US007633985B2

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

(10) **Patent No.: US 7,633,985 B2**
(45) **Date of Patent: Dec. 15, 2009**

(54) **APPARATUS AND METHODS FOR ALTERING A CHARACTERISTIC OF LIGHT-EMITTING DEVICE**

(75) Inventors: **Boris Leonidovich Volodin**, West Windsor, NJ (US); **Vladimir Sinisa Ban**, Princeton, NJ (US)

(73) Assignee: **PD-LD, Inc.**, Pennington, NJ (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 191 days.

(21) Appl. No.: **11/481,445**

(22) Filed: **Jul. 6, 2006**

(65) **Prior Publication Data**

US 2006/0251143 A1 Nov. 9, 2006

Related U.S. Application Data

(62) Division of application No. 10/884,524, filed on Jul. 2, 2004, now Pat. No. 7,298,771.

(60) Provisional application No. 60/484,857, filed on Jul. 3, 2003, provisional application No. 60/564,526, filed on Apr. 22, 2004.

(51) **Int. Cl.**
H01S 5/00 (2006.01)

(52) **U.S. Cl.** **372/50.11**; 372/99; 372/102

(58) **Field of Classification Search** 372/50.11, 372/99, 102
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,396,343	A	8/1968	Gustaaf	372/107
3,580,657	A	5/1971	Sheridon	
3,603,690	A	9/1971	Hard	356/521
3,647,289	A	3/1972	Weber	
3,936,143	A	2/1976	Sato	350/96 C
4,013,338	A	3/1977	Sato et al.	350/3.5
4,017,318	A	4/1977	Pierson et al.	
4,057,408	A	11/1977	Pierson et al.	65/18
4,095,875	A	6/1978	Lee et al.	350/320
4,215,937	A	8/1980	Borsuk	356/73.1
4,239,333	A	12/1980	Dakss et al.	350/96.21
4,398,797	A	8/1983	Wedertz et al.	385/137
4,514,053	A	4/1985	Borrelli et al.	350/162.2
4,719,635	A	1/1988	Yeh	

(Continued)

FOREIGN PATENT DOCUMENTS

EP 0 310 438 A1 4/1989

(Continued)

OTHER PUBLICATIONS

Jannson, T., et al., "Lippmann-bragg broadband holographic mirrors," J. of the Optical Soc. of Am., 1991, 8(1), 201-211.

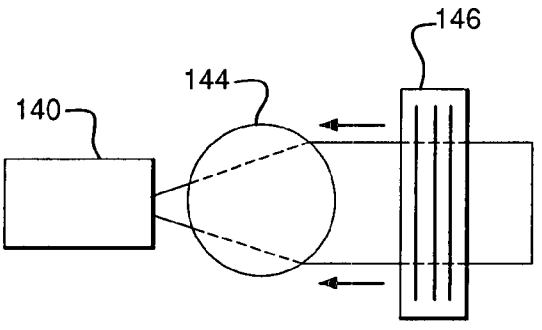
(Continued)

Primary Examiner—Dung T Nguyen
(74) *Attorney, Agent, or Firm*—Woodcock Washburn LLP

(57) **ABSTRACT**

Apparatus and methods for altering one or more spectral, spatial, or temporal characteristics of a light-emitting device are disclosed. Generally, such apparatus may include a volume Bragg grating (VBG) element that receives input light generated by a light-emitting device, conditions one or more characteristics of the input light, and causes the light-emitting device to generate light having the one or more characteristics of the conditioned light.

19 Claims, 28 Drawing Sheets



U.S. PATENT DOCUMENTS

4,737,946	A		4/1988	Yamashita et al.
4,747,657	A		5/1988	Chaoui et al. 350/96.2
4,896,933	A	*	1/1990	Yano et al. 359/328
4,923,271	A		5/1990	Henry et al.
4,942,102	A		7/1990	Keys et al. 430/1
4,943,126	A		7/1990	Lang et al. 359/12
4,946,245	A		8/1990	Chamberlin et al.
5,115,338	A		5/1992	DiGiovanni et al. 359/337
5,335,098	A		8/1994	Leyva et al. 359/7
5,386,426	A	*	1/1995	Stephens 372/20
5,440,669	A		8/1995	Rakuljic et al. 359/7
5,452,124	A		9/1995	Baker 359/341.2
5,491,570	A		2/1996	Rakuljic et al. 359/7
5,548,676	A		8/1996	Savage 385/92
5,619,609	A		4/1997	Pan et al. 385/136
5,637,868	A		6/1997	Tamiya
5,648,946	A	*	7/1997	Yamazaki 369/44.23
5,655,040	A		8/1997	Chesnoy et al. 385/37
5,684,611	A		11/1997	Rakuljic et al. 359/7
5,691,989	A	*	11/1997	Rakuljic et al. 372/20
5,757,487	A		5/1998	Kersey
5,777,763	A		7/1998	Tomlinson, III 359/130
5,796,096	A		8/1998	Rakuljic et al. 250/226
5,798,859	A		8/1998	Colbourne et al. 359/247
5,812,258	A		9/1998	Pierson 356/153
5,825,792	A		10/1998	Villeneuve et al. 372/32
6,055,250	A		4/2000	Doerr et al. 372/23
6,064,685	A		5/2000	Bissessur et al.
6,093,927	A		7/2000	Wickham 250/227.23
6,122,043	A		9/2000	Barley 356/73.1
6,163,391	A		12/2000	Curtis et al.
6,184,987	B1		2/2001	Jang et al. 356/388
6,198,759	B1		3/2001	Broderick et al. 372/39
6,221,566	B1		4/2001	Kohnke et al.
6,249,624	B1		6/2001	Putnam et al. 385/37
6,269,203	B1		7/2001	Davies et al. 385/24
6,285,813	B1		9/2001	Schultz et al. 385/37
6,385,219	B1		5/2002	Sonoda 372/28
6,385,228	B1		5/2002	Dane et al. 372/99
6,411,323	B1		6/2002	Waarts et al.
6,414,973	B1		7/2002	Hwu et al. 372/19
6,434,175	B1		8/2002	Zah 372/20
6,470,120	B2		10/2002	Greene et al. 385/52
6,476,345	B1		11/2002	Sator 219/121.63
6,524,913	B1		2/2003	Lin et al.
6,529,675	B1		3/2003	Hayden et al. 385/141
6,580,850	B1		6/2003	Kazarinov et al. 385/28
6,584,133	B1	*	6/2003	Walker et al. 372/92
6,586,141	B1		7/2003	Efimov et al. 430/1
6,673,493	B2		1/2004	Gan et al. 429/233
6,673,497	B2		1/2004	Efimov
6,829,067	B2		12/2004	Psaltis et al. 359/15
7,031,573	B2		4/2006	Volodin et al. 385/37
7,125,632	B2		10/2006	Volodin et al.
7,184,616	B2		2/2007	Mead et al. 385/10
7,248,617	B2		7/2007	Volodin et al. 372/102
7,298,771	B2		11/2007	Volodin et al.
7,324,286	B1		1/2008	Glebov
7,326,500	B1		2/2008	Glebov
2001/0016099	A1		8/2001	Shin et al. 385/37
2001/0028483	A1		10/2001	Buse 359/15
2002/0012377	A1		1/2002	Suganuma et al. 372/98
2002/0045104	A1		4/2002	Efimov et al. 430/2
2002/0176126	A1		11/2002	Psaltis et al. 359/15
2002/0192849	A1		12/2002	Bullington et al. 438/22
2003/0174749	A1		9/2003	Capasso et al. 372/45
2003/0214700	A1		11/2003	Sidorin et al. 359/334
2003/0219205	A1		11/2003	Volodin et al.
2004/0004746	A1	*	1/2004	Riza 359/204
2004/0120643	A1		6/2004	Viswanathan et al.
2005/0018743	A1		1/2005	Volodin et al.
2005/0168819	A1	*	8/2005	Vail et al. 359/557
2005/0207466	A1		9/2005	Glebov et al. 372/92
2005/0265416	A1		12/2005	Zucker et al. 372/50.12
2006/0029120	A1		2/2006	Mooradian et al. 372/102
2006/0123344	A1		6/2006	Volkov et al.
2006/0156241	A1		7/2006	Psaltis et al. 715/730
2006/0256827	A1		11/2006	Volodin et al. 370/50.121
2008/0137698	A1		6/2008	Sorin et al.

FOREIGN PATENT DOCUMENTS

EP	0 322 218	A3	6/1989
JP	4287001		10/1992
SU	178-429	A1	11/1990
WO	WO 03/036766	A2	5/2003

OTHER PUBLICATIONS

Loiseaux, B., et al., "Characterization of perpendicular chirped phase volume grating pairs for laser pulse stretching," Optic Letters, OSA, 1996, 21(11), 806-808.

Applicant calls to the Office's Attention, Application No:. 820/CAL/93, Filed Dec. 28, 1993, Inventors-Victor Leyva and George Rakuljic, "Method for Writing Reflection Mode Gratings in Photorefractive Materials in the Infrared.", and U.S. Appl. No. 08/842,645, filed Apr. 15, 1997, Inventors-Koichi Sayano and F. Zhao, "High Resolution Holographic Image and Data Storage System." Applicant has no Further Information Regarding these References.

Borgman, V.A., et al., "Photothermal refractive effect in silicate glasses," *Sov. Phys. Dokl.*, Nov. 1989, 1011-1013.

Borrelli, N.F., et al., "Photosensitive glasses and glass-ceramics," *Glass Processing*, 439-444.

Breer, S., et al., "Low-crosstalk WDM by bragg diffraction from thermally fixed reflection holograms in lithium niobate," *Electronics Letts.*, 1998, 34(25), 2419-2421.

Chang-Hasnain, C.J., et al., "High power with high efficiency in a narrow single-lobed beam from a diode laser array in an external cavity," *Appl. Phys. Lett.*, 1987, 50(21), 1465-1467.

Churin, E.G., et al., "Design of free-space WDM router based on holographic concave grating," *IEEE Photonics Techn. Letts.*, Feb. 1999, 11(2), 221-223.

Datta, S., et al., "Modeling of nonideal volume Bragg reflection gratings in photosensitive glass using a perturbed transmission matrix approach," *IEEE J. of Quantum Electronics*, 2004, 40(5), 580-590.

Dicing Solutions for DWDM optical filter applications; advertising brochure of *ADT Advanced Dicing Technologies*, Stockholm, Sweden, 2003, 2 pages.

Dmitriyev, A.L., et al., "Volume holograms in the optical devices of optical-fiber data transmission systems, A review," *Telecommun. & Radio Eng.*, 1995, 49(12), 9-15.

Efimov, O.M., et al., "High-efficiency bragg gratings in photothermorefractive glass," *Applied Optics*, Feb. 1, 1999, 38(4), 619-627.

Glebov, L.B., et al., "Polychromic glasses-a new material for recording volume phase holograms," *Sov. Phys. Dokl.*, Oct. 1990, 35(10), 878-880.

Glebov, L.B., "High-efficiency volume hologram recording in silicate glass," *School of Optics and CREOL*, University of Central Florida, Orlando, FL, 16 pages.

Glebov, L.B., "Photosensitive glass for phase hologram recording," *Glass Science and Technology*, 1998, 71C, 85-90.

Goodman, J.W., "Introduction to fourier optics," *McGraw-Hill Co., Inc., 2nd Ed.*, 1996, 329-330.

Hendow, S.T., "Crystal bragg gratings stabilize laser sources," *Laser Focus World*, Nov. 1996, S19-S24.

Kogelnik, H., et al., "Coupled wave theory for thick hologram gratings," *The Bell System Technical Journal*, Nov. 1969, 48(9), 2909-2947.

Liu, J., et al., "Modeling and design of planar slanted volume holographic gratings for wavelength-division-multiplexing applications," *Applied Optics*, Dec. 1, 1999, 6981-6986.

Moser, C., et al., "Volume Bragg grating devices," *Friday Morning*, 2003, 2, 644-645.

Moslehi, B., et al., "Fiber-optic wavelength-division multiplexing and demultiplexing using volume holographic gratings," *Optics Letters*, Oct. 1, 1989, 1088-1090.

Qiao, J., et al., "Dispersion-enhanced volume hologram for dense wavelength-division demultiplexer," *IEEE Photonics Technology Letts.*, Aug. 2000, 12(8), 1070-1072.

Optical Interference Filters Catalogue, 17th Ed., *Spectrogon*, Taeby, Sweden, www.spectrogon.com, (no date available), 3-21.

Rakuljic, G.A., et al., "Volume holographic narrow-band optical filter," *Optical Engineering*, Oct. 1997, 36(10), 459-461.

Sakamoto, M., et al., "20 W CW monolithic AIGaAs (810nm) laser diode arrays," *Electronic Letts.*, 1992,, 28(2), 178-180.

Sayano, K., "Holographic grating filters in optical glasses for C31 WDM networks," *Accuwave Corp., sponsored by Ballistic Missile Defense Organization*, May 1998, AFRL-SN-RS-TR-1998-81, Final Technical Report, 1-35, DL-1—DL-3.

Sayano, K., et al., "Modular WDM add/drop multiplexers," *SPIE*, 1997, 3234, 102-107.

Timofeev, F.N., et al., "Free-space grating multi/demultiplexer and wavelength-router for densely spaced WDM networks," *IEE*, Nov. 1-5, 1997, 372-373.

Volodin, B.L., et al., "High-resolution compact imaging holographic Bragg grating spectrometer," *CLEO*, 1998, 401-402.

Yiou, S., et al., "Improvement of the spatial beam quality of laser sources with an intracavity Bragg grating," *Optics Letts.*, 2003, 28(4), 242-244.

Zhao, F., et al., "Reliable grating-based wavelength division (de)multiplexers for optical networks," *Opt. Eng.*, Jul. 2001, 40(7), 1204-1211.

Zhao, F., et al., "Subpicometer accuracy laser wavelength sensor using multiplexed bragg gratings," *IEEE Photonics Technology Letts.*, Nov. 1997, 9(11), 1493-1495.

Zhao, F., et al., "Ultraviolet Ca K-line narrow-bandwidth imaging filters based on holographic Bragg gratings in photorefractive materials," *Opt. Eng.*, Oct. 1997, 36(10), 2918-2921.

U.S. Appl. No. 10/390,521, filed Jul. 3, 2003, Volodin, et al.

Efimov, O.M. et al., "Diffractive Optical Elements in Photosensitive Inorganic Glasses", Proceedings of the SPIE Inorganic Materials III, Aug. 2001, 4452, 39-47.

Remy, Lehrbuch der Anorganishen Chemic Band, 1960, 1.

Scholes, S. R. Modern Glass Practice, 1975, 217.

Shelby, J.E., "Introduction to Glass Science and Technology", *Royal Society of Chemistry*, 1997, 43.

Harrison, J. et al., "Coherent Summation of Injection-Locked, Diode-Pumped Nd: YAG Ring Lasers", *Optics Letters*, Feb. 1998, 13(2), 111-113.

Kozlov, V.A. et al., "All-Fiber Coherent Beam Combining of Fiber Lasers", *Optic Letters*, Dec. 15, 1999, 24(24), 1814-1816.

Leger, J.R. et al., "Efficient Side Lobe Suppression of Laser Diode Arrays", *Appl. Phys. Lett.*, 1987, 50(16), 1044-1046.

Leger, J.R. et al., "Coherent Beam Addition of GaAiAs Lasers by Binary Phase Gratings", *Appl. Phys. Lett.*, Apr. 1986, 48(14), 888-890.

Leger, J.R. et al., "Coherent Laser Addition Using Binary Phase Gratings", *Applied Optics*, 1987, 26(20), 4391-4399.

Menard, S. et al., "Highly Efficient Phase Locking and Extracavity Coherent Combination of Two Diode-Pumped Nd: YAG Laser Beams", *Optics Letters*, Dec. 15, 1996, 21(24), 1996-1998.

Rodgers, B.C. et al., "Laser Beam Combining and Cleanup by Stimulated Brillouin Scattering in a Multimode Optical Fiber", *Optics Letters*, Aug. 15, 1999, 24(16), 1124-1126.

Swanson, G.J. et al., "Aperture Filling of Phase-Locked Laser Arrays", *Optics Letters*, Apr. 1987, 12(4), 245-247.

Veldkamp, W. B. et al., "Coherent Summation of Laser Beams Using Binary Phase Gratings", *Optics Letters*, May 1986, 11(5), 303-306.

Mills, P., "Single-Mode Operation of 1.55 μm Semiconductor Lasers Using A Volume holographic Grating", *Electronic Letters*, Jul. 1985, 21(15), 648-649.

In the United States District Court for the District of New Jersey, *PD-LD, Inc.*, v. *Ondax, Inc.*, Case No. 08-cv-03494, Draft Amended Answer to Complaint; Affirmative Defenses; Counterclaims and Jury Demand, Sep. 18, 2008, 34 pages.

In the United States District Court for the District of New Jersey, *PD-LD, Inc.*, v. *Ondax, Inc.*, Case No. 08-cv-03494, Initial Disclosures of Defendant Ondax, Inc. Pursuant to FRCP 26(a)(1), Sep. 12, 2008, 10 pages.

In the United States District Court for the District of New Jersey, *PD-LD, Inc.*, v. *Ondax, Inc.*, Case No. 08-cv-03494, Third Party Complaint by Defendant Ondax, Inc. Against Arasor International Limited and Jury Demand, Aug. 22, 2008, 9 pages.

In the United States District Court for the District of New Jersey, *PD-LD, Inc.*, v. *Ondax, Inc.*, Case No. 08-cv-03494, Answer to Complaint: Affirmative Defenses; Counterclaims and Jury Demand, Aug. 13, 2008, 31 pages.

