



US007848381B2

(12) **United States Patent**
Barnes et al.

(10) **Patent No.:** **US 7,848,381 B2**
(45) **Date of Patent:** **Dec. 7, 2010**

- (54) **MULTIPLE-WAVELENGTH TUNABLE LASER**
- (75) Inventors: **Norman P. Barnes**, Yorktown, VA (US);
Brian M. Walsh, Poquoson, VA (US);
Donald J. Reichle, Seaford, VA (US)
- (73) Assignee: **The United States of America as represented by the Administrator of the National Aeronautics and Space Administration**, Washington, DC (US)
- (*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 149 days.

| | | |
|--------------|---------|----------------|
| 4,734,912 A | 3/1988 | Scerbak et al. |
| 4,864,584 A | 9/1989 | Martins |
| 5,022,041 A | 6/1991 | Jacobs |
| 5,058,980 A | 10/1991 | Howerton |
| 5,295,143 A | 3/1994 | Rao et al. |
| 5,333,142 A | 7/1994 | Scheps |
| 5,408,481 A | 4/1995 | Scheps |
| 5,457,707 A | 10/1995 | Sobey et al. |
| 5,471,493 A | 11/1995 | Mirov et al. |
| 5,577,060 A | 11/1996 | Nighan et al. |
| 5,633,883 A | 5/1997 | Shi et al. |
| 5,661,595 A | 8/1997 | Stamm et al. |
| 5,764,662 A | 6/1998 | Pinto |
| 6,654,391 B2 | 11/2003 | Adams |

FOREIGN PATENT DOCUMENTS

| | | |
|----|----------|--------|
| JP | 63184383 | 7/1988 |
| JP | 04111484 | 4/1992 |
| JP | 06077577 | 3/1994 |
| JP | 08240528 | 9/1996 |

(21) Appl. No.: **12/366,722**

(22) Filed: **Feb. 6, 2009**

(65) **Prior Publication Data**

US 2009/0207868 A1 Aug. 20, 2009

Related U.S. Application Data

(60) Provisional application No. 61/029,020, filed on Feb. 15, 2008.

(51) **Int. Cl.**

H01S 3/10 (2006.01)

H01S 3/08 (2006.01)

H01S 3/082 (2006.01)

(52) **U.S. Cl.** **372/97; 372/20; 372/92**

(58) **Field of Classification Search** **372/20, 372/21, 22, 92, 97, 99, 101, 108**

