this way, phase stability is preserved for the retroreflected beam from the output-coupler-prism, and no active servo-control for this retroreflected light is necessary. This phase stability ensures stable single-frequency operation. If necessary, an active control
20 of the temperature of the laser cavity can be employed to assure long-term single-frequency oscillation.

A further object of the present invention is to provide a compact ring laser which uses frequency selective elements inside the cavity, such as a birefringent filter, one or two
25 etalons or a Bragg grating, in order to achieve single-frequency

oscillation in lasers with large gain bandwidth such as Ti:sapphire, Cr:LISAF, Alexandrite, and others.

A further object of the present invention is to provide a planar ring cavity laser system which, because of its small size, allows for tight focus in the gain medium, and therefore allows for very low threshold. As an example, demonstrated prototypes of Ti:sapphire lasers achieve threshold of 300 mW when pumped by a single-frequency laser at 532nm. This low threshold makes possible to use pump lasers with 1 or 2 Watts of output power to pump a Ti:sapphire laser. Output powers of 1.5 W have been demonstrated for a Ti:sapphire laser pumped by 5 Watts at 532 nm.

Yet a further object of the present invention is to provide a planar ring cavity laser system which is unidirectional, single-frequency and has no intracavity elements, except the gain media, such as a Ti:sapphire crystal. A reflective volume Bragg grating is used both as a cavity mirror and as a frequency selective element. This design greatly simplifies the versions of single-frequency tunable lasers (such as Ti:sapphire) available today and should imply into a significant reduction in costs and size.

Yet a further object of the present invention is to provide a planar ring cavity laser system which is unidirectional and operate in mode-locked regime, producing ultra-short pulses. Mode-locking is either active or passive, in this last case through the mechanism of Kerr lensing. For this purpose, chirped mirrors

are used for the laser cavity in order to produce negative group velocity dispersion, which compensates the positive group velocity dispersion introduced by the gain medium. Alternately, a prism pair can be used instead of chirped mirrors, to introduce
5 negative group velocity dispersion. The use of the output-coupler-prism assures unidirectional oscillation of the ring cavity always in the desired direction and, therefore without need of any other component for this purpose.

DESCRIPTION OF THE DRAWINGS

10 FIG.1 is an illustration of a prior art ring cavity laser using an optical diode based on Faraday rotation to achieve unidirectional oscillation. A Faraday crystal (28), such as TGG, is placed at Brewster angle under a magnetic field produced by permanent magnets. A thin quartz plate (30) or a waveplate
15 compensates the Faraday rotation.

FIG.2 is an illustration of a prior art ring cavity laser configured for unidirectional and single-frequency oscillation. The laser cavity includes an optical diode (30) (Fig.1), a birefringent filter (32) and two etalons (34,36), one of which is
20 thin (36) and the other thick (34), and this last one can be formed by two prisms such as its length can be varied.

FIG.3 is an illustration of another prior art ring cavity laser configured for unidirectional and single-frequency oscillation. The cavity includes an optical diode (30), a
25 birefringent filter (32) and only one etalon (34) to achieve unidirectional and single-frequency oscillation.

FIG.4 is a schematic diagram of the special prism used as the output coupler of the compact ring cavity laser of the present invention.

FIG.5 is a schematic diagram illustrating one embodiment of the compact ring cavity laser of the present invention with a reflecting volume Bragg grating (24) used as one of the cavity mirrors and also as a frequency selective element to achieve single-frequency oscillation. In addition, a prism (28) is used both as the output coupler and to enforce unidirectional oscillation.

FIG.6 is a schematic diagram illustrating one embodiment of the compact ring cavity laser of the present invention with a transmission volume Bragg grating (30) is used as a frequency selective element to achieve single-frequency oscillation. In addition, a prism (28) is used both as the output coupler and to enforce unidirectional oscillation.

FIG.7 is a schematic diagram illustrating one embodiment of the compact ring cavity laser of the present invention in which a birefringent filter (30) and a thin etalon (32) are used as frequency selective elements to achieve single-frequency oscillation. In addition, a prism (28) of figure 4 is used both as the output coupler and to enforce unidirectional oscillation.

FIG.8 is a schematic diagram illustrating one embodiment of the compact ring cavity laser of the present invention in which two etalons (30,32) are used as frequency

selective elements to achieve single-frequency oscillation. In addition, a prism (28) is used both as the output coupler and to enforce unidirectional oscillation.