* cited by examiner

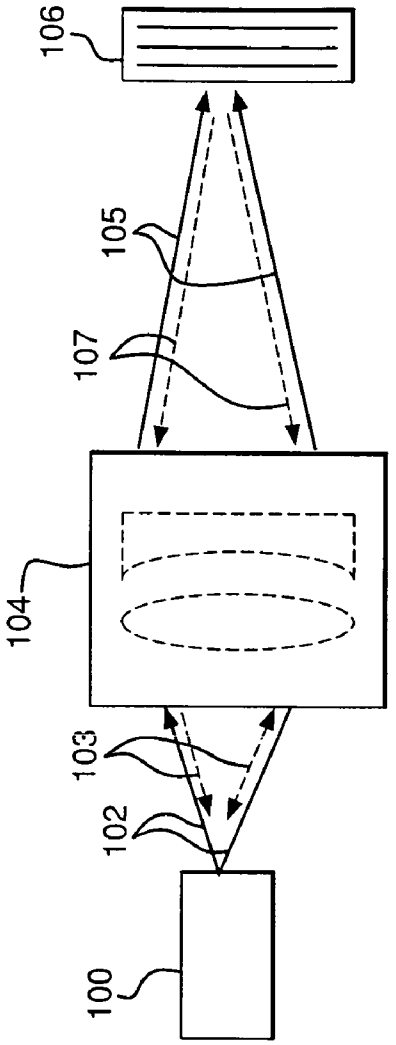


FIG. 1A

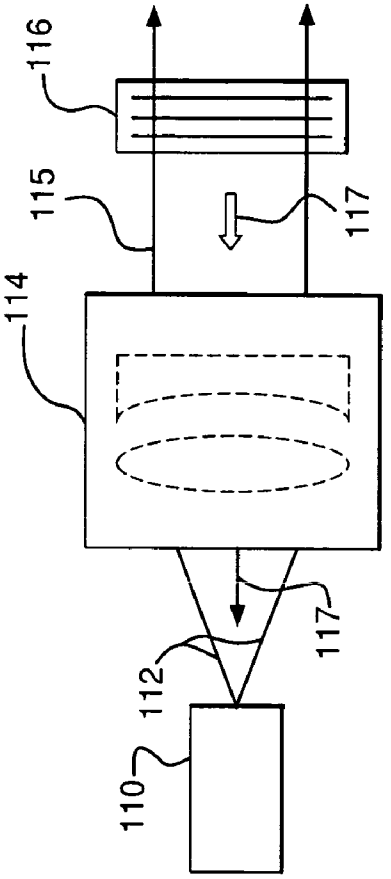


FIG. 1B

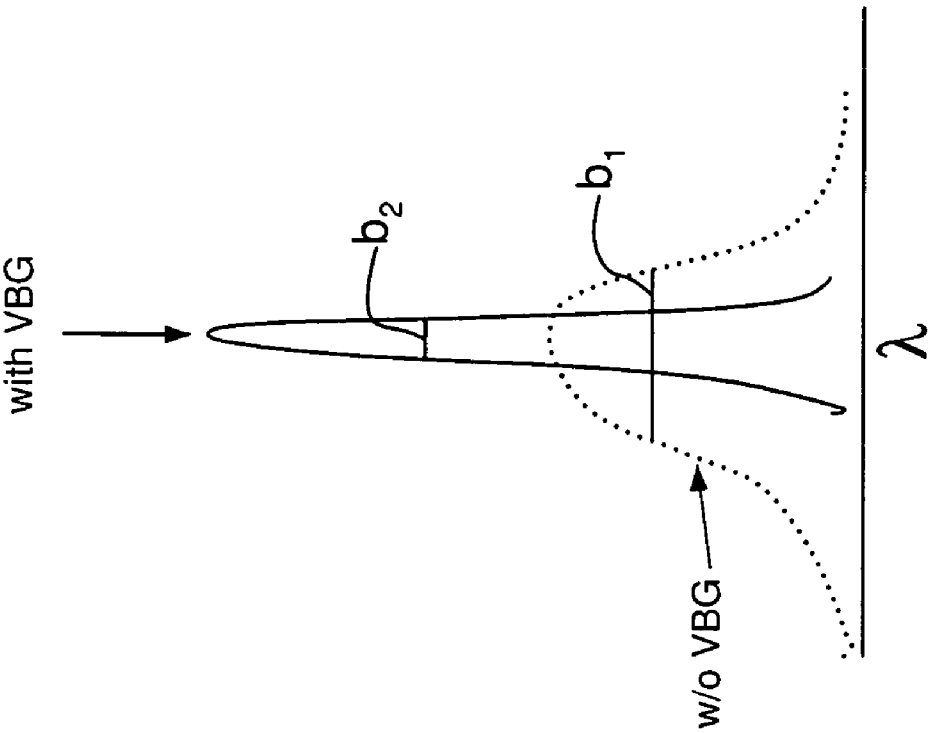


FIG. 1D

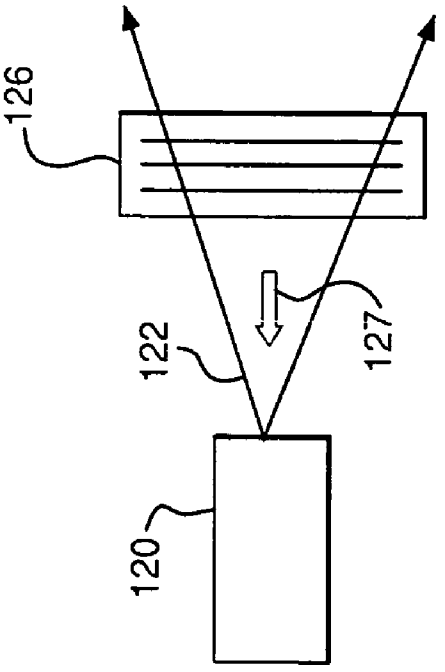


FIG. 1C

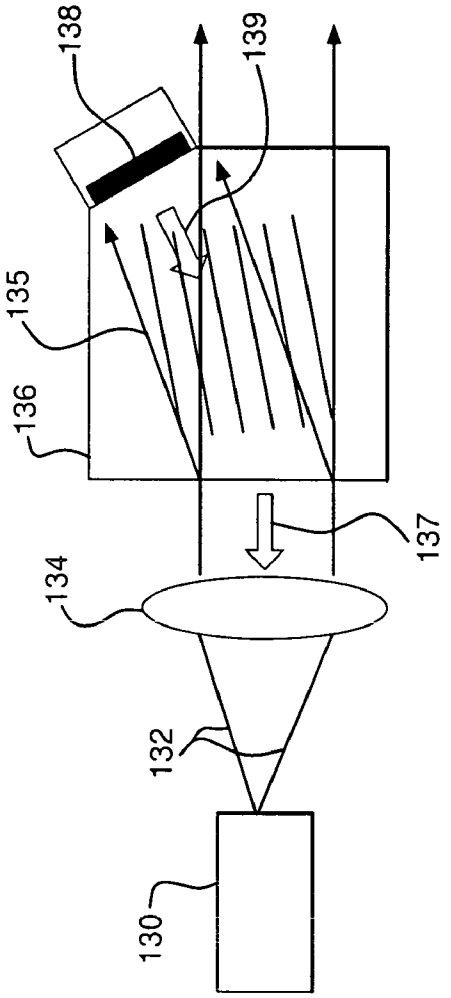


FIG. 2A

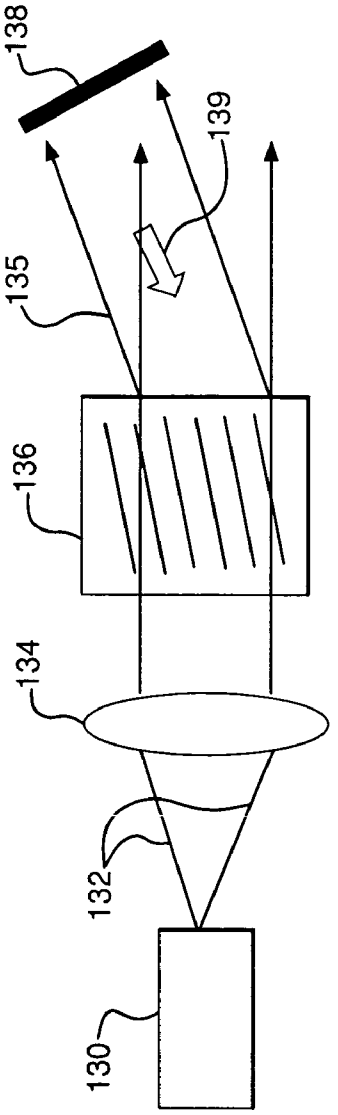


FIG. 2B

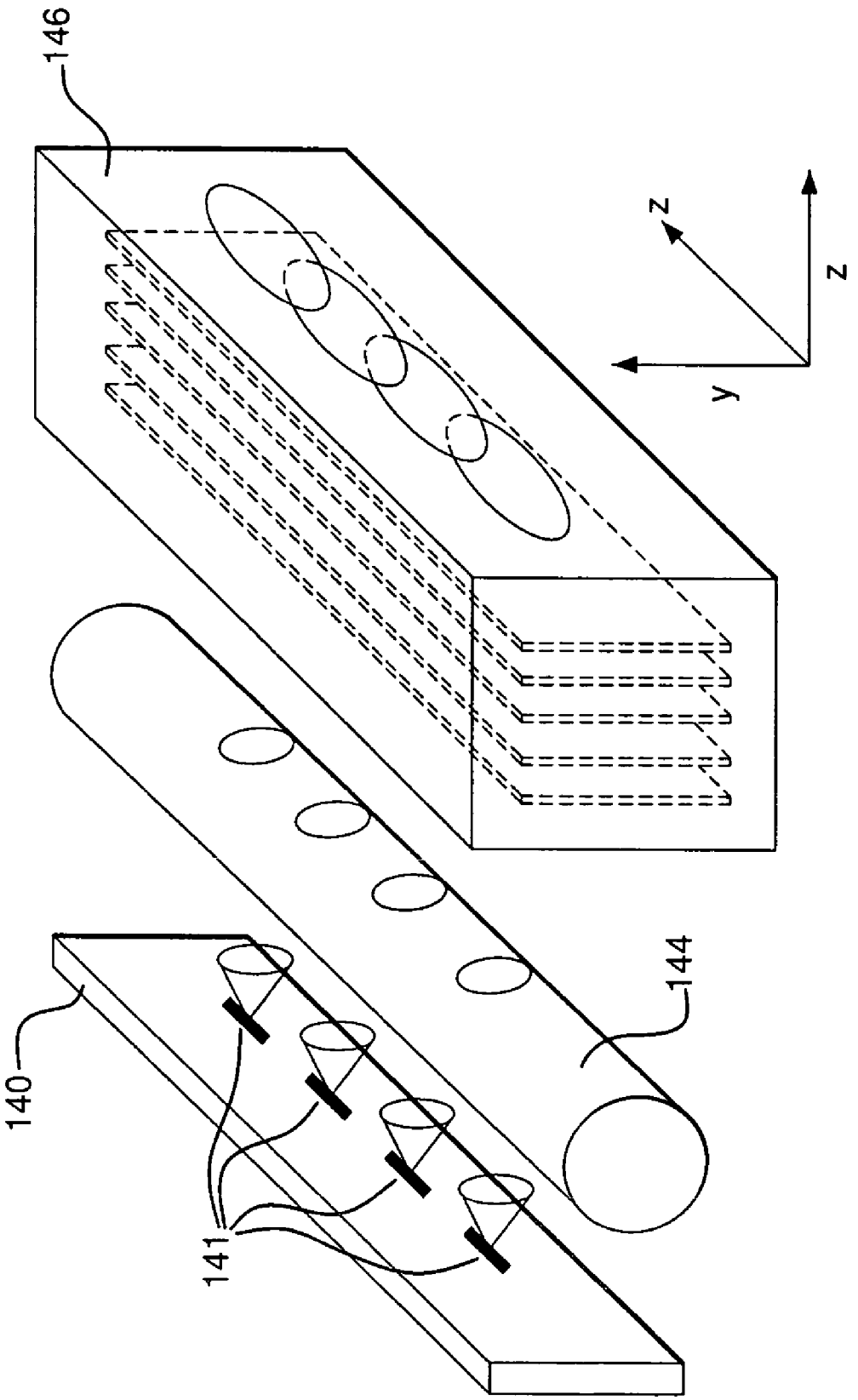


FIG. 3

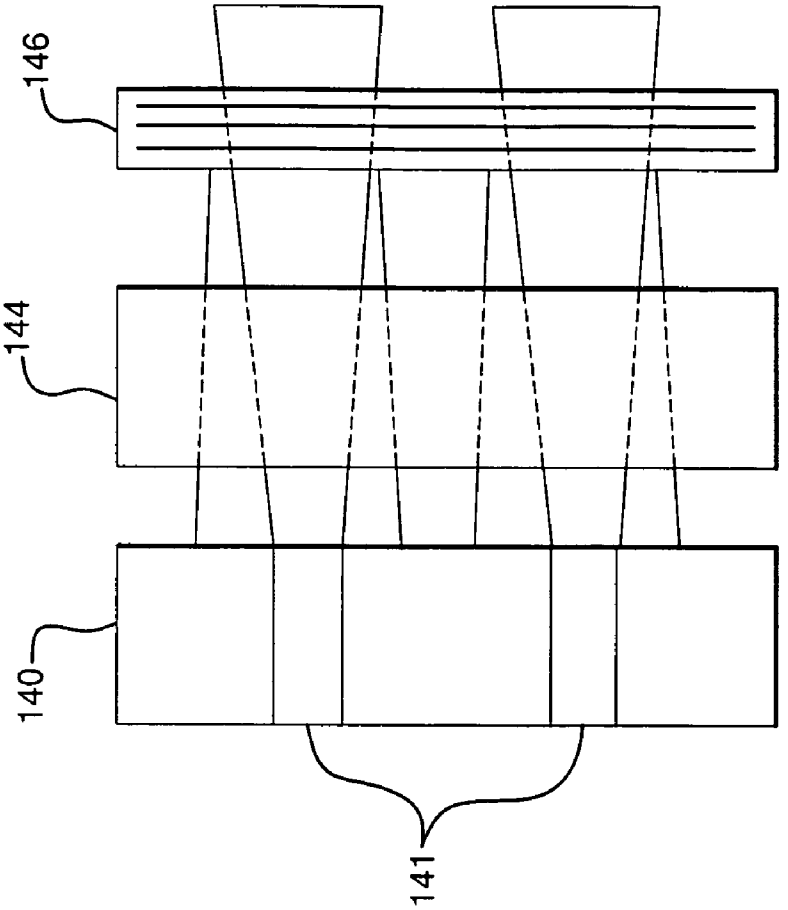


FIG. 4B

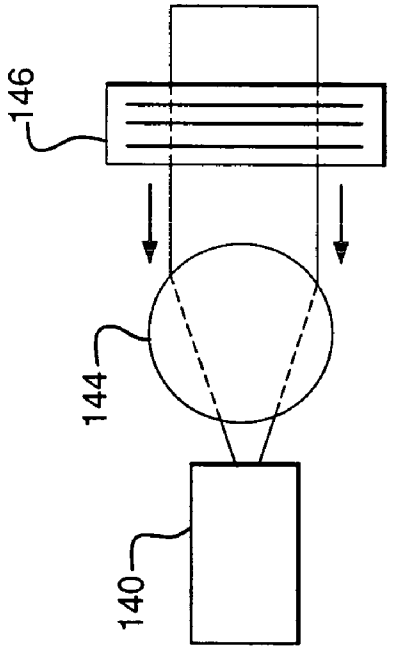