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,947,688 A 3/1976 Massey

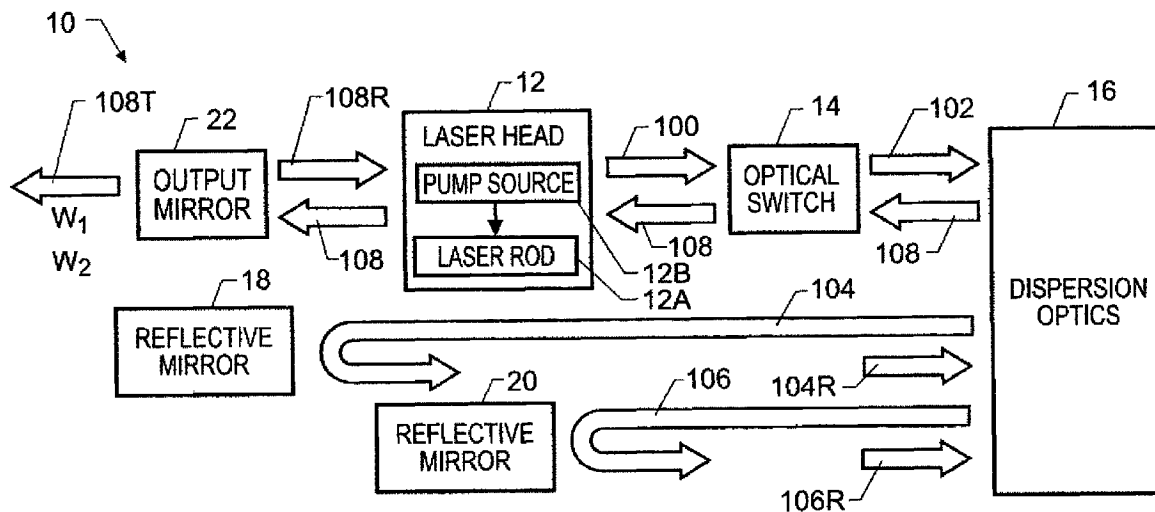
Primary Examiner—Armando Rodriguez

(74) Attorney, Agent, or Firm—Andrea Z. Warmbier; Helen M. Galus

(57) **ABSTRACT**

A tunable laser includes dispersion optics for separating generated laser pulses into first and second wavelength pulses directed along first and second optical paths. First and second reflective mirrors are disposed in the first and second optical paths, respectively. The laser's output mirror is partially reflective and partially transmissive with respect to the first wavelength and the second wavelength in accordance with provided criteria. A first resonator length is defined between the output mirror and the first mirror, while a second resonator length is defined between the output mirror and the second mirror. The second resonator length is a function of the first resonator length.