FIG.9 is a schematic diagram illustrating one embodiment of the compact ring cavity laser of the present invention in which chirped mirrors (18, 22, 24) are used to achieve mode-locking. In addition, a prism (28) is used both as output coupler and to enforce stable unidirectional oscillation.

DETAILED DESCRIPTION OF THE 10 PREFERRED EMBODIMENTS

Referring now to FIG.4, a prism 18 is used as the laser output coupler and at the same time as an optical element that enforces unidirectional oscillation. It has internal angles α (12), β (14) and γ (16) and faces 6, 8 and 10. The two counterpropagating beams 2 and 4, circulating inside the ring cavity and having linear polarizations in the plane of FIG.4, inside at face 6 of the prism 18, with angles ϕ . Face 6 has a partially transmitting coating with reflectivity optimized for maximum laser output power, as a regular output coupler mirror. Beams 2 and 4 refract at the prism with angles θ , as shown in figure 4. Beam 2 inside on face 8 of the prism at Brewster angle $\theta_B = \text{tg}^{-1}(1/n)$, where n is the index of refraction of the prism material at the laser wavelength λ . Beam 2 is then totally transmitted and constitutes the useful output beam. Beam 4, instead, suffers total internal reflection at face 8 and insides at face 10 at normal

incidence (zero degree). Face 10 has a high reflecting coating, so that beam 4 is totally reflected and is then redirected towards the cavity along the same path. Assuming the just described criteria of total transmission of beam 2 at face 8, total internal reflection of beam 4 at face 8, followed by its retroreflection at face 10, it then follows in this case that the prism angles must be $\alpha = \theta + \theta_B$, $\beta = \theta + 2\theta_B$ and $\gamma = \pi - \alpha - \beta$.

In another embodiment, the face 8 of the prism has a coating such that beam 2 is highly transmitted and beam 4 is highly reflected at their different incidence angles. In this case the prism does not need to be constructed with the angles mentioned above, however the coating of face 8 is more difficult to be done, since for a small angle variation it should go from highly reflector to highly transmissive.

In the embodiment of FIG.5 of the compact ring cavity laser, a pump laser 10 is directed by mirrors 12 along the path 14 towards the laser cavity. A pump lens 16 is used to focus the pump beam into the gain medium 20, and to match the parameters of the pump beam to the ones of the laser cavity. The laser cavity is formed by mirrors 18 and 22, by a reflective Bragg grating 24 also used as a mirror, and by the output-coupler-prism 28, described in Fig. 4. The reflective Bragg grating works both as a cavity mirror and as a frequency selective element. Its use in a ring cavity ensures single-frequency oscillation even for large gain bandwidth lasers such as Ti:sapphire, Cr:LISAF or Alexandrite. In one embodiment, the grating 24 is chirped, in

which case it can be translated transversely for wavelength selection and tuning. In another embodiment, if the grating 24 has fixed period (e.g, is not chirped), it is rotated in order to do tuning.

5 In one embodiment of FIG.5, the rotation of grating 24 is done by a galvanometer or a servo motor. In this last case, control of the grating angle is done digitally by a computer, microcontroller, microprocessor or digital signal processor (DSP). The laser wavelength is calibrated externally by a spectrum
10 analyzer or spectrometer, so that the grating angular position is mapped into laser wavelength. A microcontroller, microprocessor or computer stores these values such that, after calibration, tuning to a desired wavelength is done digitally in a simple way. A largely tunable laser, such as Ti:sapphire or Cr:LISAF, is then
15 wavelength calibrated once at the factory, which eliminates the need for a laser wavelength meter by the user, except when recalibration becomes necessary. Fine tuning of the laser wavelength is done by a piezo element 26 that supports one of the cavity mirrors 18 or 22, or even the Bragg grating 24.