FIG. 4A

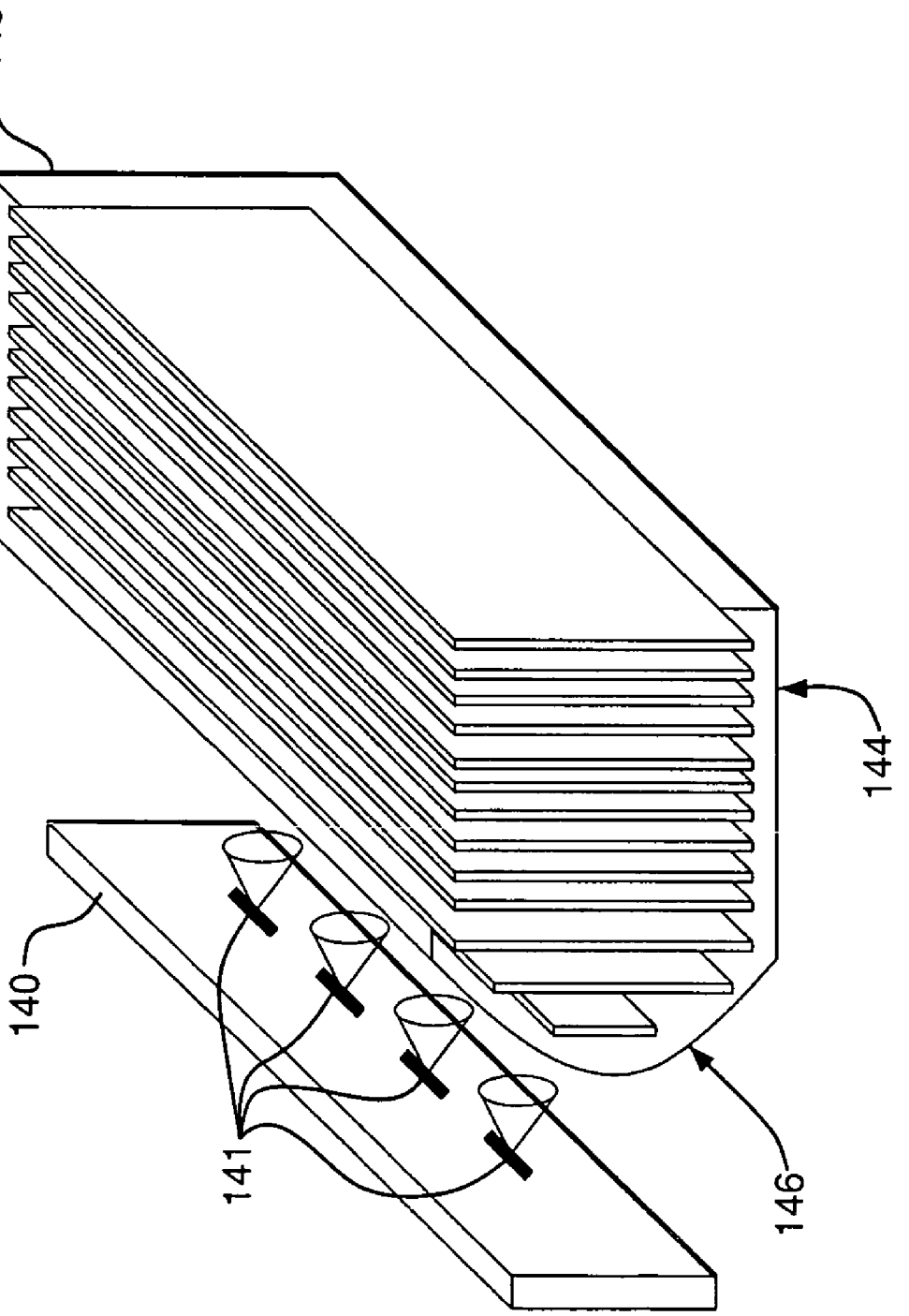


FIG. 5

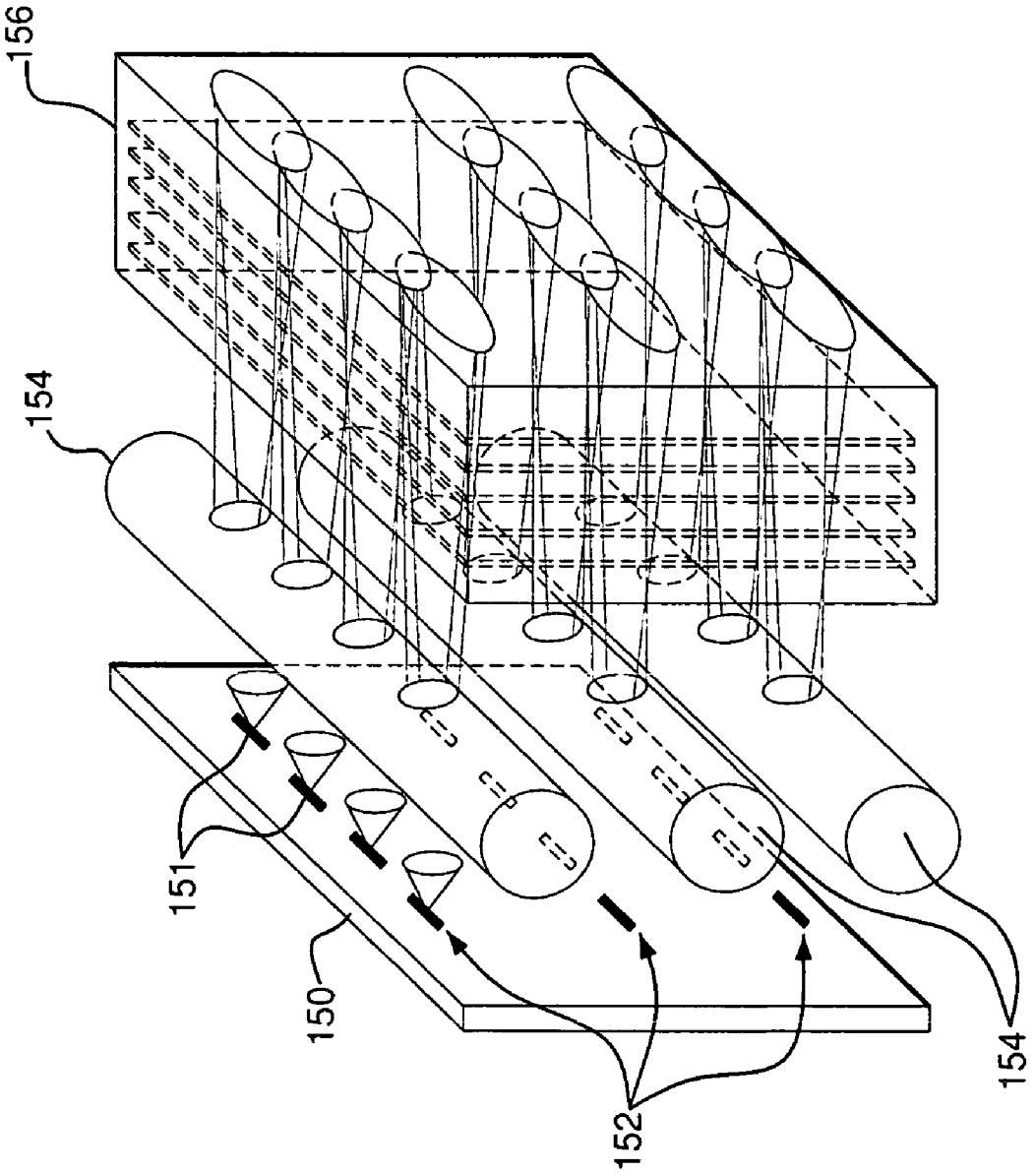


FIG. 6

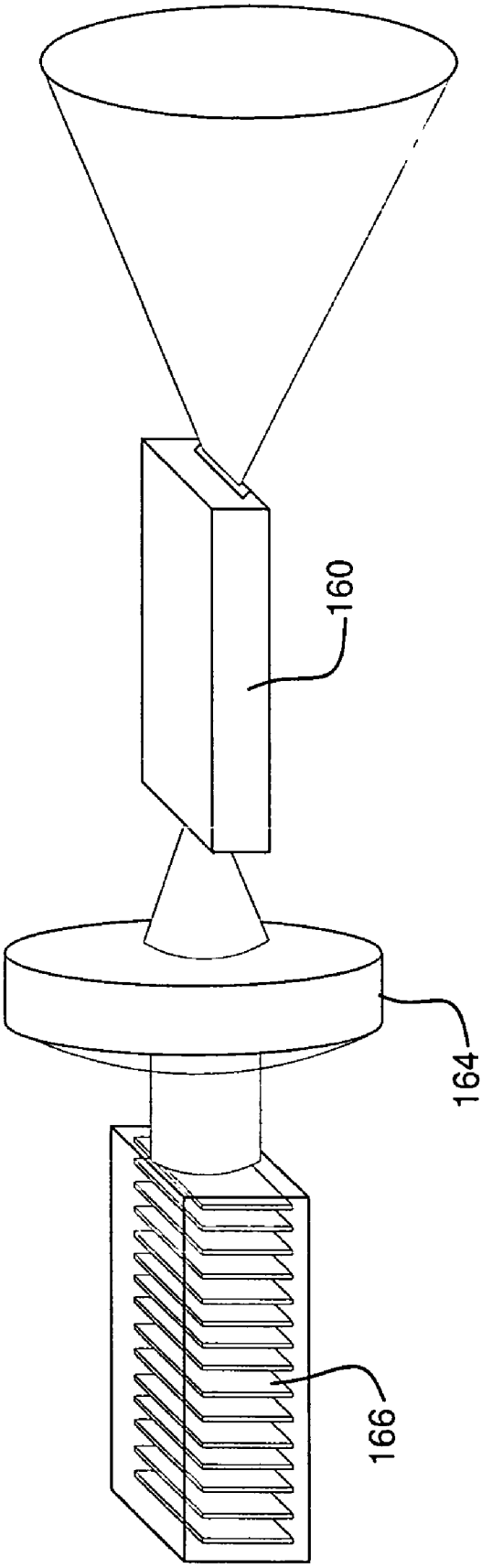


FIG. 7

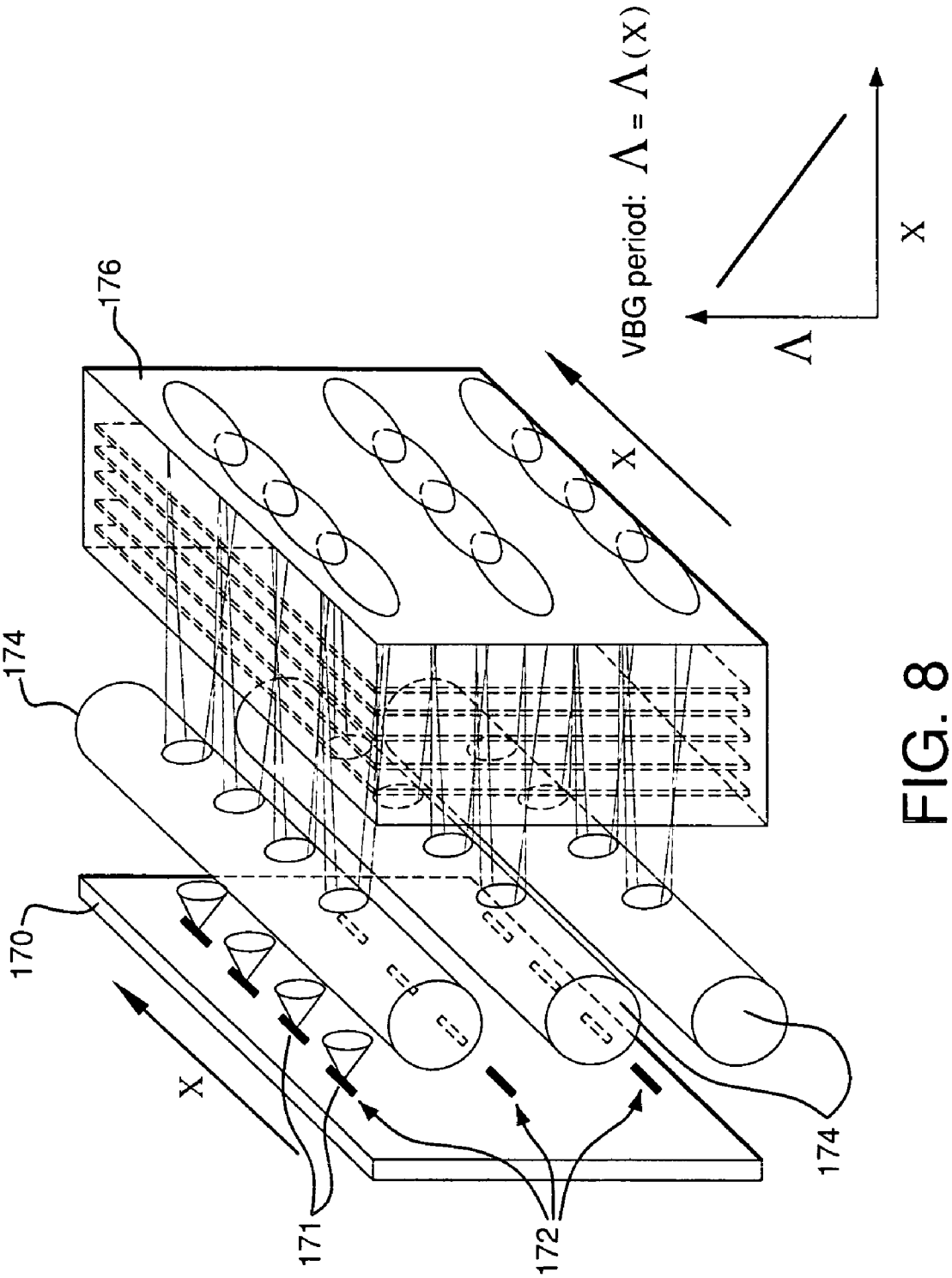


FIG. 8

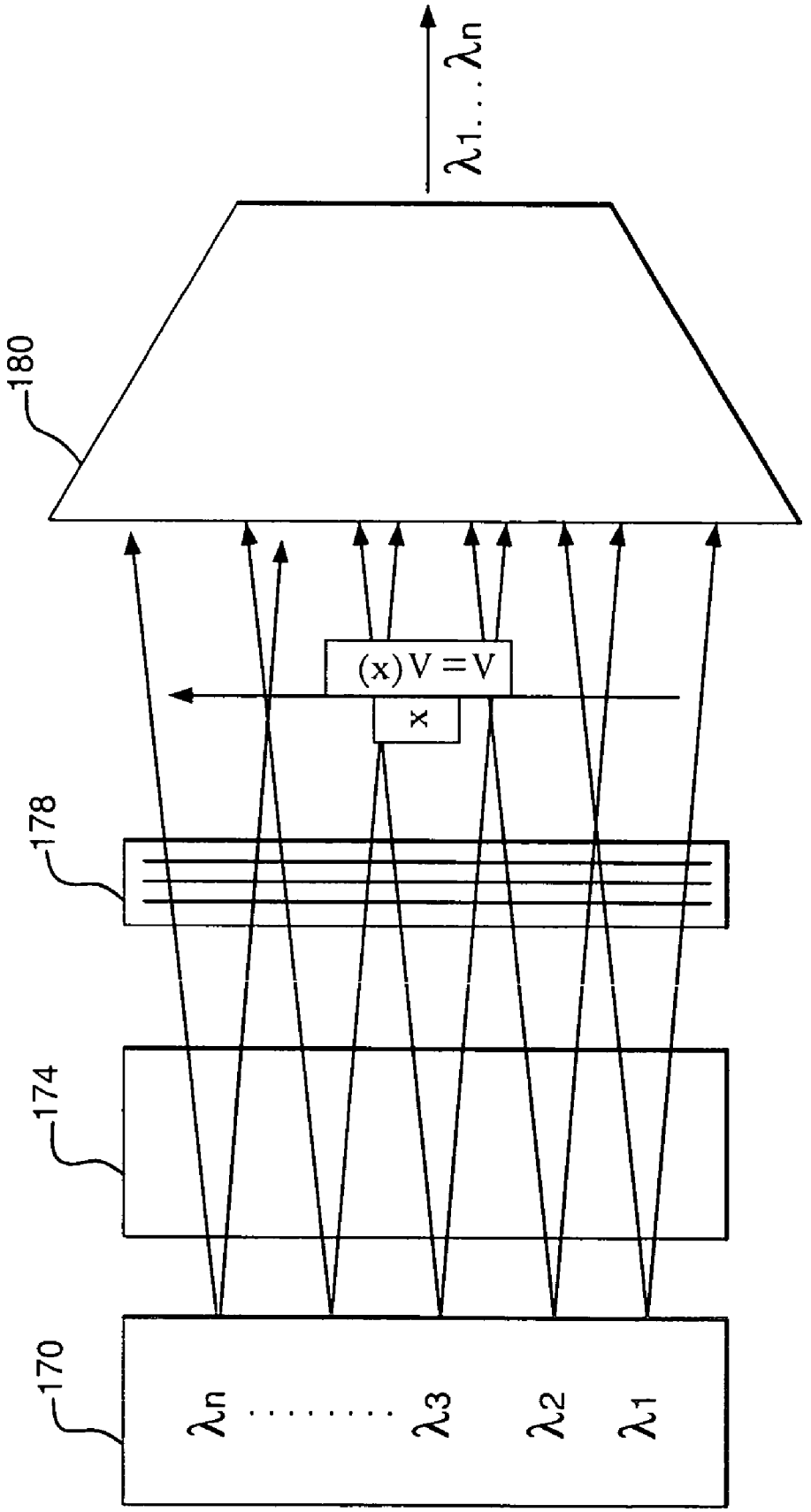


FIG. 9

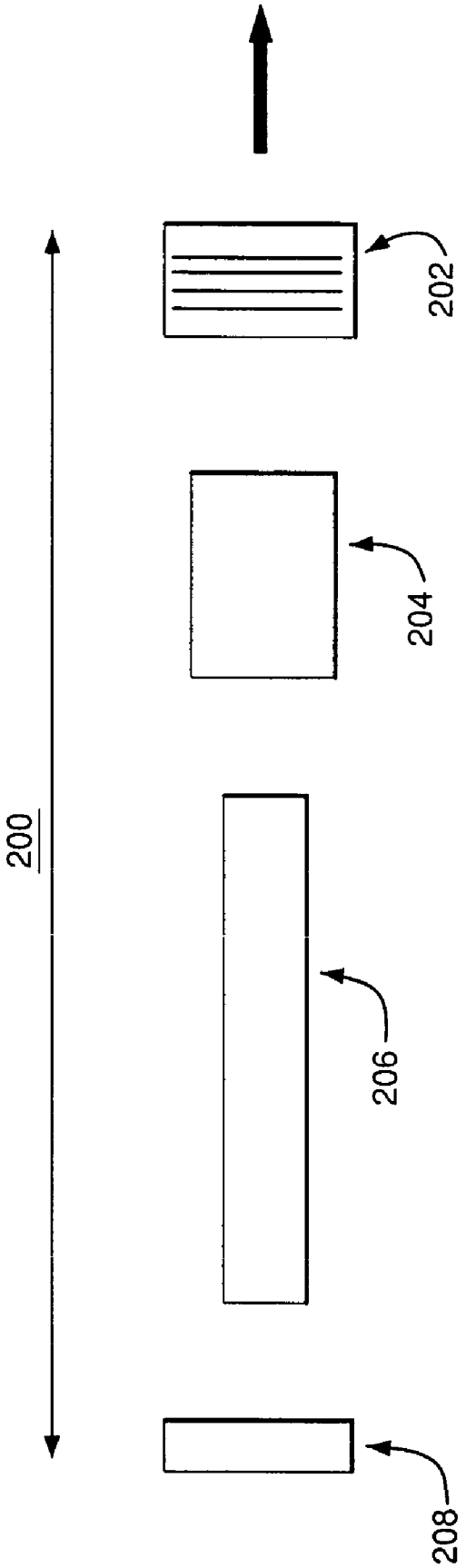


FIG. 10

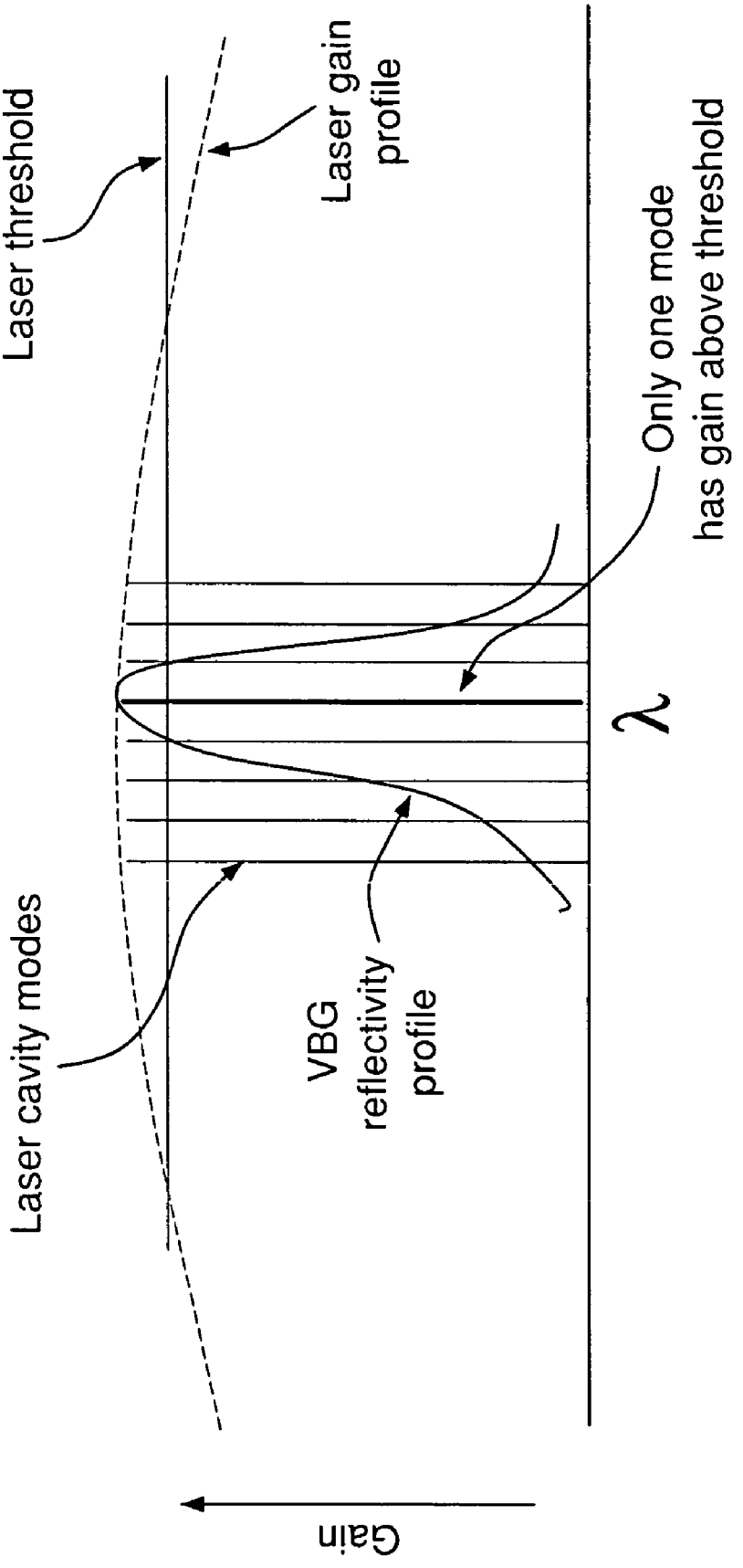

Laser threshold
Laser gain profile
Only one mode has gain above threshold
λ
Laser cavity modes
VBG reflectivity profile
Gain