26 Claims, 2 Drawing Sheets



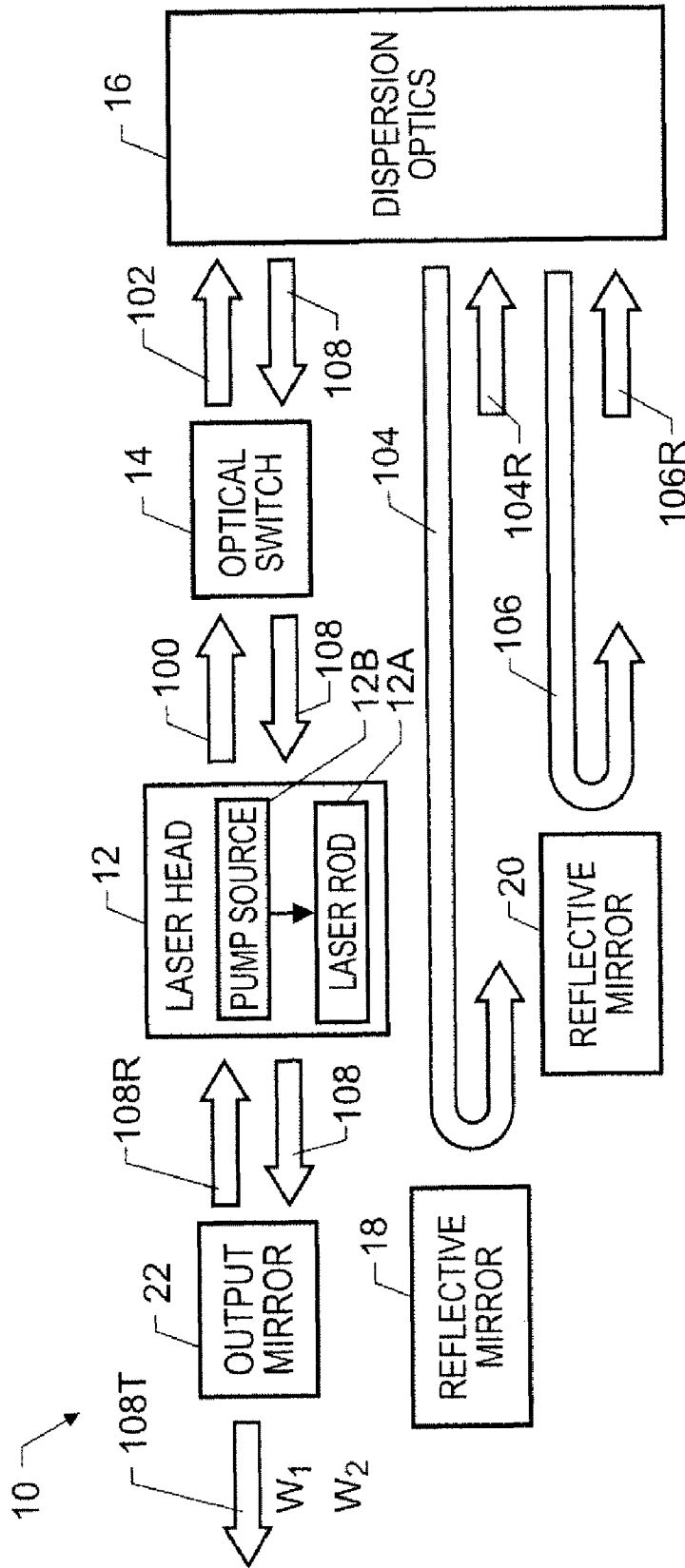


FIG. 1

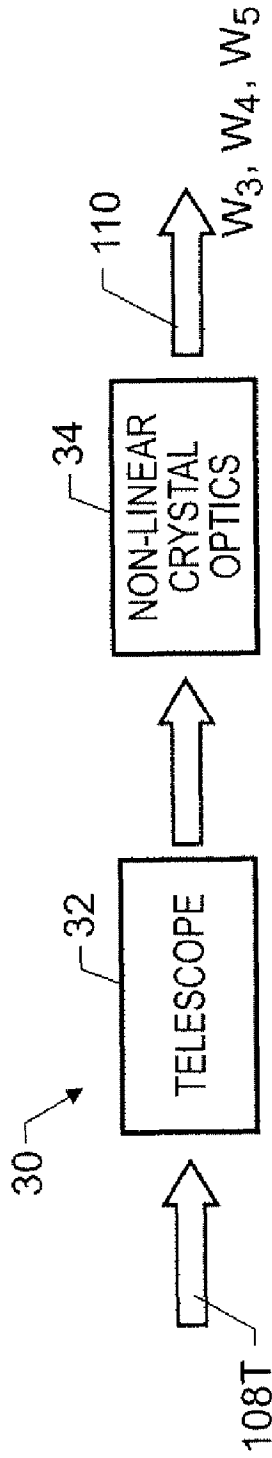


FIG. 2

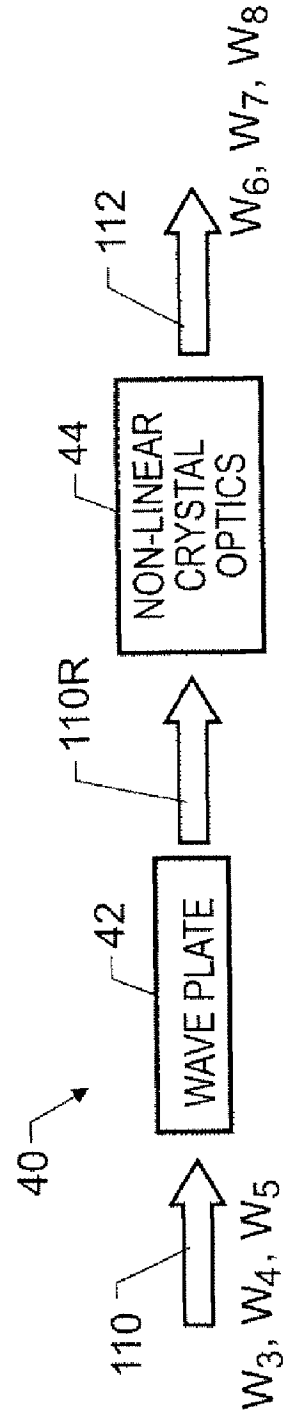


FIG. 3

1

MULTIPLE-WAVELENGTH TUNABLE LASER

Pursuant to 35 U.S.C. §119 the benefit of priority from provisional application 61/029,020, with a filing date of Feb. 15, 2008, is claimed for this non-provisional application

ORIGIN OF THE INVENTION

The invention was made by employees of the United States Government and may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION**1. Field of the Invention**

This invention relates to tunable lasers. More specifically, the invention is a tunable laser that can simultaneously produce multiple synchronized laser beams at unique wavelengths using a single laser source.

2. Description of the Related Art

High-peak pulsed laser sources are needed at various wavelengths throughout the visible and ultraviolet region. Many applications also require a pulsed laser source to be tunable. Among the applications requiring tunable lasers are remote sensing applications (e.g., remote ozone sensing), color displays, and lithography.

Although there are some lasers that can possibly address the needed spectral regions, most present serious drawbacks. For example, dye lasers can be used to produce laser wavelengths throughout much of the visible spectrum. However, the dyes have a short lifetime and must be replaced frequently. Furthermore, some of the dyes and solvents are carcinogenic thereby complicating their replacement and disposal. In addition, the high-gain and short upper laser level lifetime lasers associated with dye lasers makes it difficult for these lasers to provide good beam quality.