20 In another embodiment of FIG.6 of the compact ring cavity laser, a pump laser 10 is directed by mirrors 12 along the path 14 towards the laser cavity. A pump lens 16 is used to focus the pump beam into the gain medium 20, and to match the parameters of the pump beam to the ones of the laser cavity. The
25 ring cavity is formed by mirrors 18, 22, 24, by a transmission Bragg grating 30 and by the output-coupler-prism 28, described in

Fig. 4. The transmission Bragg grating works as a frequency selective element. Its use in a ring cavity ensures single-frequency oscillation even for large gain bandwidth lasers such as Ti:sapphire, Cr:LISAF or Alexandrite. The grating 24 can be
5 chirped, in which case it can be translated transversely for wavelength selection and tuning. Alternately, if its period is fixed (e.g., is not chirped), it can be rotated for perform wavelength tuning. The mirror 24 (or another mirror of the laser cavity) is supported by the piezo 26, which is used either for fine
10 wavelength tuning or as an actuator for laser frequency control.

In another embodiment of FIG.7 of the compact ring cavity laser, a pump laser 10 is directed by mirrors 12 along the path 14 towards the laser cavity. A pump lens 16 is used to focus the pump beam into the gain medium 20, and to match the
15 pump beam parameters to the ones of the laser cavity. The ring cavity is formed by mirrors 18, 22, 24, a birefringent filter 30, a thin etalon 32 and by the output-coupler-prism 28, described in Fig. 4. The birefringent filter 30 and the thin etalon 32 work together as frequency selective elements to enforce single-
20 frequency oscillation. Their use in a ring cavity ensures single-frequency oscillation even for large gain bandwidth lasers such as Ti:sapphire, Cr:LISAF or Alexandrite. In one embodiment of FIG. 7, the birefringent filter 30 and etalon 32 are precisely rotated by a galvanometer or a servo motor. In this last case,
25 control of the etalon angle is done digitally by a computer, microcontroller, microprocessor or digital signal processor (DSP).

The laser wavelength is calibrated externally by a spectrum analyzer or spectrometer, so that the etalon angular position is mapped into laser wavelength. A microcontroller, microprocessor or computer stores these values such that, after calibration, tuning
5 to a desired wavelength is done digitally in a simple way. A largely tunable laser, such as Ti:sapphire or Cr:LISAF, is then wavelength calibrated once at the factory, which eliminates the need for a laser wavelength meter by the user, except when
10 of the laser cavity) is supported by the piezo element 26, which is used for fine wavelength tuning or as an actuator for laser frequency control.

In another embodiment of FIG.8 of the compact ring cavity laser, particularly suitable for largely tunable lasers
15 such as Ti:sapphire, Cr:LISAF or Alexandrite, a pump laser 10 is directed by mirrors 12 along the path 14 towards the laser cavity. A pump lens 16 is used to focus the pump beam into the gain medium 20, and to match the pump beam parameters to the ones of the laser cavity. The ring cavity is formed by mirrors 18, 22,
20 24, by two thin etalons 30 and 32 and by the output-coupler-prism 28, described in Fig. 4. The thin etalons 30 and 32 work together as frequency selective elements and can have slightly different thickness, so that their transmission peaks coincide at very large spectral intervals (in a Vernier effect), which can be several
25 TeraHertz. This is important to establish single-frequency oscillation in ring cavities for largely tunable lasers such as

Ti:sapphire, Cr:LISAF or Alexandrite. The etalons 30 and 32 are precisely rotated by a galvanometer or a servo-motor. In this last case, simultaneous control of both etalon angles is done digitally by a computer, microcontroller, microprocessor or digital signal processor (DSP). The laser wavelength is calibrated externally by a spectrum analyzer or spectrometer, so that the etalons angular positions are mapped into laser wavelength. A microcontroller, microprocessor or computer stores these values such that, after calibration, tuning to a desired wavelength is done digitally in a simple way. A proper algorithm that maps the angular position of both etalons into wavelength is used by the microprocessor. A largely tunable laser, such as Ti:sapphire or Cr:LISAF, is then wavelength calibrated once at the factory, which eliminates the need for a laser wavelength meter by the user, except when recalibration becomes necessary. The mirror 24 (or another mirror of the laser cavity) is supported by the piezo 26, which is used for fine wavelength tuning or as an actuator for laser frequency control.