FIG. 11

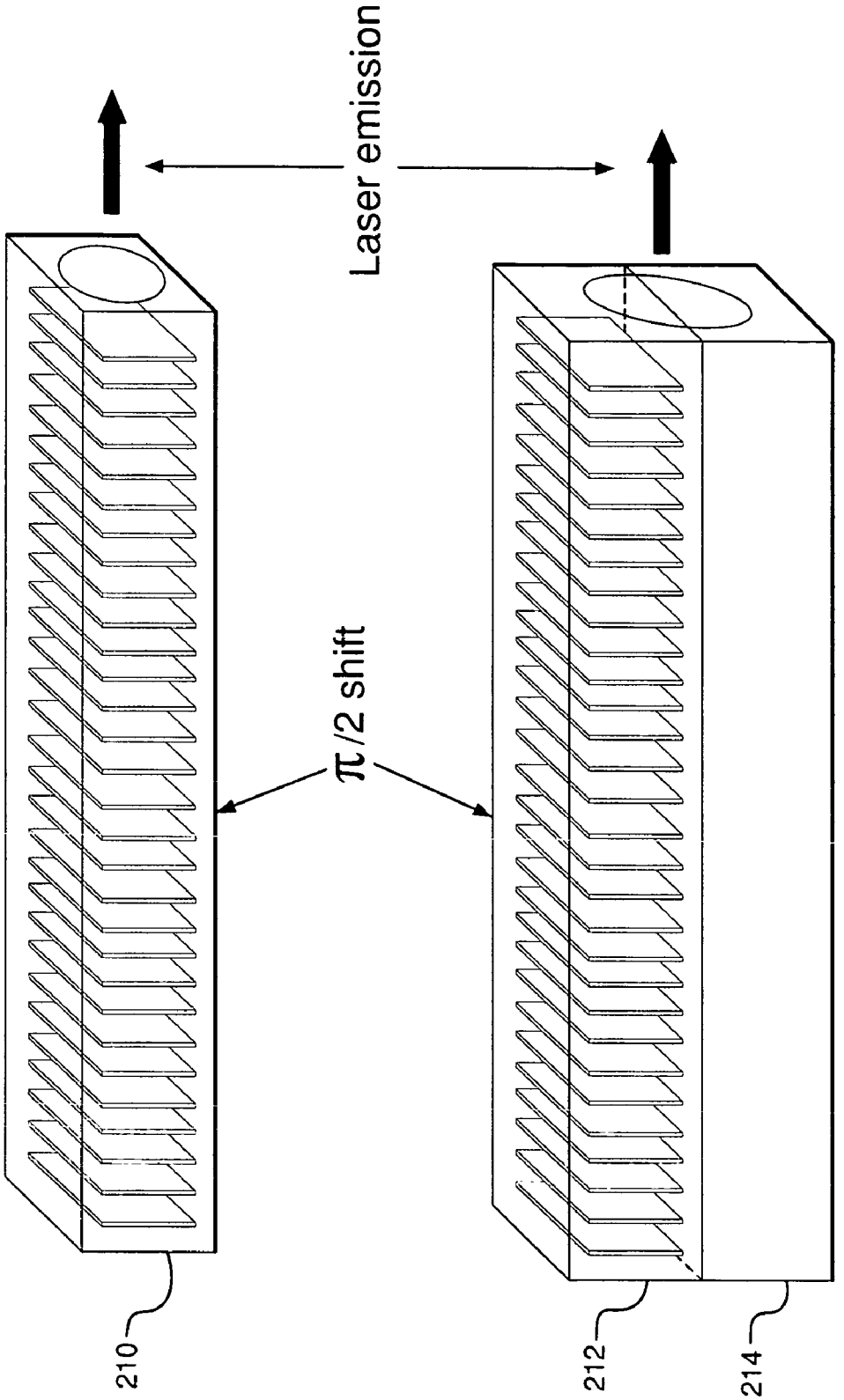


FIG. 12A

FIG. 12B

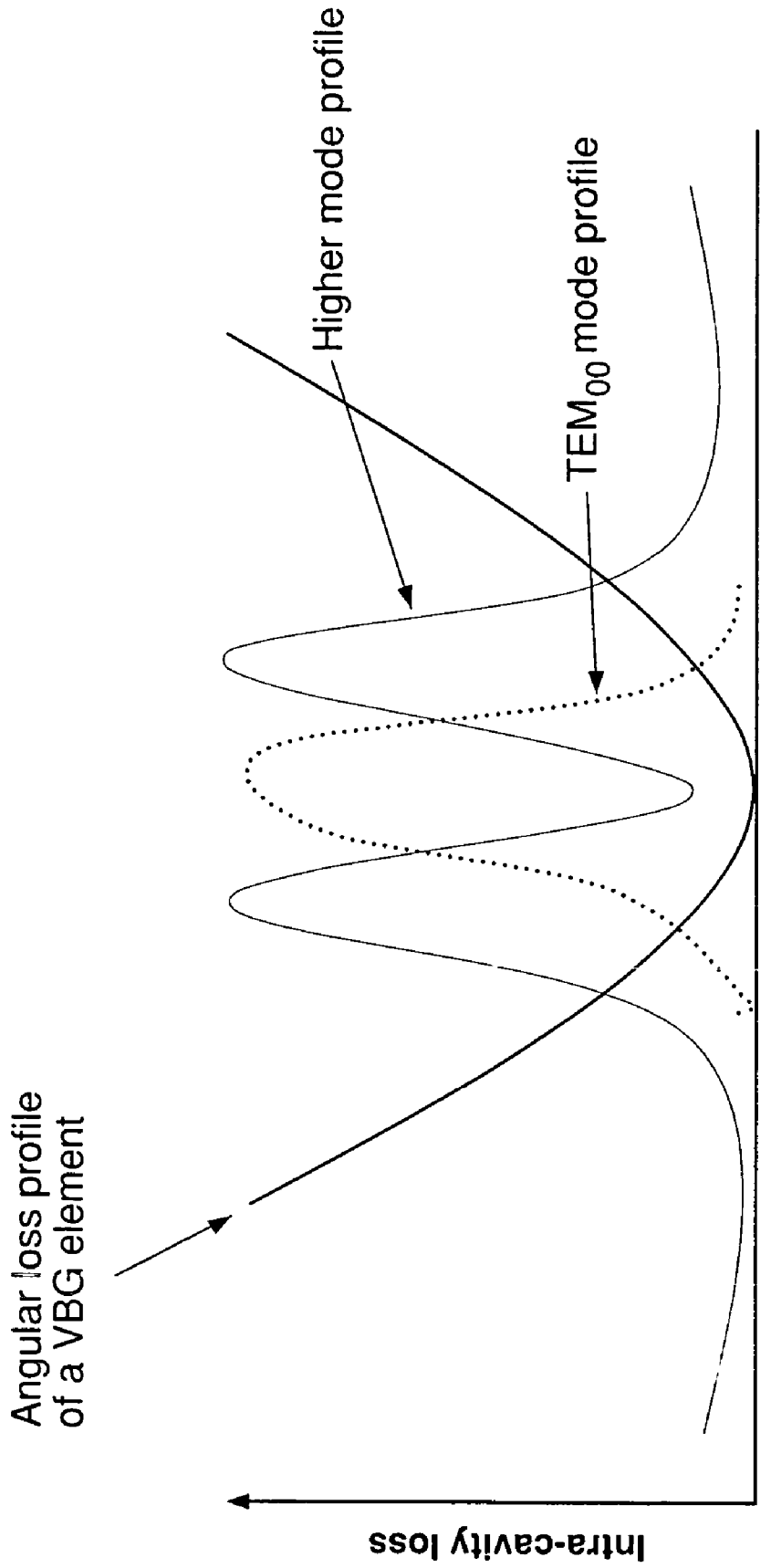

Higher mode profile
TEM_{00} mode profile
Angular loss profile of a VBG element
Intra-cavity loss
Angle

FIG.13

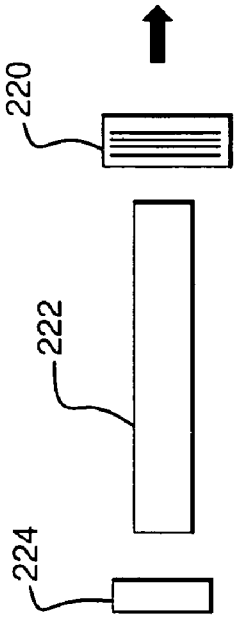


FIG. 14B

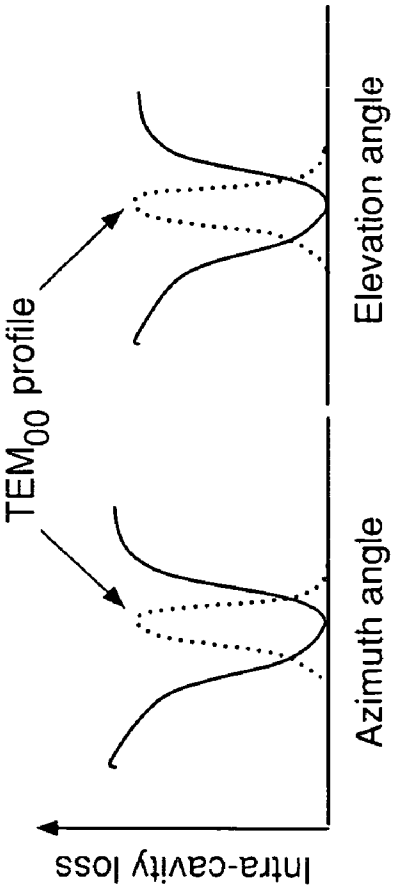


FIG. 14A

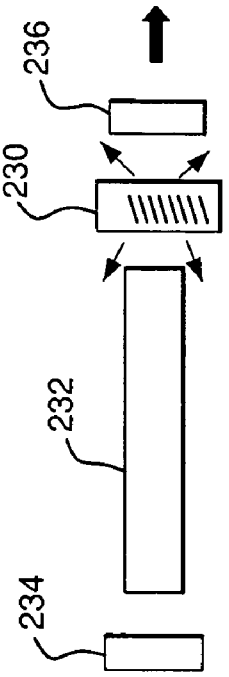


FIG.14D

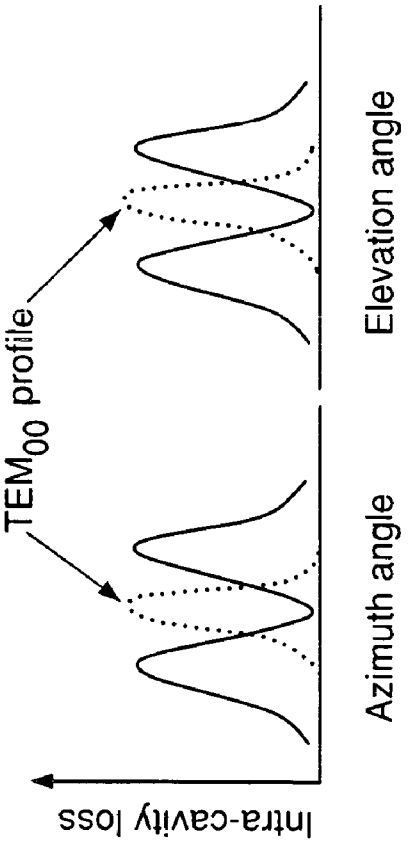


FIG.14C

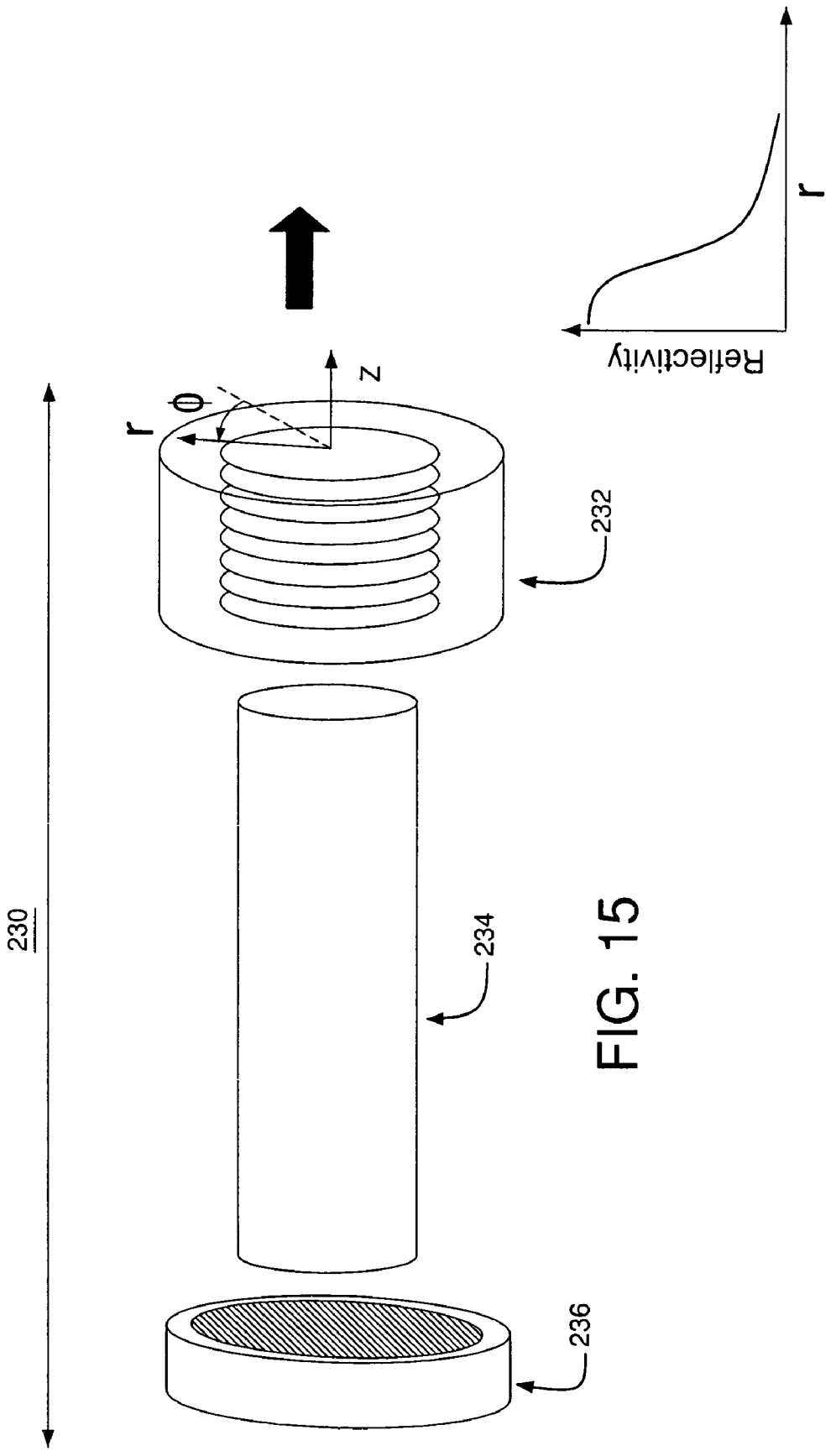


FIG. 15

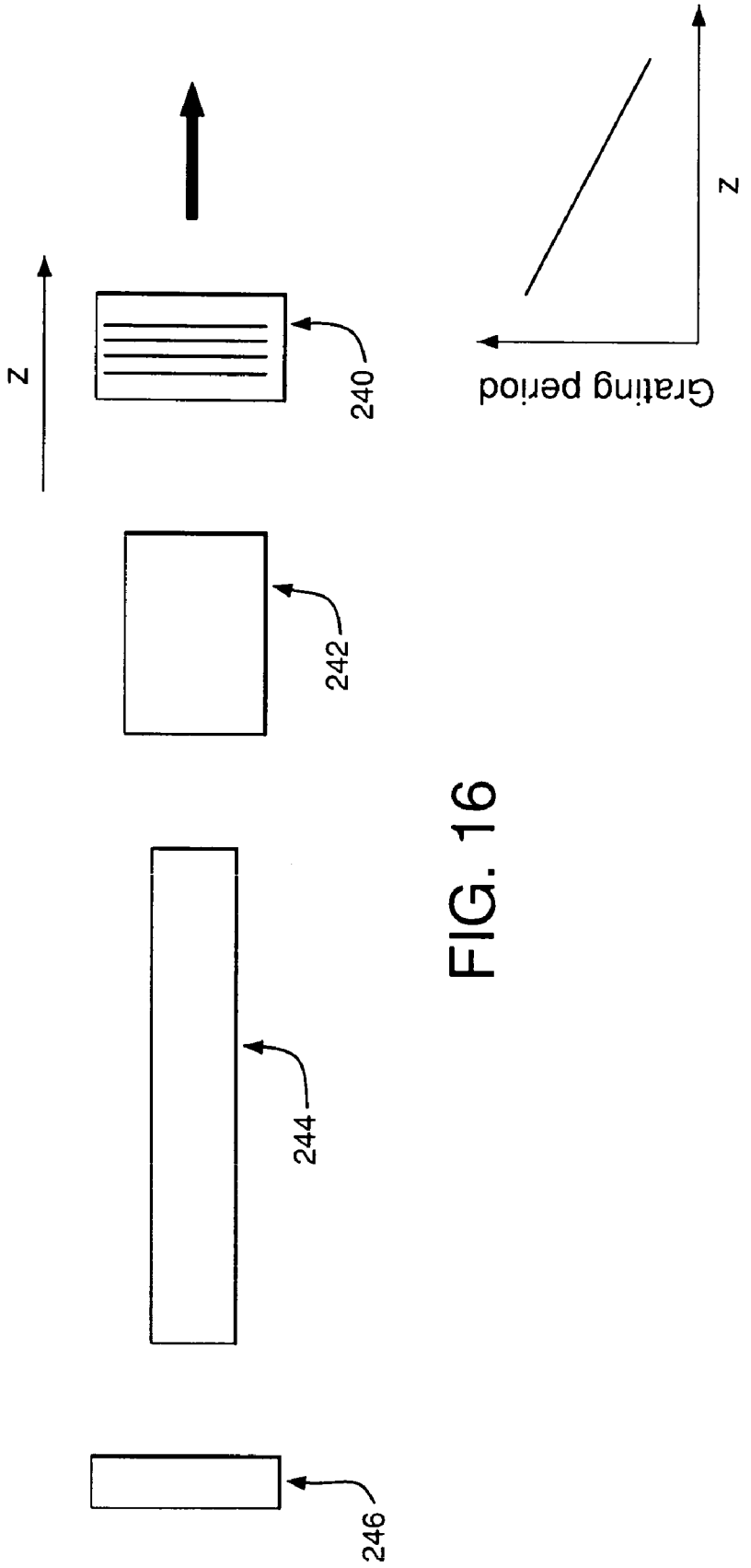


FIG. 16

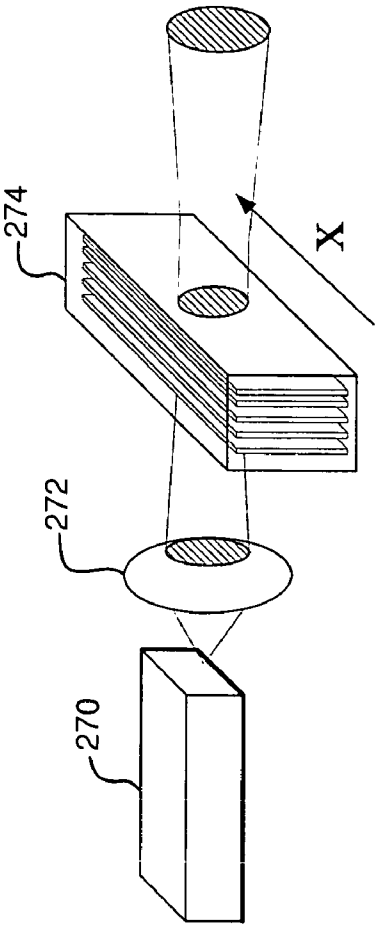
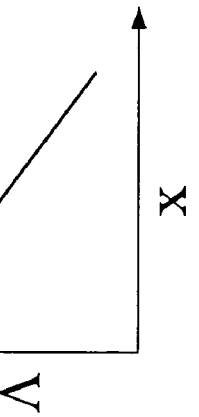