With respect to the ultraviolet spectrum, rare gas halogen excimer lasers provide coverage for some of this wavelength spectrum. However, the halogens corrode the laser chamber and simultaneously deplete themselves. Halogens also pose a health hazard. Still further, the short upper laser level lifetimes associated with excimer lasers require the use of high-voltage, high-current electrical discharges. These discharges cause reliability concerns and may affect other electronic instruments.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a tunable laser.

Another object of the present invention is to provide a tunable laser that can produce multiple wavelengths in a variety of spectral regions.

Still another object of the present invention is to provide a tunable laser that can produce multiple wavelengths in a variety of spectral regions in a simple and safe manner.

Other objects and advantages of the present invention will become more obvious hereinafter in the specification and drawings.

In accordance with the present invention, a tunable laser has a laser resonator that includes dispersion optics for separating generated laser pulses into processed laser pulses having first and second wavelengths where the processed laser pulses are directed for travel along first and second optical paths. The laser resonator is defined at one end thereof by first

2

and second mirrors with the first mirror being disposed in the first optical path and designed to be reflective at the first wavelength. In a similar fashion, the second mirror is disposed in the second optical path and is designed to be reflective at the second wavelength. The laser resonator is defined at another end thereof by an output mirror that is partially reflective and partially transmissive with respect to the first wavelength and the second wavelength in accordance with provided criteria. A first resonator length is defined between the output mirror and the first mirror, while a second resonator length is defined between the output mirror and the second mirror. The second resonator length is a function of the first resonator length.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a multiple-wavelength tunable laser that produces simultaneous and synchronous laser pulses at two infrared wavelengths in accordance with an embodiment of the present invention;

FIG. 2 is a block diagram of a laser wavelength converter for converting the infrared wavelength laser pulses to laser pulses having visible wavelengths; and

FIG. 3 is a block diagram of a laser wavelength converter for converting the visible wavelength laser pulses to laser pulses having ultraviolet wavelengths.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings and more particularly to FIG. 1, a multiple-wavelength tunable laser in accordance with an embodiment of the present invention is shown and is referenced generally by numeral 10. In the illustrated embodiment, tunable laser 10 simultaneously produces synchronous laser pulses at two distinct wavelengths W_1 and W_2 that can be in the infrared spectrum. However, as will be apparent to one of ordinary skill in the art, the principles of the present invention can be readily extended to simultaneously produce synchronous laser pulses at more than two wavelengths.

Tunable laser 10 includes a laser head 12 and a number of optical components that define a laser resonator. Laser head 12 typically includes a rod 12A of lasing material and a pump source 12B (e.g., a flash lamp) as would be understood in the art. For example, in terms of generating laser pulses at multiple infrared wavelengths, rod 12A is typically a neodymium-doped yttrium aluminum garnet (Nd:YAG) and pump source 12B can be, for example, a flash lamp or a diode laser. However, it is to be understood that the particular construction of laser head 12 to include the choice of lasing material and pump source are not limitations of the present invention.

Tunable laser 10 essentially defines two laser resonator paths, one for each of the two wavelengths being produced. In general, the two resonator paths share common elements and path portions, and have distinct elements and path portions. More specifically, laser head 12 generates laser pulses (i.e., when rod 12A is pumped by source 12B) that are output to an optical switch 14 (e.g., a Q-switch) as indicated by arrow 100 in accordance with conventional laser principles. The laser pulses are then passed to dispersion optics 16 as indicated by arrow 102. Dispersion optics 16 tune and separate the incoming laser pulses 102 into two distinct wavelengths by creating angular separation of the laser pulses at selected lasing transitions inherent in rod 12A. That is, dispersion optics 16 serves as the starting point for the distinct portions of the two laser resonator paths.

3

The angular separation of laser pulses **102** can be achieved in a variety of ways. By way of example, dispersion optics **16** can be an arrangement of dispersive prisms (e.g., Brewster angle prisms arranged for low loss) positioned to polarize laser pulses **102** at the desired transitions and to create a desired amount of angular separation. The laser pulses at the two distinct wavelengths are output from dispersion optics **16** along spatially separated paths as indicated by arrows **104** and **106**.