In another embodiment of FIG.9 of the compact ring cavity laser, particularly suitable for largely tunable lasers such as Ti:sapphire, Cr:LISAF or Alexandrite, a pump laser 10 is directed by mirrors 12 along the path 14 towards the laser cavity. A pump lens 16 is used to focus the pump beam into the gain medium 20, and to match the pump beam parameters to the ones of the laser cavity. The ring cavity is formed by mirrors 18, 22, 24, and by the output-coupler prism 28, described in Fig. 4. Either

one of the mirrors 18, 22, and 24, or even the coating of the output-coupler prism , can be dispersive (chirped) such as to introduce negative group velocity dispersion, such as to compensate the positive dispersion introduced by the gain
5 medium. In this way the laser oscillates in mode-locking regime, producing ultrashort pulses. The output-coupler-prism assures unidirectional oscillation of the ring cavity mode-locked laser and eliminates, therefore, any intracavity element used for this purpose, such as for example, acousto-optical modulators used
10 today for this purpose in various commercial models. The mirror 24 (or another mirror of the laser cavity) is positioned by the piezoelectric transducer 26, which can be used as actuator to stabilize the repetition rate of the mode-locked laser. In another embodiment, which is a natural variation of the scheme of Fig. 9,
15 a prism pair, instead of chirped mirrors, is used inside the laser cavity to introduce negative group velocity dispersion. This is a usual method employed today to produce ultrashort pulses through the mechanism of passive Kerr lens mode-locking.

As the invention has been described, it will be
20 apparent to those skilled in the art that the same may be varied in many ways without departing from the spirit and scope of the invention. Any and all such modifications are intended to be included within the scope of the appended claims.

CLAIMS

1. A prism (“output-coupler-prism”) characterized by having a partially reflecting coating in one of its faces (called first face) which acts as output coupler, and having
5 angles such as one of the linearly polarized beams circulating in the ring cavity (called first beam) is transmitted through the first face and suffer total transmission at Brewster angle on the second face, while the other beam circulating in opposite direction in the ring cavity (called second beam) is transmitted through the first
10 face and suffer total internal reflection at the second face, this prism also having a highly reflecting coating deposited on the third remaining face, where the second beam reflected by the second face is totally reflected in this third face along itself such that it is reinjected into the optical cavity of the laser.

15 2. Prism of claim 1, characterized by the fact that if the two counterpropagating beams of the ring cavity reach the first face of the prism with incidence angles ϕ and refract with internal angles Θ inside the prism, and if this same prism has index of refraction n at a wavelength λ , then the prism is
20 constructed with internal angles α , β and γ , such that $\alpha = \Theta_B + \Theta$, $\beta = \Theta_B + 2\Theta$ and $\gamma = \pi - \alpha - \beta$ in which Θ_B is the Brewster angle for total internal transmission defined as $\text{tg}^{-1}(1/n)$.

3. Prism of claim 1, characterized by that this output-coupler-prism alternately has a dielectric coating in the

second face (exit face) such as it transmits beam 1 and reflects beam 2, which propagate inside the prism.

4. Prism of claims 1, 2 and 3, characterized by being made from a material with low thermal expansion, such as fused silica.

5. Prism of claims 1, 2, 3 and 4, characterized by that this output-coupler-prism can have the first face either flat or curve (concave or convex), such as it can be used as a flat or curved output coupler.

10 6. Prism of claims 1, 2, 3 and 4, characterized by that this output-coupler-prism can have the third face either flat or curve (specially concave) in the direction transverse to the plane of the optical cavity, such as to reduce the sensitivity to alignment to the plane of the optical cavity.

15 7. Laser with planar ring cavity geometry which achieves unidirectional oscillation and characterized by having an optical cavity which includes an active medium (particularly solid state), at least one mirror (particularly dielectric, including the case in which they are deposited directly in one or more faces of the solid state active medium) and the prism of any of the claims 1, 2, 3, 4, 5 and 6.

25 8. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, characterized by that the laser optical cavity still includes other optical elements, such as frequency filters, etalons, electro-optical modulators, acousto-optical modulators, nonlinear crystals,

Brewster plates, volume Bragg gratings, lenses, prisms and their combinations.

9. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, wherein it can operate in continuous-wave (cw), mode-locked or Q-switched regimes, or simply as an optical amplifier.

10. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7 or 9, wherein when operated in continuous-wave (cw) or mode-locked regimes, the laser still includes an external optical cavity that is used as frequency reference for stabilizing the laser frequency.

11. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 9, wherein for a cw laser, its optical cavity is compact enough such as its length variations, induced by vibrations or thermal variations, are comparable or smaller than the laser wavelength.

12. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to any of the claim 7, 8, 9, 10 or 11, wherein single-frequency operation is obtained when unidirectional operation is obtained by reinjection of the light from the second beam by the prism-output coupler mirror.

13. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7,

wherein the largest linear dimension of the cavity is smaller than 20 cm.

14. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, wherein the laser optical cavity is constructed with materials with low thermal expansion coefficients such as INVAR, fused silica, and others.

15. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, wherein the optical cavity is constructed in a monolithic structure.

16. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, wherein at least one mirror can be curved or flat.

17. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, wherein the solid state active medium has Brewster-cut faces.

18. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, wherein the incidence angles on the curved mirrors are such to compensate astigmatism generated by each Brewster face of the crystal, in order to produce a non-astigmatic laser beam.

19. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, wherein the active medium is a solid-state material such as Ti:sapphire, Cr:LiSAF, Cr:LiSGaF, Cr:LiCaF, Alexandrite, Cr:Forsterite, Nd:YAG, Nd:YVO₄, and others.

20. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7 or 19, wherein frequency-doubled Nd:YVO₄, Yb:YVO₄, Nd:YAG, or Yb:YAG lasers are used as pump sources.

5 21. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7 or 19, wherein the solid-state active medium is a short Ti:sapphire or Cr:LiSAF crystal (smaller than 5 mm), with doping level such as to absorb at least 60% of the pump laser power.

10 22. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 7, wherein the laser optical cavity is mounted on a metallic baseplate or a baseplate of another material.

23. Laser with planar ring cavity geometry
15 which achieves unidirectional oscillation according to claim 22, wherein this baseplate is temperature stabilized.

24. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 22, wherein the material employed for the supports of the optical
20 elements of the laser cavity and the baseplate have low thermal expansion coefficient, such as the cavity length is stable within half wavelength of the laser.

25 25. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to any of claims 7 or 8, wherein a volume Bragg grating is employed as frequency selective element or frequency filter.

26. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to any of the claims 7, 8 or 25, wherein a volume Bragg grating is employed to achieve single-frequency operation.

5 27. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to any of the claims 7, 8, 25 or 26, wherein the volume Bragg grating is reflective, transmissive or chirped.

10 28. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to any of the claims 7, 8, 25, 26 or 27, wherein the Bragg grating is rotated or translated to select a single longitudinal mode, whose wavelength is measured or calibrated by a spectral analyzer or wavemeter.

15 29. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to any of claim 28, wherein the rotation or translation of the Bragg grating is performed by a servo motor which is actuated by a computer, microcontroller, microprocessor or digital signal processor.

20 30. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 29, wherein the computer, microcontroller, microprocessor or digital signal processor stores the angles as function of wavelength, such that tuning to a specific wavelength is done electronically by the user.

25 31. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to any of the

claims 7 or 8, wherein two etalons are employed to achieve single-frequency operation.

32. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 31,
5 wherein the angular position of the etalons is controlled by a galvanometer or servo-motor.

33. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 32,
wherein the galvanometer is controlled digitally by a computer,
10 microprocessor, microcontroller or digital signal processor.

34. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 31,
wherein the two etalons have slightly different thickness such that their respective transmission peaks coincide at large frequency
15 intervals which can be several terahertz, allowing therefore the selection of a single longitudinal mode, particularly for lasers with large bandwidths such as Ti:sapphire and Cr:LiSAF.

35. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to any of the
20 claims 7 or 8, wherein a birefringent filter and a thin etalon are employed to achieve single-frequency oscillation.

36. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 35,
wherein the angular position of the etalon is controlled by a
25 galvanometer or servo-motor.

37. Laser with planar ring cavity geometry which achieves unidirectional oscillation according to claim 36, wherein the galvanometer is controlled analogically or the servomotor is controlled digitally by a computer, microprocessor, microcontroller or digital signal processor.