FIG. 17C



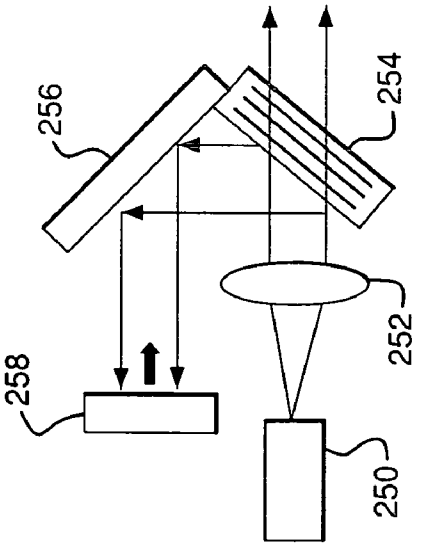


FIG. 17A

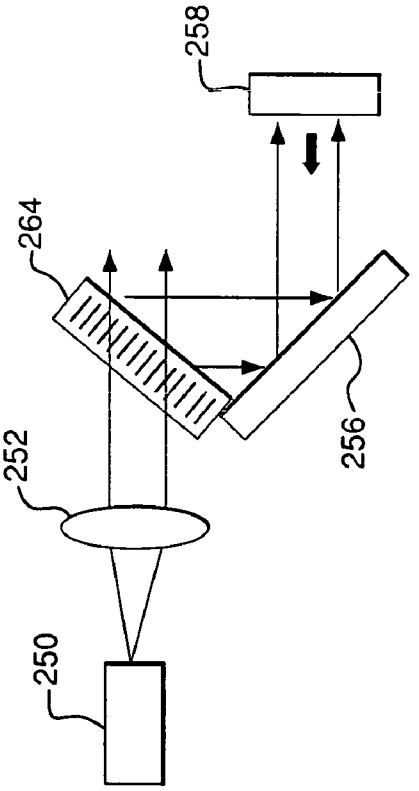


FIG. 17B

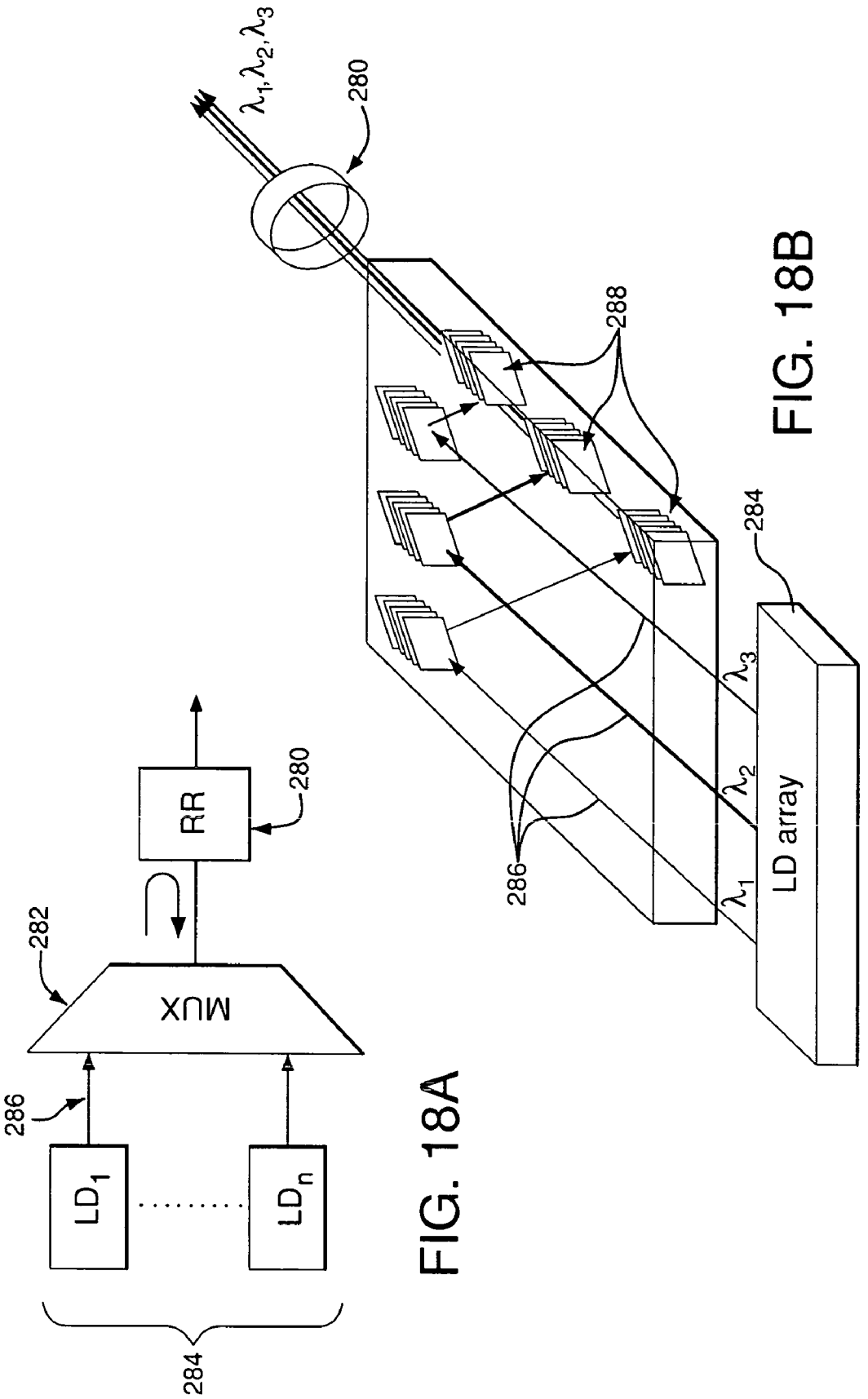


FIG. 18B

FIG. 18A

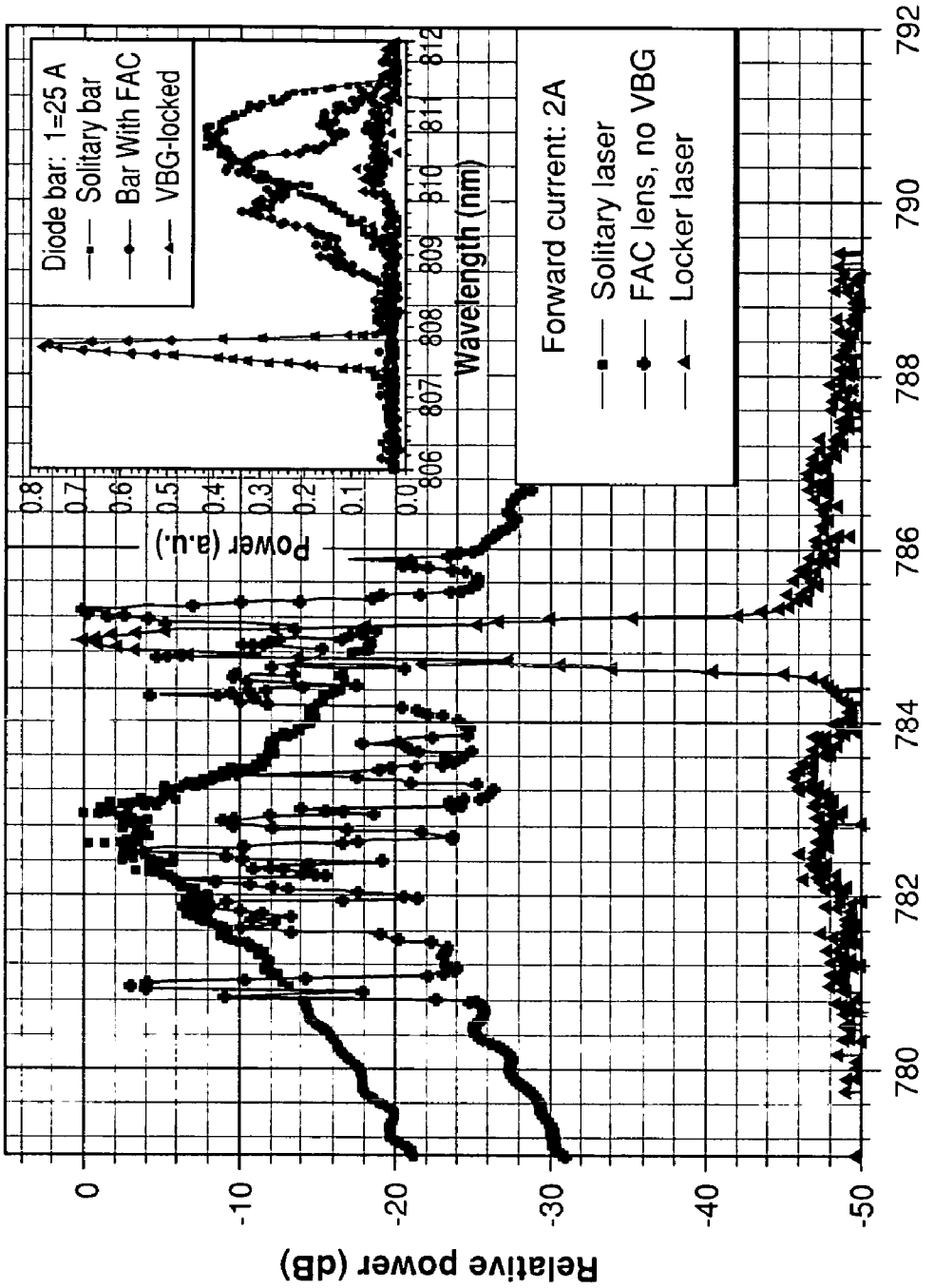

Relative power (dB)
0
-10
-20
-30
-40
-50
780
782
784
786
788
790
792
Wavelength (nm)
Forward current: 2A
Solitary laser
FAC lens, no VBG
Locker laser
Diode bar: 1=25 A
Solitary bar
Bar With FAC
VBG-locked
Power (a.u.)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
806
807
808
809
810
811
812
Wavelength (nm)

FIG. 19

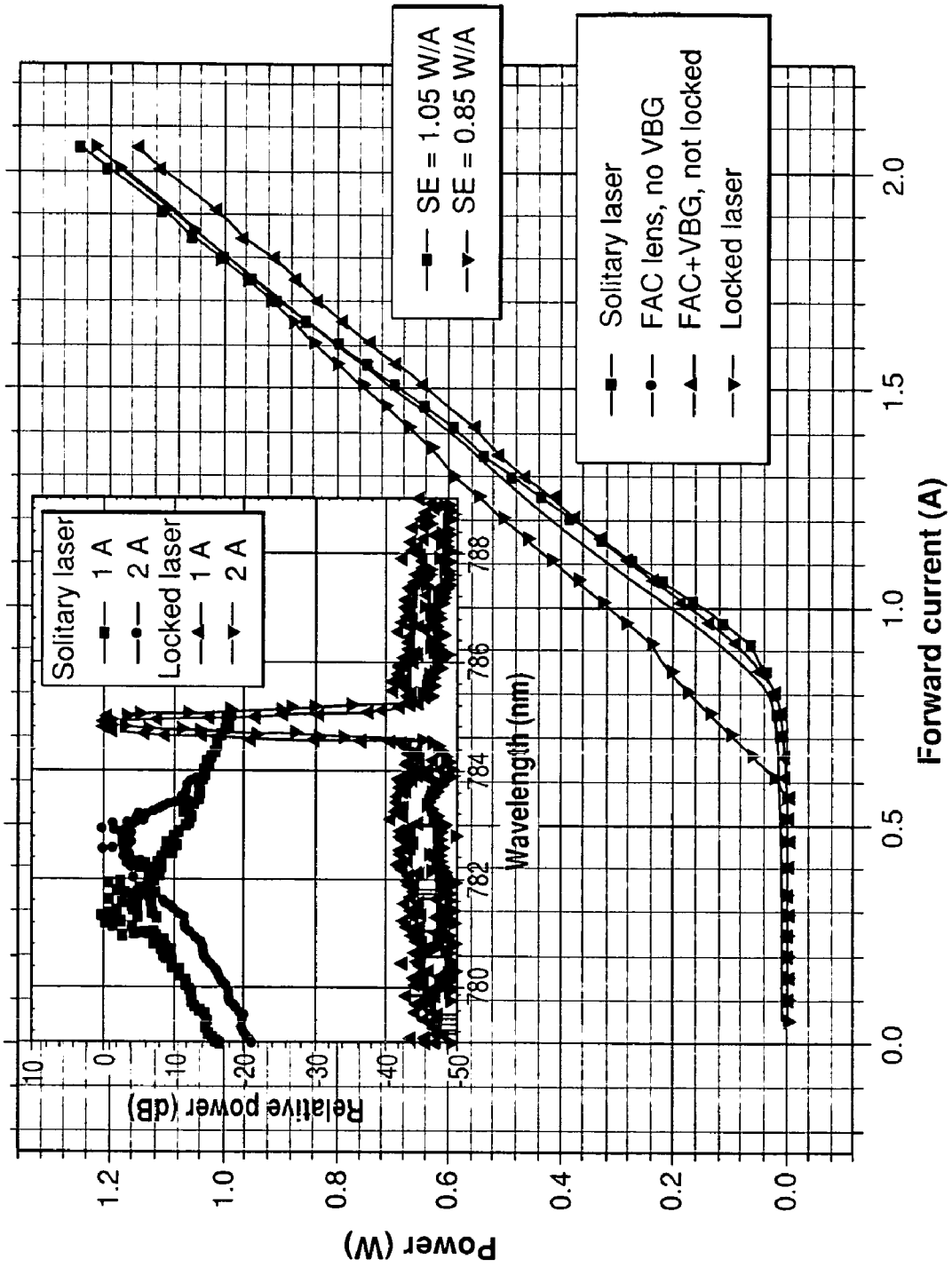

Power (W)
Forward current (A)
SE = 1.05 W/A
SE = 0.85 W/A
Solitary laser
FAC lens, no VBG
FAC+VBG, not locked
Locked laser
Relative power (dB)
Wavelength (nm)
Solitary laser
1 A
2 A
Locked laser
1 A
2 A

FIG. 20

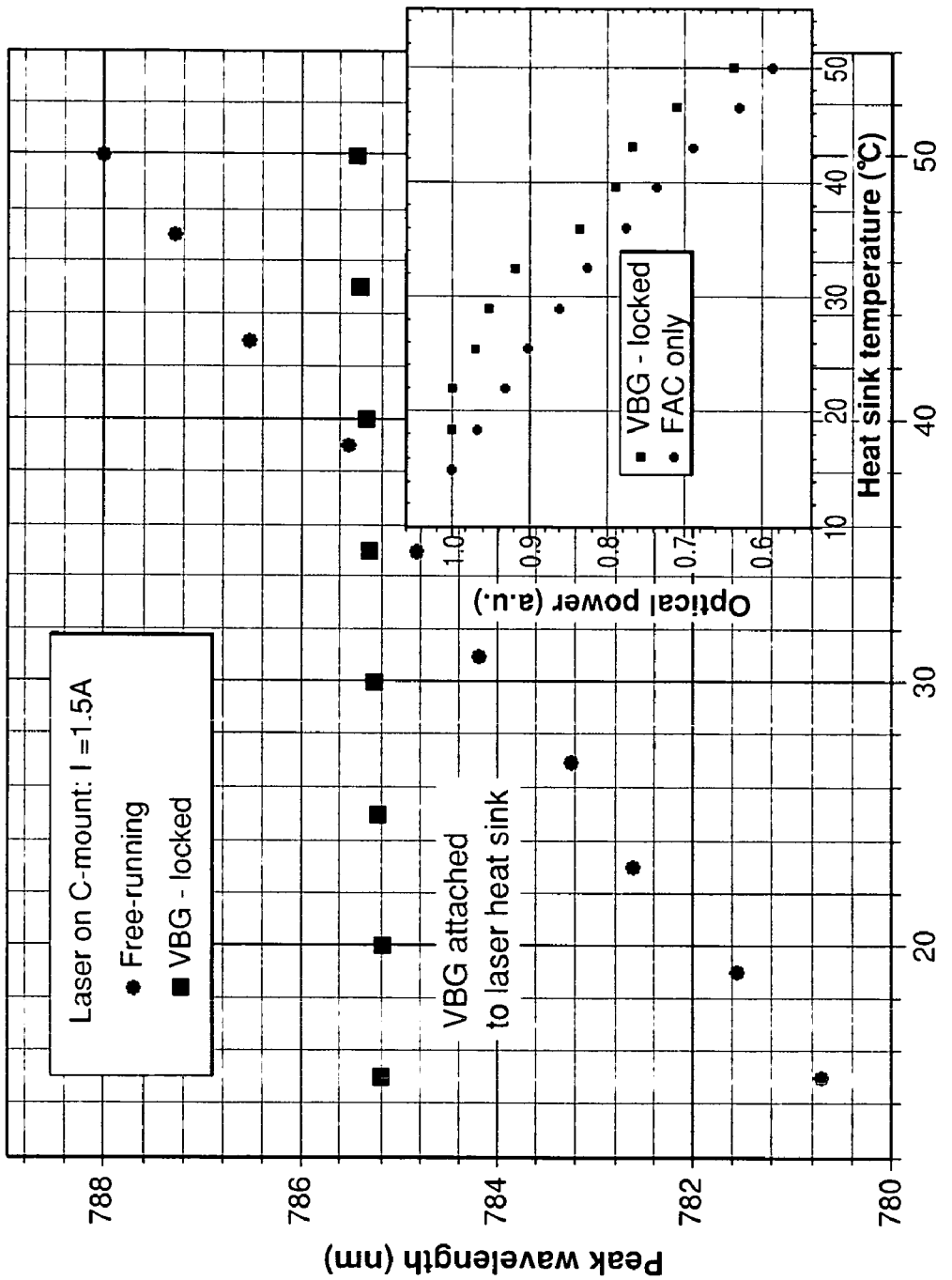

Laser on C-mount: I =1.5A
Free-running
VBG - locked
VBG attached
to laser heat sink
Peak wavelength (nm)
Heat sink temperature (°C)
Optical power (a.u.)
VBG - locked
FAC only
Heat sink temperature (°C)

FIG. 21

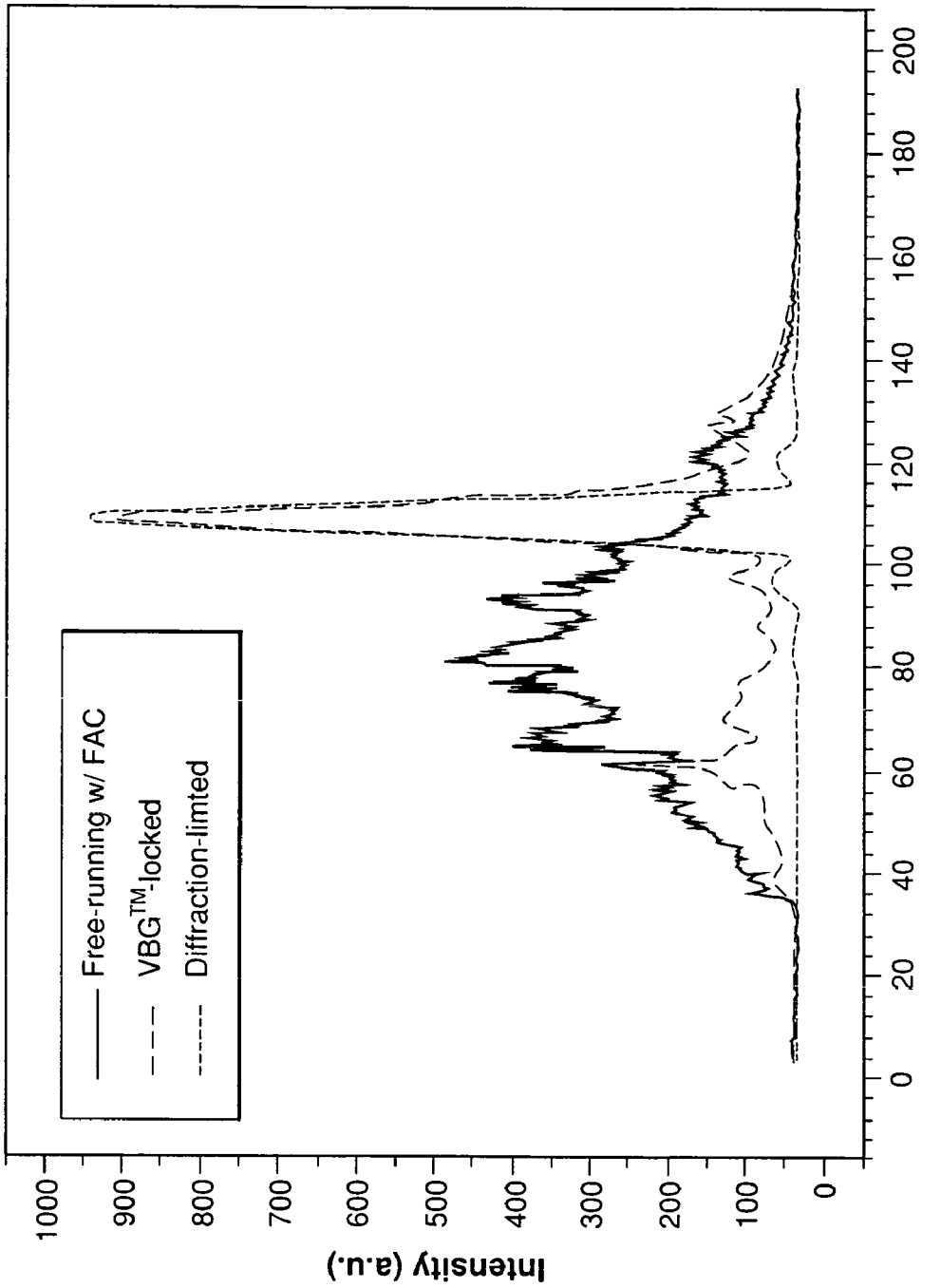

Free-running w/ FAC
VBG™-locked
Diffraction-limted
Intensity (a.u.)
Angle (mrad)
0
100
200
300
400
500
600
700
800
900
1000
0
20
40
60
80
100
120
140
160
180
200