Positioned unique distances from dispersion optics **14** and in the paths of respective laser pulses **104** and **106**, are reflective mirrors **18** and **20**. Reflective mirror **18** should be totally reflective with respect to light at wavelength W_1 , while reflective mirror **20** should be totally reflective with respect to light at wavelength W_2 . Typically, each of reflective mirrors **18** and **20** is a curved mirror as would be understood in the art. The particular positioning of mirrors **18** and **20** will be explained further below. The reflected laser pulses **104R** and **106R** are passed back through dispersion optics **16** where the laser pulses are re-collimated and output as laser pulses **108**.

In accordance with conventional laser resonator designs, laser pulses **108** are next directed back to/through Q-switch **14** and laser head **12** before impinging on an output mirror **22**. In general and as is known in the art of laser resonators, an output mirror is partially reflective and partially transmissive with respect to the laser resonator's lasing wavelength. In the present invention, output mirror **22** (e.g., a flat mirror) must be partially reflective/transmissive with respect to both wavelengths W_1 and W_2 . The transmitted output pulses are indicated by arrow **108T** and the pulses reflected back into the laser resonator are indicated by arrow **108R**. The method for determining the reflective properties of output mirror **22** to achieve multiple wavelength reflection/transmission will be explained further below.

A great advantage of the present invention is that a single laser source can be used to produce multiple wavelengths. Since the multiple wavelength pulses use the same flat output mirror **22**, the transmitted output pulses **108T** at the multiple wavelengths are automatically parallel. Further, since both wavelengths are generated in the same laser rod **12A**, transmitted output pulses **108T** have the same pulse initiation time. In addition, tunable laser **10** is designed such that its laser resonators have the same pulse evolution time interval. This is accomplished in the present invention by adjusting the lasers and laser resonator lengths so that the pulse evolution time for each resonator is the same.

Each laser resonator is defined by common elements (i.e., laser head **12**, optical switch **14**, dispersion optics **16** and output mirror **22**) and unique elements (i.e., reflective mirror **18** and reflective mirror **20**). That is, one laser resonator has its path length defined between output mirror **22** and reflective mirror **18**, while the other laser resonator has its path length defined between output mirror **22** and reflective mirror **20**.

The present invention provides novel criteria to set laser resonator path length and output mirror reflectivity. Specifically, the mirror reflectivities R_1 and R_2 for output mirror **22** at wavelengths W_1 and W_2 , respectively, satisfy the following relationship

$$R_2 = \exp\{2L[\alpha - \alpha'(\sigma/\sigma') + (\sigma/\sigma')\ln(R_1)]\}$$

where α' is intrinsic losses of the laser resonator defined between mirrors **18** and **22**, i.e., laser resonator associated with the first wavelength W_1 ; α is intrinsic losses of the laser resonator defined between mirrors **20** and **22**, i.e., laser resonator associated with the second wavelength W_2 ; σ' is the emission cross-section associated with the laser pulses at the

4

first wavelength W_1 (i.e., the emission cross-section of the photon transition associated with the laser pulses at the first wavelength); and σ is the emission cross-section associated with said laser pulses at said second wavelength (i.e., the emission cross-section of the photon transition associated with the laser pulses at the second wavelength).

The two resonator path lengths L_1 (between output mirror **22** and reflective mirror **18**) and L_2 (between output mirror **22** and reflective mirror **20**) satisfy the relationship

$$L_2 \approx (\sigma/\sigma')L_1.$$

As mentioned above, tunable laser **10** simultaneously produces two unique-wavelength laser pulses that can be in the infrared spectrum. The transmitted laser pulses **108T** can be further processed to produce laser pulses in one or both of the visible and ultraviolet spectrums. For example, transmitted laser pulses **108T** (e.g., at infrared wavelengths W_1 and W_2 in the illustrated example) can be provided to a laser wavelength converter **30** illustrated in FIG. **2**. Laser wavelength converter **30** can include a telescope **32** that collects and focuses laser pulses **108T** onto non-linear crystal optics **34** that convert the infrared-spectrum laser pulses **108T** into laser pulses at one or more visible-spectrum wavelengths. In tests of the present invention, a single crystal oriented for phase matching has been used to achieve wavelength conversion. For a laser rod **12A** made from Nd:YAG, a single Beta Barium Borate (BBO) crystal (β -BaB₂O₄) was used.