Figure 1

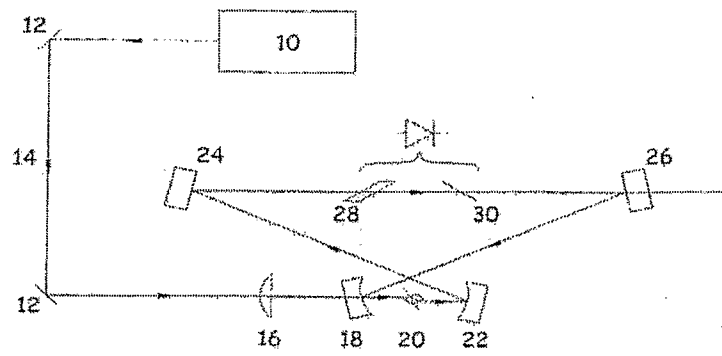


Figure 2

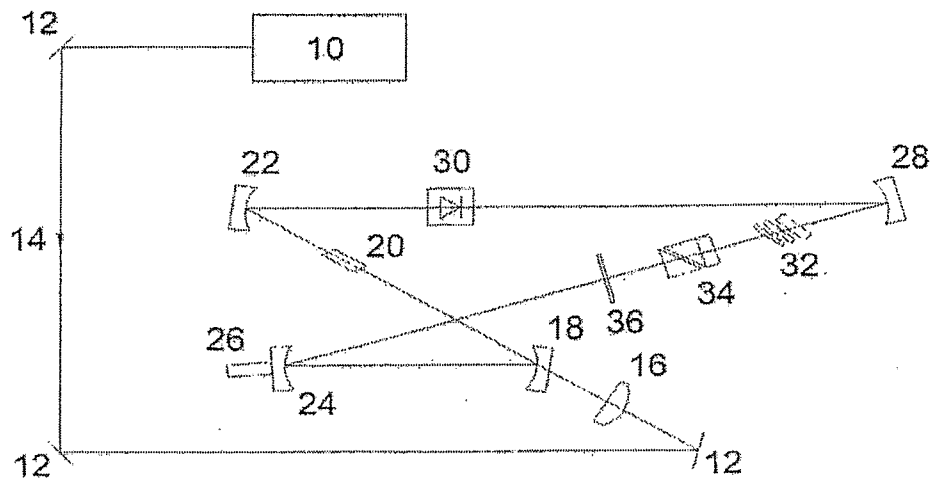


Figure 3

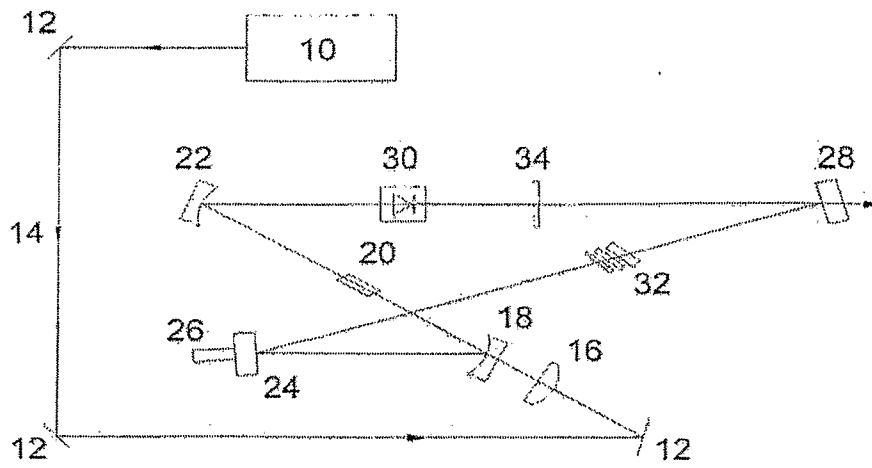


Figure 4

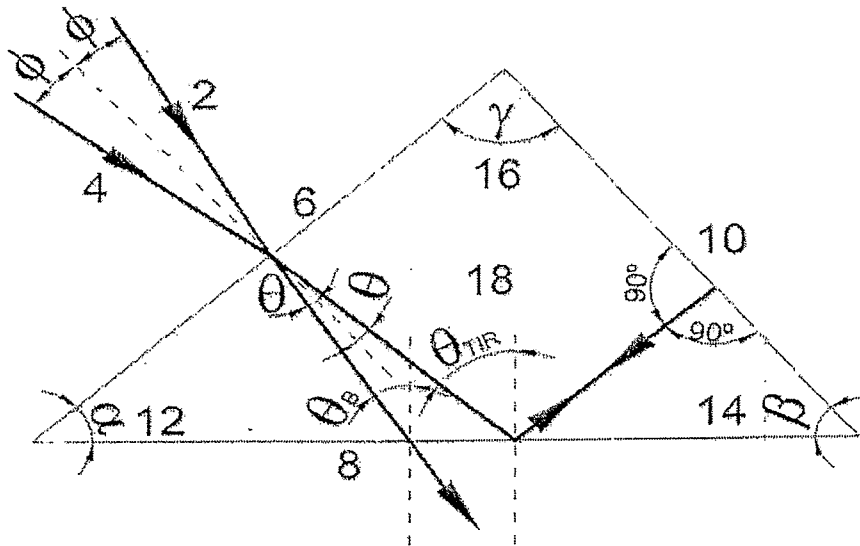