FIG. 22

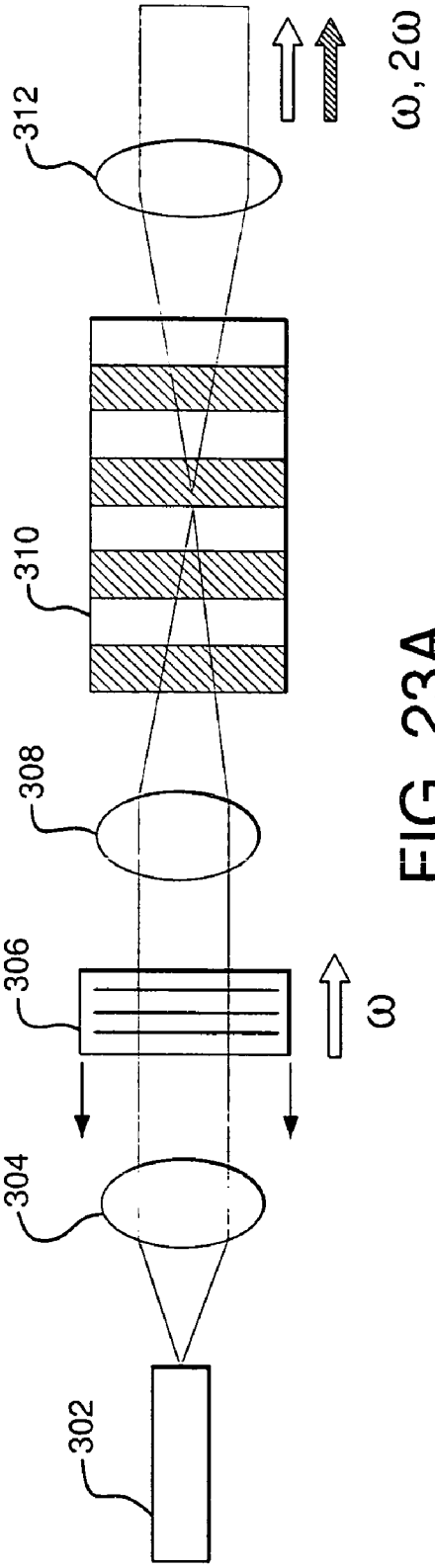


FIG. 23A

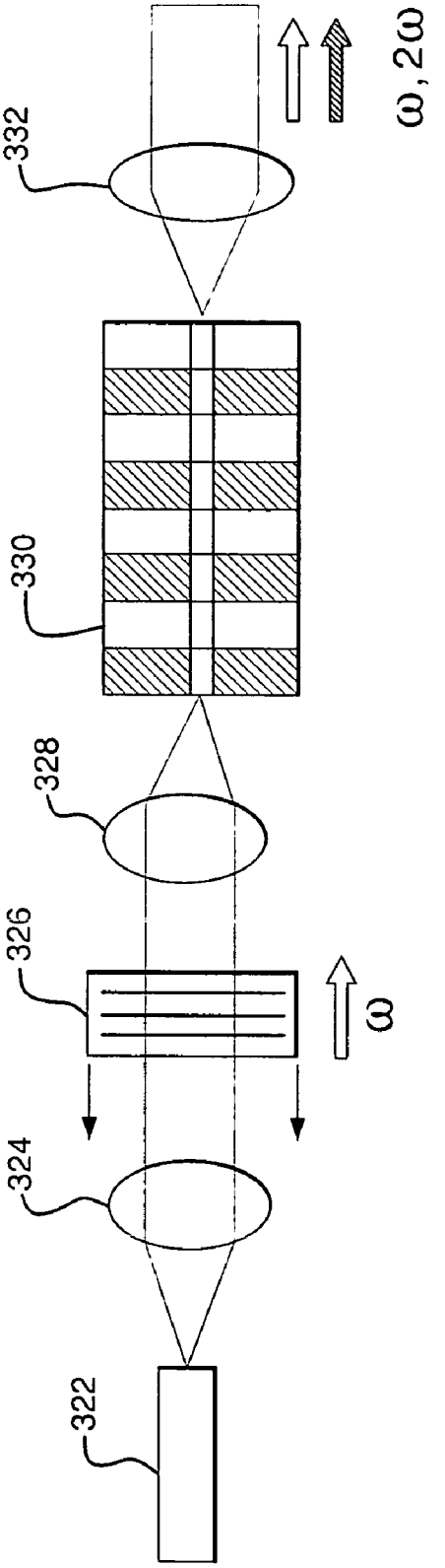


FIG. 23B

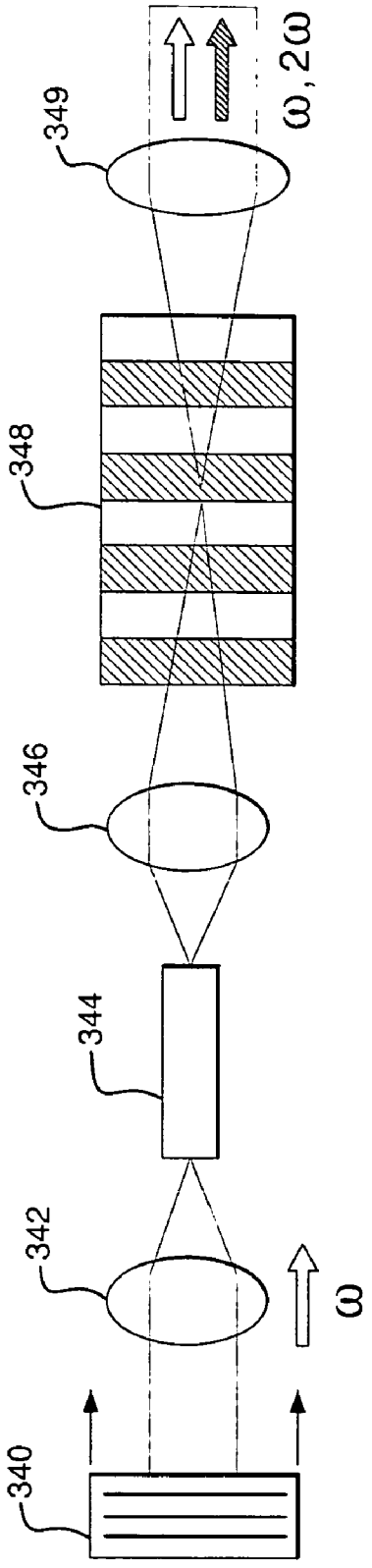


FIG. 24A

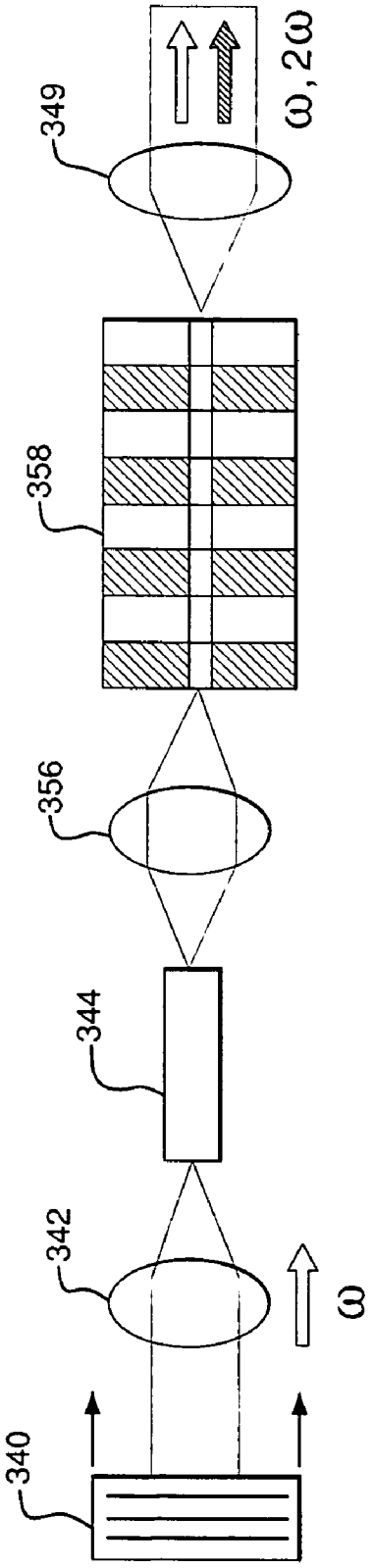


FIG. 24B

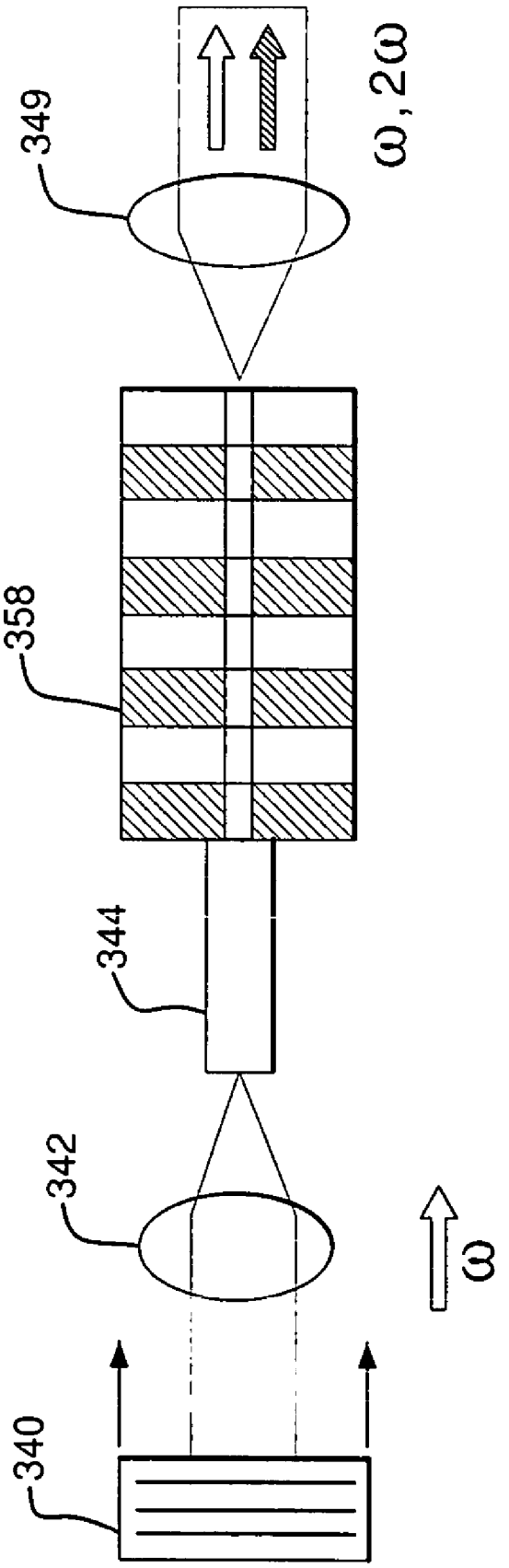


FIG. 24C

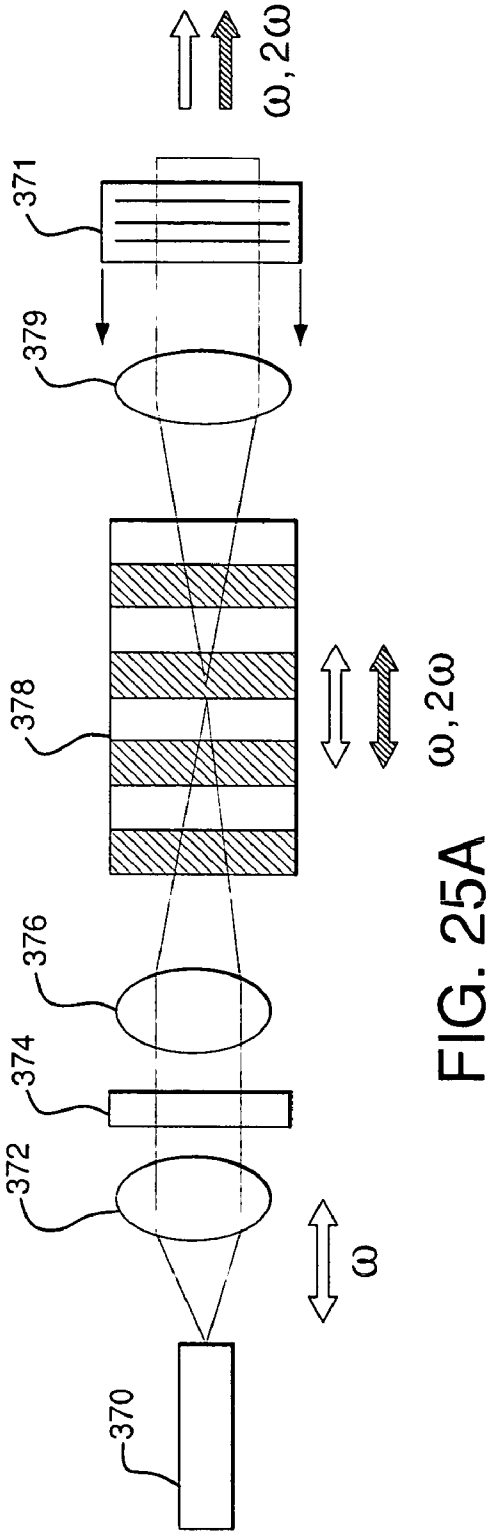


FIG. 25A

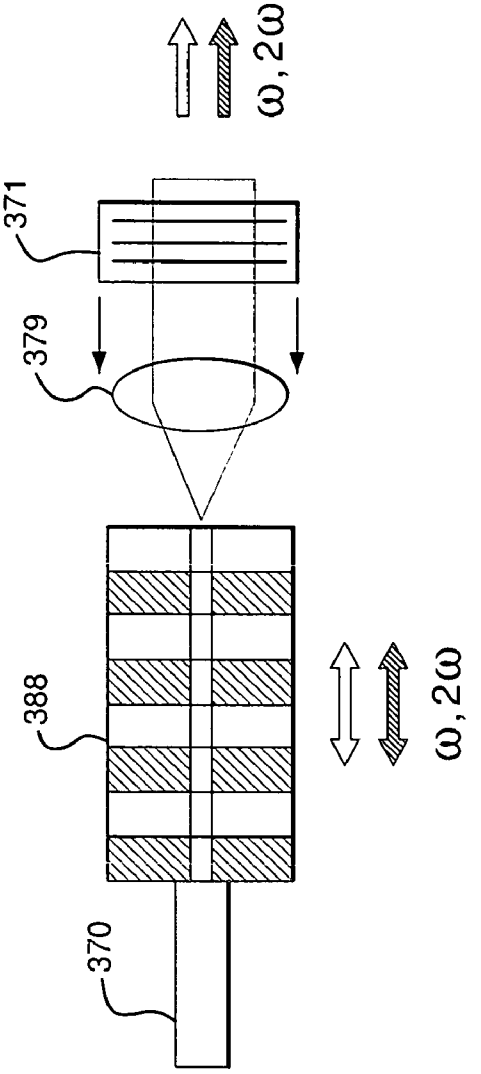


FIG. 25B

APPARATUS AND METHODS FOR ALTERING A CHARACTERISTIC OF LIGHT-EMITTING DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a division of U.S. patent application Ser. No. 10/884,524, filed Jul. 2, 2004, now U.S. Pat. No. 7,298,771 which claims benefit under 35 U.S.C. § 119(e) of provisional U.S. patent applications Ser. Nos. 60/484,857, filed Jul. 3, 2003, and 60/564,526, filed Apr. 22, 2004. The respective disclosures of each of the above-referenced patent applications are incorporated herein by reference.

FIELD OF THE INVENTION

The invention is related generally to light emitting devices, such as lasers, laser diodes, light-emitting diodes, super-luminescent laser diodes, etc. More specifically, the invention provides for using one or more volume Bragg grating (VBG) elements for modifying (or conditioning) one or more output characteristics of such devices.

BACKGROUND OF THE INVENTION

Laser cavities or resonators, however complex, typically include two or more mirrors or other reflecting devices that form a closed optical path for rays traveling in a certain direction. An optical element positioned in that closed optical path, which includes mirrors and/or other reflecting devices that form the path, may be referred to as "intra-cavity." An optical element positioned in the path of light that has departed from the resonator may be referred to as an "extra-cavity" element.

Using extra-cavity partial reflectors as feedback elements with a solitary laser cavity has been attempted in the past with a purpose of achieving single longitudinal mode operation of the otherwise multi-mode laser. Such reflectors, however, were not wavelength-selective devices. Such designs may be referred to as the "coupled-cavity" approach. This approach suffered from instabilities stemming from the non-selective nature of the feedback.

Another approach used was to employ a dispersive element, such as surface diffraction grating, as an extra- or intra-cavity wavelength-selective device in order to induce narrow-band or single longitudinal mode operation of a semiconductor laser. Although successful in a laboratory, this approach results in rather bulky devices, which are difficult to align and to maintain in the field.

A somewhat more practical approach for inducing narrow-band operation of a single-transverse mode semiconductor laser proved to be a fiber Bragg grating functioning typically as an extra-cavity element. This device is a narrow-band reflector that functions only in an optical fiber waveguide. It is, therefore, inapplicable to solid-state lasers, laser diode arrays, and, most likely, even to multi-mode (transverse) broad-area high-power single-emitter laser diodes, whether fiber-coupled or not.

The use of a volume Bragg grating element has been suggested as an intra-cavity element to induce single-longitudinal mode (also called single-frequency) operation of a single-transverse mode laser diode. In this approach, the volume Bragg grating element forms the external Bragg mirror of an external-cavity single-spatial mode semiconductor laser diode. However, to the inventors' knowledge, neither the possibility of using a VBG element for extra-cavity narrow-band feedback nor a practical device for achieving narrow-band operation of a single-transverse mode semiconductor laser diodes have been disclosed previously. Furthermore, to the inventors' knowledge, not even the possibility of applying VBG elements to multiple-transverse mode, broad-area laser diodes, laser diode arrays or the possibility of conditioning other attributes of laser emission (such as its spatial mode and temporal profile) have been disclosed previously.

To the inventors' knowledge, there are currently no devices in the market that employ volume Bragg grating elements for conditioning of laser characteristics, nor are there any successful practical devices in the market that use any of the above-mentioned approaches to improve the output characteristics of arrays of lasers.

SUMMARY OF THE INVENTION

The invention provides methods and apparatuses that can overcome the problems known in the prior art. The invention provides several practical embodiments of using VBG elements for conditioning any or all of the output characteristics of lasers and other light-emitting devices.

The inventors have found that volume Bragg grating (VBG) elements recorded in photorefractive materials, particularly those recorded in inorganic photorefractive glasses (PRGs), have many properties that can improve one or more characteristics of light-emitting devices such as solid-state lasers, semiconductor laser diodes, gas and ion lasers, and the like. A volume Bragg grating ("VBG") element may be any structure that: a) has a periodically varying index of refraction in its bulk (the shape of the surface of the constant index of refraction can be any smooth figure, flat or curved); b) is generally transparent in the spectral region of its operation; and c) has a thickness in the direction of propagation of light of 0.05 mm or more.

A photorefractive material may include any material that has the ability to change its index of refraction subsequent to illumination by light of certain wavelength region or regions. Such a change in refractive index may occur in the material either immediately upon illumination by light or as a result of secondary processing step or steps, whether chemical, thermal, etc. Such a material may also be generally transparent in the spectral region of its photosensitivity, i.e. the light at the recording wavelength may have the ability to penetrate sufficiently deep into the material (>0.1 mm) without suffering excessive absorption (>90%). Further, the material may be amorphous and generally isotropic.

Though the embodiments described herein are directed to certain examples of laser devices, it should be understood that the principles of the invention apply to other light-emitting devices as well. For example, applications of this invention include but are not limited to: high-power, semiconductor, solid state, ion, and gas lasers; light-emitting diodes and super-luminescent laser diodes; medical diagnostics, treatment, and surgical instruments; environmental sensors; metrology instruments; industrial applications; and defense applications.

Properties of VBG elements, and methods for manufacturing VBG elements, have been described previously (see, for example, U.S. patent application Ser. No. 10/390,521, filed Mar. 17, 2003).