For efficient non-linear interactions, the above-mentioned phase matching condition must be satisfied. Such phase matching is usually achieved by rotating the non-linear crystal in order to change the phase velocity of the interacting beams/pulses. In this way, optics **34** provides for harmonic generation as well as mixing so that optics **34** outputs laser pulses **110** in the visible spectrum.

Depending on the attributes and positioning of optics **34**, the wavelength of laser pulses **110** can be

$$W_3 = (W_1 \times W_2) / (W_1 + W_2)$$

$$W_4 = (W_1) / 2, \text{ or}$$

$$W_5 = (W_2) / 2.$$

It is to be understood that additional ones of optic **34** could be used to simultaneously provide two or all three of the visible-wavelength laser pulses without departing from the scope of the present invention.

In terms of producing simultaneous and synchronous pulses in the ultraviolet spectrum, one or more of the visible-wavelength laser pulses **110** can be provided to another laser wavelength converter **40** illustrated in FIG. **3**. As shown, laser wavelength converter **40** can include a waveplate **42** that rotates the polarization of laser pulses **110**. The rotated laser pulses **110R** are provided to non-linear crystal optics **44** that are similar to optics **34**. Optics **44** converts laser pulses **110R** at one or more of wavelengths W_3 , W_4 , and W_5 into laser pulses **112** having wavelengths

$$W_6 = (W_3) / 2$$

$$W_7 = (W_4) / 2 \text{ and/or}$$

$$W_8 = (W_5) / 2.$$

The advantages of the present invention are numerous. Simultaneous and synchronous laser pulses at multiple wavelengths can be generated with a single lasing medium (e.g., a laser rod). The multiple wavelengths can include the infrared, visible, and ultraviolet spectrums. The laser can be readily tuned for specific wavelengths in accordance with the pro-

5

vided output mirror reflectivity and resonator path length criteria. The choice of visible and ultraviolet wavelengths can be adjusted by simple re-orientation of a single non-linear crystal type of laser wavelength converter.

Although the invention has been described relative to a specific embodiment thereof, there are numerous variations and modifications that will be readily apparent to those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. A tunable laser comprising:
 - a laser resonator including dispersion optics for separating generated laser pulses into processed laser pulses having first and second wavelengths traveling along first and second optical paths, respectively,
 - said laser resonator defined at one end thereof by first and second mirrors with said first mirror being disposed in said first optical path and reflective at said first wavelength, and said second mirror being disposed in said second optical path and reflective at said second wavelength,
 - said laser resonator defined at another end thereof by an output mirror that is partially reflective and partially transmissive with respect to said first wavelength and said second wavelength, wherein a first resonator length is defined between said output mirror and said first mirror, and wherein a second resonator length is defined between said output mirror and said second mirror, said second resonator length being a function of said first resonator length.
2. A tunable laser as in claim 1 wherein said laser resonator includes a single lasing medium.
3. A tunable laser as in claim 2 wherein said lasing medium is a neodymium-doped material.
4. A tunable laser as in claim 1 wherein said first wavelength and said second wavelength are in the infrared spectrum, said tunable laser further comprising means for converting said first wavelength and said second wavelength of said processed laser pulses transmitted by said output mirror to laser pulses having at least one wavelength in the visible spectrum.
5. A tunable laser as in claim 4, further comprising second means for converting said laser pulses having at least one wavelength in the visible spectrum to laser pulses having at least one wavelength in the ultraviolet spectrum.
6. A tunable laser as in claim 1 wherein said dispersion optics comprises a plurality of prisms.
7. A tunable laser as in claim 1 wherein said function is defined as a ratio of emission cross-section associated with said laser pulses at said second wavelength to emission cross-section associated with said laser pulses at said first wavelength.
8. A tunable laser as in claim 1 wherein said output mirror comprises a flat mirror.
9. A tunable laser as in claim 4 wherein said means for converting comprises non-linear crystal optics.
10. A tunable laser as in claim 5 wherein said second means comprises non-linear crystal optics.
11. A tunable laser comprising:
 - a laser resonator including
 - (i) an output mirror,
 - (ii) a laser rod of length L ,
 - (iii) dispersion optics for separating laser pulses generated from said laser rod into laser pulses having first and