Figure 5

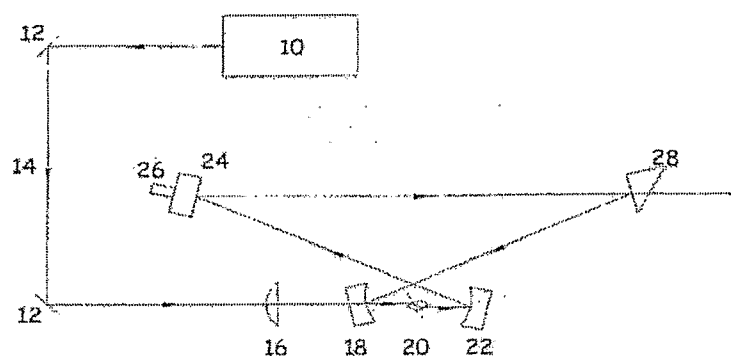


Figure 6

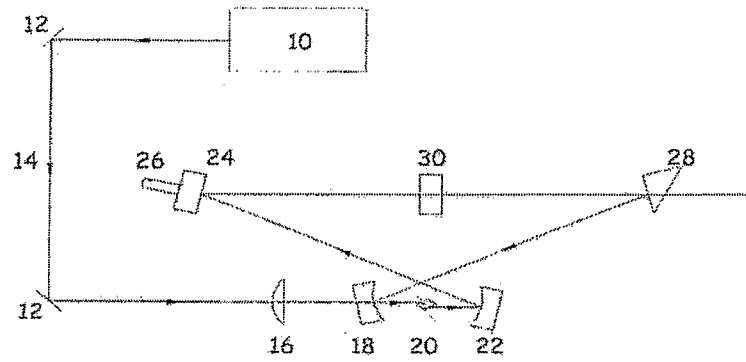


Figure 7

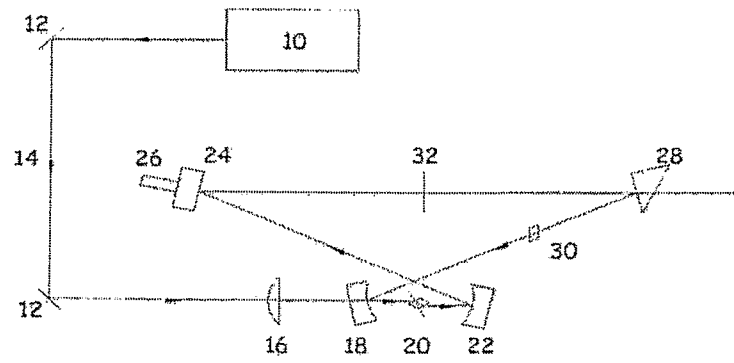


Figure 8

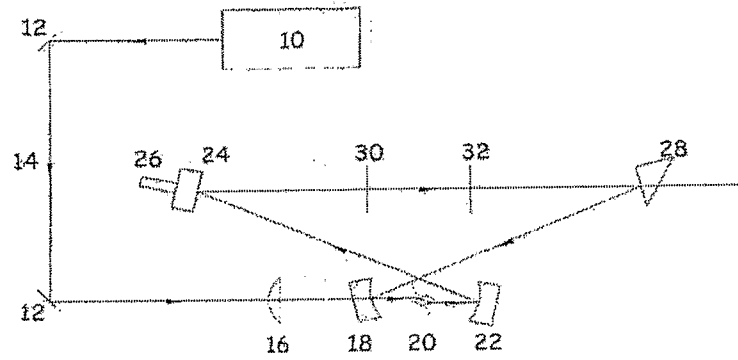


Figure 9