Generally, there are at least three distinct characteristics of the output of a laser device that may be improved using the techniques of the invention: 1) emission spectrum (e.g., peak wavelength of the laser emission and its spectral width); 2) spatial/angular beam characteristics (e.g., the angular divergence of the output laser beam and its spatial mode structure);

and 3) temporal profile of the laser pulses (e.g., the duration of the laser pulse, its temporal phase variation or chirp etc.). As used herein, spectral, spatial, or temporal conditioning, refer to affecting any of the above characteristics, respectively.

The inventors have found that VBG elements permanently recorded in a suitable material, particularly a PRG, have a number of properties that can be utilized for improving one or more of the above characteristics. These properties include, but are not limited to: 1) single spectral pass band without any extraneous pass bands; 2) ability to control the spectral width of the VBG filter pass band; 3) ability to control the amplitude and phase envelope of a VBG filter; 4) narrow acceptance angle range otherwise called field of view; 5) ability to control the acceptance angle and the field of view; 6) ability to multiplex more than one filter in the same volume of the material; 7) high damage threshold of the VBG elements manufactured in a suitable material, particularly PRG; 8) ability to be shaped into bulk optical elements with sufficiently large clear aperture; and 9) reflectivity distributed over the volume of the material.

The invention provides apparatus and methods by which these properties of VBGs may be applied to the improvement of the above-mentioned laser characteristics.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A-**1**C depict a VBG as an extra-cavity element for wavelength locking by self-seeding; FIG. **1**D provides plots of wavelength characteristics with and without laser conditioning.

FIGS. **2**A and **2**B depict wavelength locking by use of a transmission VBG.

FIG. **3** depicts a wavelength stabilization concept for a high-power laser bar.

FIGS. **4**A and **4**B depict wavelength locking by self-seeding for a laser diode bar.

FIG. **5** depicts locking of a laser diode array by use of a hybrid element combining the fast axis collimating lens and a VBG.

FIG. **6** depicts wavelength locking of laser diode stacks.

FIG. **7** depicts laser wavelength stabilization by self-seeding through a back-facet.

FIG. **8** depicts a wavelength-shifted laser diode bar/stack.

FIG. **9** depicts wavelength multiplexing of the output of a wavelength-shifted laser diode bar/stack for higher brightness.

FIG. **10** depicts a VBG mirror forming part of a laser cavity.

FIG. **11** depicts using a VBG for a single longitudinal laser mode selection.

FIGS. **12**A and **12**B depict using a VBG element for selection of a single longitudinal mode of a laser in distributed feedback configurations.

FIG. **13** depicts spatial mode stripping by use of a VBG.

FIGS. **14**A-**14**D depict examples of various angular diffraction efficiency profiles of VBG elements for spatial mode stripping in non-folding configurations.

FIG. **15** depicts simultaneous single longitudinal mode and TEM_{00} mode selection by use of VBG element with smoothly varying reflectivity profile.

FIG. **16** depicts conditioning of the temporal profile of pulsed lasers.

FIGS. **17**A-**17**C depict how a VBG may be used to construct tunable devices.

FIGS. **18**A and **18**B depict simultaneous spectral and spatial conditioning, and combining of the output of an array of emitters by use of an external feedback filtered through a wavelength multiplexing device.

FIG. **19** depicts the results of spectral conditioning of laser diodes by use of VBG in extra-cavity configuration.

FIG. **20** depicts the output power characteristics of a laser diode locked by an external VBG element.

FIG. **21** depicts the results on the improvement in thermal drift of a laser diode locked by an external VBG element.

FIG. **22** depicts the results in improving spatial characteristics of a laser diode locked by an external VBG element.

FIGS. **23**A and **23**B depict an embodiment for extra-cavity doubling of a high-power laser diode frequency.

FIGS. **24**A-**24**C depict another embodiment for extra-cavity doubling of a high-power laser diode frequency.

FIGS. **25**A and **25**B depict intra-cavity doubling of a high-power laser diode frequency.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Overview

There are at least two general approaches to using VBG elements for conditioning a characteristic of a light emitting device: a) using a VBG that is outside of the laser cavity (extra-cavity); and b) using a VBG that is inside laser cavity (intra-cavity).

As discussed above, a laser resonator may be viewed as a closed optical path formed between mirrors and/or other light-reflecting elements. Such a closed optical path is typically a condition that is necessary for lasing to occur. For this reason, it is desirable that any intra-cavity element added to the resonator does not alter this condition, lest it impede light generation via stimulated emission. By contrast to intra-cavity elements, extra-cavity elements may be free from such a constraint. Furthermore, the efficiency of light generation typically depends nonlinearly on single-pass cavity loss. Thus, it is also desirable that any intra-cavity element used for laser output conditioning have as little loss as possible. This includes the losses in the element itself, as well as the losses in the optical delivery system used to project light onto the element and back. In contrast, extra-cavity elements used for laser output conditioning may be much more tolerant to the loss factor.

When used for narrowing the spectral output of a laser, intra-cavity elements provide wavelength-selective loss that raises the lasing threshold for all but a few cavity modes. In contrast, the feedback from an extra-cavity wavelength-selective element reduces lasing threshold for just a few cavity modes, which creates preferred lasing conditions for those modes. These modes, then, consume most or all of the available laser gain and prevent other modes from lasing. Similar processes affect the formation of the spatial mode of the laser when intra- and extra-cavity elements are used for spatial mode conditioning.

An optical delivery system may be viewed as a collection of optical elements, e.g. lenses, mirrors, prisms etc., that collects some or all of the light emanating from a particular aperture of the laser cavity, projects some or all of this light onto a VBG element or a system thereof, and then collects some or all of the light returned from said VBG element and projects it back onto the aperture of laser cavity.

When considering the intra-cavity use of VBG elements, a design factor that may be considered is the reduction of the total loss of the VBG element plus the optical delivery system for the preferred longitudinal and transverse modes of the laser. In comparison, the design of an extra-cavity system for laser output conditioning may be more complex. In order to achieve stable output with desired characteristics, it may be

desirable to optimize any or all of the following factors: 1) The solitary cavity design, including, but not limited to, cavity length, reflectivity of the cavity mirrors, threshold, differential efficiency, etc., all of which may be dependent on the properties of the gain medium; 2) The intrinsic reflectivity and loss of the VBG element; 3) The spectral bandwidth of the VBG element; 4) The reflectivity of the VBG element facets; 5) The relative angle between the volume Bragg grating planes and the external facets of the element; 6) The design of the external optical delivery system projecting light onto and back from the VBG element, including, but not limited to, its total coupling efficiency into the solitary laser cavity, the length of the external cavity, the divergence of the light (in both directions) incident upon the VBG and the output coupler of the solitary cavity, etc.

For example, single-transverse mode laser diodes that are stabilized by a fiber Bragg grating may have such a fiber Bragg grating positioned rather far from the laser diode chip (typically about 1 meter) in order to induce the so-called coherence collapse regime of operation. Such a condition may be necessary to achieve stable laser output. However, if a VBG element was used as a mere free-space replacement of the fiber Bragg grating, it may result in a device 1.5 m long without an advantage of easy coiling or folding that the optical fiber affords naturally. Such a device might not be practical, however, and, therefore, different stable operating conditions might be desirable for devices using VBG elements for laser output conditioning, which are the result of the optimization of the above-described parameters.

Extra-cavity Use of VBG Elements

A VBG element may be used extra-cavity to condition, spectrally, spatially, and/or temporally, light received from a light-emitting device. At least a portion of the conditioned light may then be fed back into the laser cavity. In the process of doing so, the light emitted from the laser will assume the characteristics of the light conditioned by the VBG. Example embodiments of such extra-cavity use of VBG elements are depicted in FIGS. **1-9**. Note that, when the VBG is used in extra-cavity configuration, the laser device is operating above threshold in the absence of optical feedback from the VBG element.

In an example embodiment, a VBG element and a laser output coupler may be positioned in conjugate planes. An optical system including one or more lenses may be positioned in the light path after the light exits the laser cavity through the output coupler. Such an optical system may form an image of the output coupler in a particular location in space outside the laser cavity. A VBG element may be positioned in that plane so that the VBG element reflects the light rays incident upon it in such fashion that the reflected rays go back through the imaging optical system and form an image in the plane of the output coupler. In this case, it may be said that the output coupler and the VBG are positioned in the conjugate planes of the imaging optical system. A feature of this configuration is that it maximizes the coupling efficiency from the external element (the VBG element in this case) back into the laser cavity, essentially matching the resonator mode pattern in both transverse directions. Such an embodiment may be desirable where the laser cavity is a waveguide, such as in the case of semiconductor laser diodes, for example.

In another example embodiment, the output of a waveguide laser cavity (e.g., a semiconductor laser diode) may be approximately collimated in one axis (e.g., the fast axis) by a cylindrical lens. The other axis (e.g., the slow axis) of the laser output may be allowed to diverge freely. The VBG element may be positioned in the optical path of the laser output behind the cylindrical lens and aligned in such a way that it reflects portion of the laser light back into the laser cavity. In this embodiment the coupling efficiency of the optical delivery system (e.g., the cylindrical lens) from the VBG back into the laser cavity is very low, making it undesirable for use as an intra-cavity element. However, such a system may be designed to operate stably in an extra-cavity configuration. It will induce wavelength-stable, spectrally narrowed operation of the laser diode. In this configuration the divergence of the non-collimated laser axis (the slow axis) can also be reduced without the use of additional optics, when such a laser is a broad-area multiple transverse mode semiconductor laser diode. In this configuration an entire linear array of semiconductor lasers can be conditioned with a single cylindrical lens and a single VBG element.

An example embodiment of a broad-area high-power semiconductor laser, having an emitting aperture of greater than about 50 μm, with output conditioned by an extra-cavity VBG with a cylindrical fast-axis lens, is also disclosed. The output power of the laser changes rather insignificantly despite the fact that the VBG reflectivity is relatively high (30%). Small reduction in the output power is a factor in the design of practical systems using high-power laser diodes and may be provided by the invention.

Example design parameters for stable operation of broad-area semiconductor laser diodes may include: laser cavity, 1-3 mm long; emitting aperture, 100-500 μm; back facet reflectivity, 0.9 or greater; front facet reflectivity, 0.5-20%; FAC lens EFL, 50-2000 μm; FAC lens type, graded-index cylindrical or plano-convex aspheric cylindrical; FAC AR coating, all facets <2%; VBG reflectivity, 5-60%; VBG thickness, 0.2-3 mm; VBG position behind FAC lens, 0-10 mm; and angle of the VBG planes with respect to its facet, 0-5 degrees.

An example embodiment of an extra-cavity VBG without any optical delivery system (e.g., without any lenses) is also disclosed. In this embodiment a VBG element may be positioned in the optical path of the light behind the output coupler (e.g., the laser diode front facet) without any extra optical elements (e.g., lenses) in between. In the case of a waveguide cavity, such as the case for semiconductor laser diodes, only a very small portion of the total laser output power may be returned by the VBG into the laser cavity. However, with proper laser cavity and VBG design, it is possible to achieve spectral narrowing and stabilization of the output wavelength across a range of operating conditions.

Example design parameters for such an embodiment may include: laser cavity, 1-3 mm long; emitting aperture, 100-500 μm; back facet reflectivity, 0.9 or greater; front facet reflectivity, 0.2-5%; VBG reflectivity, 30-99%; VBG thickness, 0.05-3 mm; VBG position in front of the laser, 0-5 mm; and angle of the VBG planes with respect to its facet, 0-5 degrees.

Some of the embodiments described herein demonstrate how the output of a laser diode, laser diode bar, or stack may be modified spectrally and/or spatially. Effects of the VBG element in these cases include spectral narrowing of the emission line of a laser or laser array, stabilization of the peak emission wavelength of a laser or a laser array, and the reduction of the divergence of the slow axis of a laser or a laser array.

Note that the high total output power of the laser transmitting through the clear aperture of the VBG (>20 W for laser diode arrays), the high power density on the VBG element (>40 W/cm^2) as well as high temperature excursions suffered by such an element (T>100 C) may limit the choice of suitable materials for VBG implementation. Nevertheless, the inven-

tors have successfully demonstrated VBG elements operation in all of the above conditions when implemented in PRG materials.

FIG. **8**, for example, demonstrates how both of these properties may be utilized in order to combine the output of an entire array of lasers onto a single target using a single VBG. In that embodiment, the VBG element contains a grating having a period that varies depending on location. When positioned properly in front of an array of emitters, such a grating will force different emitters to operate at a different peak wavelength depending on their location, creating a wavelength-shifted laser array. The output of such an array may be subsequently combined by use of one of a number of well-known wavelength multiplexing techniques into a much brighter spot with intensity essentially equivalent to that of the entire array and spatial dimensions essentially equivalent to that of an individual emitter.

An embodiment for spectral power combining of a laser diode array via external feedback through a wavelength multiplexer is also disclosed. In this embodiment, a wavelength multiplexer may be positioned in the path of output light of an array of emitters and behind an optical delivery system. Such a multiplexer may be designed to combine the output of all the emitters into one beam, provided they operate at the wavelengths matching the appropriate input channels of the multiplexer. Such a condition may be achieved automatically when an external feedback is provided into the emitters from a partial reflector positioned in the light path behind the wavelength multiplexer. In this configuration, the reflected light will travel back through the multiplexer and separate into multiple channels different in wavelength. As a result, each of the emitters in the array will receive feedback at a wavelength matching that of the corresponding channel of the multiplexer. Such feedback will force each emitter to operate at appropriate wavelength, so that their output power is efficiently combined.

Other applications include, but are not limited to, stabilization of super-luminescent laser diodes, light-emitting diodes, solid-state lasers, gas and ion lasers; wavelength stabilization of sources used in telecommunications, sensing, metrology, material processing, other industrial applications and defense electronics; multi-wavelength emitters and emitter arrays for use in any of the application areas mentioned above; and tunable-wavelength emitters.

Intra-cavity Use of VBG Elements

VBG elements may be used inside a laser cavity, rather than through an external feedback, to affect laser output directly. Examples of embodiments of intra-cavity use of VBG elements are provided in FIGS. **10-16**.

A VBG may be used to force a laser to operate on a single longitudinal mode. Due to the highly selective reflectivity of a VBG reflector, only one longitudinal mode of the laser cavity has gain exceeding the lasing threshold. Conventionally, monolithic or air-spaced etalons are used to select a single longitudinal mode of a solid-state laser (e.g., Nd:YAG). Very often, additional elements (e.g., thin etalon or a birefringent filter or both) are employed in order to achieve single-frequency operation, even for a narrow gain-bandwidth medium. It may be desirable that these elements, which provide wavelength-selective loss inside the cavity, are tuned in synch with each other and with the length of the main cavity in order to provide continuous, hop-free tuning.

There are numerous ways to achieve single longitudinal mode (or single frequency) operation, with some of the embodiments described below. In one embodiment, a reflective VBG element may be used as the output coupler or the high reflector of a laser resonator. The length of the VBG element may be selected in such a way that its reflectivity drops rapidly when the wavelength is detuned from the Bragg condition. Consequently, only one resonator mode reaches lasing threshold.

In another embodiment, two VBG elements may be employed—one as the high reflector and one as an output coupler of the laser resonator. The VBG elements may have slightly shifted peak reflectivity wavelengths, which creates more rapid change in cavity loss with wavelength. This would allow the use of shorter, less selective VBG elements and/or longer laser resonators.

In yet another embodiment, the VBG may act as a distributed feedback (DFB) element, taking place of both resonator mirrors. Such an element may be monolithic, with proper phase shift between the two halves of the Bragg grating. In this embodiment, the active medium may be the VBG itself, which can be achieved with proper doping with active ions, or the active medium can be attached to the VBG element along the length of the Bragg grating, partially or entirely.

It may be desirable that a laser output include only one (e.g., the lowest) spatial mode, which in free-space resonators has the designation TEM_{00}. This mode has a smooth intensity profile and the lowest possible angular divergence. However, such TEM_{00} operation is often rather difficult to achieve in high-power lasers with high single-pass gain. The techniques for achieving TEM_{00} operation usually rely on the differences in the spatial and angular profile of the TEM_{00} and the higher modes by introducing an element or elements with position-dependent loss (apertures) or angle-dependent loss. VBGs are well suited to serve in either capacity.

Glebov, et al., have disclosed an approach for using a transmission-type VBG element inside a solid-state laser cavity to provide an angle-dependent cavity loss. However, that approach uses a VBG as an intra-cavity folding element that has very high angular sensitivity and requires very delicate and extremely accurate alignment. If the alignment of such a folding element is disturbed, the laser generation will seize, which makes this approach undesirable. A preferred approach would be to use a mode-forming element that by itself does not require critical alignment and, when perturbed, would not stop laser operation, but rather allow higher spatial modes to achieve lasing threshold, at most. This requires an element or elements that have low loss for TEM_{00} mode, have high loss for all higher modes, and do not alter the optical path of the TEM_{00} mode. This class of intra-cavity mode-forming elements may be referred to as "non-folding" mode-forming or mode-stripping elements.

It should be understood that the diffraction efficiency of a VBG element depends on the angle of incidence for a given wavelength of light. For this reason, it will produce an angle-dependent gain/loss profile in the laser cavity. Such a gain profile will create higher losses for spatial modes higher than TEM_{00} and, therefore, can be used for suppressing higher spatial mode in the laser resonator ("mode-stripping"), resulting in a clean TEM_{00} output of the laser.

To function as a spatial mode-stripping device, a VBG element may have a variety of angular diffraction efficiency profiles, such as those provided and described below in connection with FIG. **12**. It should be understood that other possible types of angular profiles of diffraction efficiency of a VBG element may lead to the desired effects on the output of a laser. It should also be understood that reflection and transmission type VBG elements, as well as hybrid elements, may be utilized to achieve the desired effect. The principles of the invention may be applied to any or all of these cases without limitation.

An example embodiment of a non-folding mode-forming element is a VBG mirror with a Gaussian or super-Gaussian reflectivity profile. In this embodiment, a reflective VBG element may have an axially-symmetric reflectivity profile with smooth radial variation of the reflectivity following, preferably, a super-Gaussian shape. Such an element, when used either as an output coupler or the high reflector of the laser cavity, may be designed to overlap spatially with the TEM_{00} mode at that particular location within the resonator, but it would have high losses for all the higher resonator modes. Such a VBG element with a soft aperture may have either plane parallel Bragg planes (e.g., a zero optical power VBG element) or have Bragg planes designed to have a particular curvature (e.g., a VBG element with finite optical power).

Another embodiment includes the use of a transmissive, non-folding VBG element to diffract higher resonator modes away from the resonator optical axis. This approach relies on the high angular selectivity of the transmissive VBGs and may be made with such angular reflectivity profile that the TEM_{00} mode is transmitted through such an element without being diffracted, that is, with little or no loss. Several or all of the higher modes, starting with TEM_{01}/TEM_{10}, may experience sufficient diffraction, and, therefore, loss, such that they do not reach the threshold for lasing. Such a VBG element may or may not have axial symmetry in its angular profile of the diffraction efficiency.

Yet another example embodiment is based on the natural angular selectivity of a reflective VBG. Such a VBG element, serving as the output coupler or the high reflector of the laser cavity, would have high reflectivity for the incident waves of a particular wavelength near the normal to the grating planes, but the reflectivity would drop rapidly for the waves incident upon such VBG element at an angle outside its angular acceptance. Therefore, the VBG element would satisfy the three criteria for non-folding mode-forming elements outlined above.

The amplitude and phase envelope of the VBG may be adjusted in order to produce a desired effect on the temporal profile of ultra-short laser pulses. One particular example is the compensation of pulse chirping produced inside the laser cavity by other elements, such as the laser gain medium.