6

second wavelengths traveling along first and second optical paths, respectively, and

(iv) first and second wavelength-sensitive reflective mirrors disposed in said first and second optical paths, respectively,

wherein a first resonator of path length L_1 is defined between said output mirror and said first reflective mirror, and a second resonator of path length L_2 is defined between said output mirror and said second reflective mirror;

said output mirror having a reflectivity R_1 at said first wavelength and a reflectivity R_2 at said second wavelength defined by

$$R_2 = \exp\{2L[\alpha - \alpha'(\sigma/\sigma')] + (\sigma/\sigma') \ln(R_1)\}$$

where α' is intrinsic losses of said first resonator,

α is intrinsic losses of said second resonator,

σ' is emission cross-section associated with said laser pulses at said first wavelength,

σ is emission cross-section associated with said laser pulses at said second wavelength; and said path length L_1 and said path length L_2 defined by

$$L_2 = (\sigma/\sigma')L_1.$$

12. A tunable laser as in claim 11 wherein said laser rod comprises a neodymium-doped material.

13. A tunable laser as in claim 11 wherein said first wavelength and said second wavelength are in the infrared spectrum, said tunable laser further comprising means for converting said first wavelength and said second wavelength of laser pulses transmitted by said output mirror to laser pulses having at least one wavelength in the visible spectrum.

14. A tunable laser as in claim 13, further comprising second means for converting said laser pulses having at least one wavelength in the visible spectrum to laser pulses having at least one wavelength in the ultraviolet spectrum.

15. A tunable laser as in claim 11 wherein said dispersion optics comprises a plurality of prisms.

16. A tunable laser as in claim 11 wherein said output mirror comprises a flat mirror.

17. A tunable laser as in claim 13 wherein said means for converting comprises non-linear crystal optics.

18. A tunable laser as in claim 14 wherein said second means comprises non-linear crystal optics.

19. A tunable laser comprising:

a first laser resonator having a first resonator path that includes an output mirror, a laser rod of length L , a Q-switch and a first reflective mirror that reflects light at a first wavelength;

a second laser resonator having a second resonator path that includes said output mirror, said laser rod, said Q-switch and a second reflective mirror that reflects light at a second wavelength;

dispersion optics disposed between said Q-switch and each of said first reflective mirror and said second reflective mirror, said dispersion optics separating laser pulses generated from said laser rod and passed through said Q-switch into laser pulses having said first and second wavelengths with said laser pulses at said first wavelength being directed to said first reflective mirror and said laser pulses at said second wavelength being directed to said second reflective mirror,

wherein said output mirror has a reflectivity R_1 at said first wavelength and a reflectivity R_2 at said second wavelength defined by

$$R_2 = \exp\{2L[\alpha - \alpha'(\sigma/\sigma')] + (\sigma/\sigma') \ln(R_1)\}$$

7

where α' is intrinsic losses of said first laser resonator,
 α is intrinsic losses of said second laser resonator,
 σ' is emission cross-section associated with said laser
 pulses at said first wavelength,
 σ is emission cross-section associated with said laser
 pulses at said second wavelength; and
 a length L_1 of said first resonator and a length L_2 of said
 second resonator are governed by

$$L_2 = (\alpha/\alpha')L_1.$$

20. A tunable laser as in claim 19 wherein said laser rod
 comprises a neodymium-doped material.

21. A tunable laser as in claim 19 wherein said first wave-
 length and said second wavelength are in the infrared spec-
 trum, said tunable laser further comprising means for con-
 verting said first wavelength and said second wavelength of

8

laser pulses transmitted by said output mirror to laser pulses
 having at least one wavelength in the visible spectrum.

22. A tunable laser as in claim 21, further comprising
 second means for converting said laser pulses having at least
 one wavelength in the visible spectrum to laser pulses having
 at least one wavelength in the ultraviolet spectrum.

23. A tunable laser as in claim 19 wherein said dispersion
 optics comprises a plurality of prisms.

24. A tunable laser as in claim 19 wherein said output
 mirror comprises a flat mirror.

25. A tunable laser as in claim 21 wherein said means for
 converting comprises non-linear crystal optics.

26. A tunable laser as in claim 22 wherein said second
 means comprises non-linear crystal optics.

* * * * *