Detailed Descriptions of Example Embodiments Depicted in The Figures

FIGS. **1**A-C illustrate applications of a VBG as an extra-cavity element for wavelength locking via self-seeding, that is, where the VBG element provides wavelength-selective feedback into the laser cavity. FIG. **1**A shows wavelength locking and narrowing by use of an optical delivery system **104**. Laser-radiation **102** is emitted from the emitting aperture of a laser **100**. The optical delivery system **104** redirects the emitted radiation **102**, as a redirected emission **105**, onto a VBG element **106**. Radiation **107** is reflected by the VBG element **106**. The optical delivery system **104** redirects the reflected radiation **107**, as redirected reflected radiation **103**, back onto the emitting aperture of the laser **100**. The redirected reflected radiation **103** acts as a narrow-wavelength seed, forcing the laser **100** to operate at the wavelength of the VBG **106** and also narrowing its emission spectrum.

As shown in FIG. **1**B, laser radiation **112** is emitted from the emitting aperture of a laser **110**. An optical delivery system **114** collimates the emitted radiation **102**, as collimated radiation **115**, onto a VBG element **116**. The VBG element **116**, having a narrow-wavelength reflectance, reflects at least a portion **117** of the laser energy back through the optical delivery system **114** and into the laser cavity of the laser **110**. The reflected radiation **117** acts as a narrow-wavelength seed, forcing the laser **110** to operate at the wavelength of the VBG **116** and also narrowing its emission spectrum.

FIG. **1**C shows wavelength locking by a VBG element without an optical delivery system. As shown, laser radiation **122** is emitted from the emitting aperture of a laser **120** and is incident onto a VBG element **126**. The VBG element **126**, having a narrow-wavelength reflectance, reflects at least a portion **127** of the laser energy back into the laser cavity of the laser **120**. The reflected radiation **127** acts as a narrow-wavelength seed, forcing the laser **120** to operate at the wavelength of the VBG **126** and also narrowing its emission spectrum.

FIG. **1**D provides plots of wavelength characteristics with and without laser conditioning. As shown, the conditioned radiation (e.g., radiation **103**, **117**, **127**) has a bandwidth, b_2, that is much more narrow than the bandwidth, b_1, of the unconditioned radiation (e.g., radiation **102**, **112**, **122**). Also, the peak intensity I_2 of the conditioned radiation is greater than the peak intensity I_1 of the unconditioned radiation.

FIGS. **2**A and **2**B illustrate wavelength locking using an extra-cavity transmission VBG. The light **132** emitted by a laser **130** may be collimated by a lens **134** and is incident upon a VBG **136**. The portion **135** of the light **132** having a wavelength within the passband of the VBG **136** is diffracted by the VBG **136**, deflected from its original path. The diffracted light **135** is incident upon a reflective surface **138**, which may be formed on the VBG element itself, as shown in FIG. **2**A, or provided as an external element, as shown in FIG. **2**B. Upon being reflected by the surface **138**, the reflected diffracted light **139** is redirected by the VBG element **136**, as redirected light **137** back through the lens **134** and into the laser cavity of the laser **130**. Thus, the laser **130** may be forced to operate at a wavelength determined by the VBG **136**.

FIG. **3** depicts the output of a laser diode bar **140** locked by a single VBG element **146** using a single micro-lens **144**. The radiation output by the laser diode bar **140** may be collimated on an axis (say, the y-axis as shown in FIG. **3**) by the micro-lens **144**, which may be a cylindrical lens, for example, and is incident upon the VBG element **146**. The VBG element **146**, which may have generally the same grating period through its entire volume, reflects at least a portion of the light back into the cavities of the individual emitters **141** in the bar **140**. The effect produced on the output of the emitter array is essentially the same as on an individual emitter. As a result, the output of the entire bar **140** is locked to one wavelength determined by the VBG element **146**.

FIGS. **4**A and **4**B illustrate the use of a cylindrical lens **144** for locking a bar **140** of multimode laser diodes **141**. FIG. **4**A shows a cross-section of the laser diode bar **140**. The light emitted by the laser bar **140** may be collimated or reduced in divergence on the fast axis (y-axis as shown in FIG. **3**) by the cylindrical lens **142** and is incident upon the VBG element **146**. The VBG element **146** reflects some light back into the laser cavity. FIG. **4**B shows the top view of the laser diode bar **140**. The light emitted by the individual emitters **141** in the diode bar **140** is incident upon the cylindrical lens **142**. The slow axis of the emitted light cone is not collimated. It is subsequently incident upon the VBG element and is reflected back onto the face of the diode bar.

FIG. **5** shows how a hybrid optical element **148**, which may be a combined lens and VBG element, can be used for conditioning of an entire array **140** of emitters **141**. The lens portion **146** of the hybrid optical element **148** can be formed directly on the surface of the VBG element **144** or seamlessly fused onto it.

FIG. **6** shows the concept of locking a stack **150** of diode bars **151**. There are several diode bars **152** in the stack **150**, each of which includes a plurality of individual emitters **151** exposed at the face of the stack **150**. The light emerging from the individual emitters **151** may be collimated by a set of cylindrical micro-lenses **154**. Preferably, a respective lens **154** is provided for each diode bar **152** (though it should be understood that other lens arrangements may be used as well). The lenses **154** collimate the fast axes of the bars **152** and the emitted light subsequently enters the VBG element **156**. The VBG element **156** may have essentially the same period grating through its entire volume. The VBG element **156** reflects at least a portion of the incident light back through the lenses **154** onto the face of the stack **150**, with at least a portion of the reflected light entering the cavities of the individual emitters **151**. The result is that the output of the entire stack **150** is locked to the same wavelength determined by the VBG element **156**.

FIG. **7** depicts locking a light emitter **160** by placing a VBG element **166** behind the back facet of the emitter **160**. The back facet of the emitter **160** is partially transmissive to light. The light exiting that facet is collimated by an optical delivery system (e.g., a lens) **164** and then is incident upon the VBG element **166**. The VBG element **166** reflects at least a portion of this light back onto the back facet of the emitter **160**, with at least a portion of the reflected light entering the laser cavity of the emitter **160**. This results in locking the wavelength of the emitter **160** to that of the VBG element **166**.

FIG. **8** depicts producing an array of emitters with different wavelength outputs. This concept may be applied to either one- or two-dimensional arrays. All the emitters **171** in the array **170** may be made from the same material, and, therefore, may have essentially the same natural output wavelength. The light emerging from the individual diode bars **172** in the stack **170** may be collimated by a set of cylindrical micro-lenses **174**. Preferably, a respective lens **174** is provided for each diode bar **172** (though it should be understood that other lens arrangements may be used as well). The lenses **174** collimate the fast axes of the bars **172** and the emitted light subsequently enters the VBG element **176**. The grating period of the VBG element **176** may differ depending on the location along the grating coordinate parallel to the laser bar(s) **172**. The VBG element **176** reflects at least a portion of the incident light back onto the face of the stack **170**, and at least a portion of the reflected light enters the cavities of the individual emitters **171**. As a result, the emitting wavelength of the individual laser diodes **171** in the bar(s) **172** may be locked to different values depending on the location of the emitters **171** relative to the VBG **176**.

FIG. **9** depicts wavelength multiplexing of the output of the wavelength-shifted laser diode bar/stack **170** described in FIG. **8** to produce a higher brightness light source. The output of an array of emitters **170** is conditioned by a lens or lens array **174** and subsequently enters a VBG element **178**. The VBG element **178** has a grating period that may vary depending on the location along the grating coordinate parallel to the array of the emitters **170**. The VBG element **178** thus forces the individual emitters to operate at different wavelengths depending on the location within the array.

The output of such a wavelength-shifted emitter array may be directed into a wavelength multiplexer **180** capable of multiplexing different wavelengths of light into a single output. Such a multiplexer **180** may be constructed using any of a number of well-established techniques, including, but not limited to diffraction gratings, VBG elements, thin-film dielectric filters, arrayed-waveguide grating(s), or any other optical elements or a combination of optical elements capable of delivering this basic function. The output of the entire emitter array **170** may thus be combined into a single spot with essentially all optical power of the entire array concentrated in one spot on a target (not shown), which can be or include, without limitation, an optical fiber, optical fiber array, detector, detector array, emitter, emitter array, solid-state material that needs to be processed (e.g., cut, welded, melted, etc.), liquid, gas, or the like.

FIG. **10** depicts a VBG element **202** inside a laser cavity **200**. The laser cavity **200** may include one or more mirrors **208** (back facet, as shown, or front facet, not shown), a gain medium **206**, conditioning optics **204**, and a VBG element **202**. Preferably, the gain medium **206** may be or include a solid-state, gas, or ion medium, and the conditioning optics may include lenses, mirrors, prisms, birefringent filters, and the like. It should be understood, however, that any type of gain medium and conditioning optics may be used. Also, the gaps shown in FIG. **10** between the individual components within the laser cavity **200** may or may not be employed. The function of the VBG **202** may be spectral, spatial, or temporal conditioning of the laser output.

FIG. **11** provides plots showing how a VBG element can force a laser to operate on a single longitudinal mode. As an example, a VBG element may be used as a partially reflective output coupler. The VBG element has a narrow wavelength reflectivity, considerably narrower than the width of the gain curve of the active medium of the laser. In order to lase, the individual longitudinal modes of the laser resonator have to exceed the lasing threshold. Due to the highly selective reflectivity of a VBG output coupler, however, only one longitudinal mode of the laser cavity has a gain exceeding the lasing threshold.

FIGS. **12**A and **12**B depict a VBG element used as a distributed feedback element of a solid-state laser. As shown in FIG. **12**A, the VBG element **210** can serve as both the active medium and the feedback element. As shown in FIG. **12**B, the VBG element **212** can be attached via an optical contact (e.g., fused) to the active medium **214**. The resonator mode can be formed by either the VBG element itself or some additional elements. Both configurations can be used in free-space or waveguide applications.

Similar to narrow wavelength pass-band, a VBG element may have a narrow angle pass-band, as shown in FIG. **13**. Preferably, the angular passband of the VBG element should be wider than the angular width of the TEM_{00} mode of the laser cavity. Due to the relatively sharp roll-off of the diffraction efficiency of a VBG element with angle of incidence (the laser wavelength is fixed), a higher mode of the laser cavity will experience higher losses and, therefore, will be essentially suppressed by the VBG element. The VBG element thus functions to strip the laser from its higher spatial modes and force it to operate on the TEM_{00} mode only.

As shown in FIGS. **14**A and **14**B, the VBG element has a high diffraction efficiency for the TEM_{00} mode only and produces higher loss for the higher spatial modes. The drawing on the right shows an embodiment of how it can be used in a laser cavity, comprising at least one mirror **224**, a gain medium **222**, and a VBG element **220** functioning as an output coupler. The VBG element **220** may have high reflectivity, and, therefore, low losses, only for the TEM_{00} mode.

By contrast, as shown in FIGS. **14**C and **14**D, the VBG element **230** may have a diffraction efficiency profile with a dip at nearly normal incidence, both in azimuth and elevation angle profile. Therefore, it will have low loss for the TEM_{00} mode in transmission. Such a VBG element **230** may be used as an essentially transparent (i.e., lossless) element inside the laser cavity, which may include at least one mirror **234** and a

gain medium **232**. Feedback may be provided by a conventional output coupler **236**, for example, or by a VBG output coupler with angular diffraction efficiency profile as is shown in FIG. **14**A.

In the embodiment shown in FIG. **14**D, the higher spatial modes will experience diffraction on the VBG element **230** and, therefore, will be directed out of the cavity, producing higher losses for those modes and, therefore, eliminating them. In either case the result is TEM_{00} output of the laser. VBG elements of both transmission and reflection type can be used to achieve TEM_{00} operation. The embodiments depicted in FIGS. **14**B and **14**D are of the so-called "non-folding" type.

FIG. **15** shows a concept for using a reflective VBG element with smoothly varying reflectivity profile ("soft aperture") for inducing simultaneously single longitudinal mode operation of a laser as well as TEM_{00}-only operation. The VBG element **232** depicted in FIG. **15** functions as the output coupler of the laser cavity **230**, and is axially symmetric around the resonator axis Z. The laser cavity **230** may include a high-reflectivity mirror **236** and a gain medium **234**.

FIG. **16** depicts an embodiment suitable for shaping the temporal profile of ultra-short laser pulses. In this embodiment, a VBG element **240** may be used inside a laser cavity having at least one mirror **246**, a gain medium **244**, and other optics **242** (such as lenses, prisms, gratings, and the like). It is known that ultra-short laser pulses (e.g., <10 ps duration) have wide spectral range and will, therefore, likely experience dispersion inside the gain medium. The gain medium may be bulk solid-state, fiber, planar waveguide or any other. Such dispersion is generally undesirable because it leads to broadening of the ultra-short laser pulse. In accordance with an aspect of the invention, the VBG element **240** may be manufactured with a grating period that varies slightly along the axis, z, of the laser. Such a grating may produce slightly different delays for different wavelengths and, therefore, will compensate for the dispersion of the gain medium **244** of the laser. This improves the temporal characteristics of the laser pulse. Alternatively, the same technique may be used for compression of the chirped and stretched high peak power ultra-short pulses subsequent to their amplification in an optical amplifier. The pulses must be stretched prior to the amplification to avoid damage to the amplifier as well as nonlinear effects.

FIGS. **17**A-C depict a VBG element used to construct tunable devices. As shown in FIGS. **17**A and **17**B, light emerging from the cavity of an emitter **250** may be collimated by a lens **252**, if necessary, and incident upon a VBG element **254**/**264**. FIG. **17**A shows an embodiment using a reflective-type VBG element **254**; FIG. **17**B shows an embodiment using a transmissive-type VBG element **256**. The VBG element **254**/**264** reflects or deflects the incident light at an angle onto a folding mirror/reflector **256**. The folding mirror **256** may then redirect the light to a retro-reflector **258**, which reflects the light back on its path. The light retraces it path back into the cavity of the emitter **250**, forcing the emitter **250** to operate at the peak wavelength of the VBG filter. Since the peak wavelength of a VBG element **254**/**264** depends on the incident angle, rotation of the VBG/folding reflector assembly continuously tunes the emitted wavelength of light.

As shown in FIG. **17**C, light emerging from the cavity of an emitter **270** may be collimated by a lens **272**, if necessary, and incident upon a VBG element **274**. The VBG element **274** may have a period and peak wavelength that vary smoothly and continuously as a function of position across its clear aperture. Thus, the device may include a transverse chirp VBG reflector. When such a VBG element is translated across the output beam of the laser the wavelength of the laser emission will change to follow that of the particular location on the VBG element **274**. It should be understood that, in the absence of an emitter, the VBG element (plus auxiliary optics) shown in FIGS. **17**A-**17**C may function as a tunable filter.

FIGS. **18**A and **18**B depict spectral/spatial conditioning of an array of emitters with simultaneous wavelength combining/multiplexing. The light emitted by each of the emitters in the array **284** is depicted going though a particular channel in a wavelength multiplexer **282** positioned in the optical path of light emitted by the array **284**. The multiplexer **282** combines all different wavelength channels **286** into one output channel. The multiplexed light is partially reflected by a retro-reflecting device **280** and the reflected portion of the light retraces its path back into the different emitters in the array **284**. As a result, each emitter in the array **284** receives wavelength-selective feedback and, therefore, will be forced to operate at the wavelength of the multiplexer channel **286** it is coupled to. Efficient spectral and spatial conditioning can be achieved in this way with simultaneous combining of the output of all the emitters in the array. FIG. **18**B depicts an embodiment where such a multiplexer **282** is constructed of a monolithic glass chip with wavelength-specific VBG nodes **288** recorded in its bulk.

FIG. **19** provides a comparison of the output spectrums of free-running and VBG-locked, single-emitter lasers. The laser diode parameters were: 2 mm cavity length, 1×100 μm emitting aperture, and approximately 0.5% front facet reflectivity. The VBG parameters were: approximately 30% maximum reflectivity, and 0.84 mm thickness. Shown in the inset is a comparison of the output spectrums of free-running and VBG-locked laser diode bars. The laser bar parameters were: 19 emitters, 1×150 μm emitting aperture for each emitter, and approximately 17% front facet reflectivity. The VBG parameters were: approximately 60% maximum reflectivity, and 0.9 mm thickness.

FIG. **20** provides plots of output power vs. current for a single-emitter laser diode under different conditions. The laser diode and the VBG parameters were the same as those described in connection with FIG. **19**. The inset provides plots of emission spectra of the laser diode at different currents when free-running and locked by the VBG.

FIG. **21** provides plots of emission wavelength of a single-emitter laser diode as a function of the heatsink temperature when free running w/o FAC lens (circles) and locked by a VBG (squares). Drive current was 1.5 A in both cases. The VBG element was attached to the laser heatsink during the experiment. Shown in the inset is a plot of output power of a locked laser diode (squares) and a fast-axis collimated laser diode (circles) as a function of its heatsink temperature.

FIG. **22** provides plots that demonstrate the effect of VBG locking on the divergence of the slow axis of a single-emitter laser diode. The dotted curve shows the calculated far-field pattern of the light diffracted on the exit aperture of the laser diode.

FIGS. **23**A and **23**B depict extra-cavity doubling of a high-power laser diode frequency. As shown in FIG. **23**A, light emitted by a laser diode **302** with a high-reflectivity (HR) coating on the back facet and an anti-reflection (AR) coating on the front facet is collimated by a lens **304** and is incident upon a VBG element **306**. The VBG element **306** reflects a certain amount of light in a narrow spectral region. The reflected light is directed back into the cavity of the laser diode **302**, thus locking the frequency of the laser emission to that of the peak reflectivity of the VBG element **306**. The VBG element **306** also narrows the emission bandwidth of the laser **302**, making it equal to or smaller than the acceptance

bandwidth of the quasi-phase-matched (QPM) nonlinear crystal **310**. The nonlinear crystal **310** is periodically poled to achieve QPM. The light that passes through the VBG element **306** may be focused into the QPM crystal **310** by a lens **308**. The QPM crystal **310** generates the second harmonic of the light emitted by the laser diode **302**. The QPM crystal **310** preferably has AR coating for the fundamental and the second harmonic on both facets. Light out of the QPM crystal **310** may be redirected through another lens **312**.

As shown in FIG. **23**B, the VBG element **326** locks the frequency and narrows the emission spectrum of the laser diode **322**. The laser diode **322** may have the same characteristics as described above in connection with FIG. **23**A. The emitted light is focused into a QPM nonlinear waveguide **330**, which generates the second harmonic of the incident light. The QPM nonlinear waveguide **330** preferably has AR coating for the fundamental and the second harmonic on both facets. Lenses **324**, **328**, and **332** may be provided as desired.

FIGS. **24**A-C depict extra-cavity doubling of a high-power laser diode frequency. Light emitted through the back facet by a laser diode **344** with AR coating on both facets is collimated by a lens **342** and is incident upon a VBG element **340**. The VBG element **340** reflects most of the light in a narrow spectral region. The reflected light is directed back into the laser cavity, thus forming an external cavity and locking the frequency of the laser emission to that of the peak reflectivity of the VBG element **340**. The front facet of the laser **344** should have enough reflectivity for the laser **344** to operate above threshold and at a desired output power level. The VBG element **340** also narrows the emission bandwidth of the laser **344**, making it equal to or smaller than the acceptance bandwidth of the quasi-phase-matched (QPM) nonlinear crystal **348**. A lens **346** may be used to focus the light into the QPM crystal **348**, which then generates the second harmonic of the incident light. The QPM crystal **348** preferably has AR coating for the fundamental and the second harmonic on both facets. A lens **349** may be used to focus the light output from the QPM crystal.

As shown in FIG. **24**B, the light emitted by the laser diode **344** may be focused into a QPM nonlinear waveguide **358**, via a lens **356**. The waveguide **358** may generate the second harmonic of the incident light. The QPM nonlinear waveguide **358** preferably has AR coating for the fundamental and the second harmonic on both facets. As shown in FIG. **24**C, the QPM nonlinear waveguide **358** abuts the laser diode **344** so that most of the light emitted by the laser diode **344** is coupled into the QPM waveguide **358**.

FIGS. **25**A and **25**B depict intra-cavity doubling of a high-power laser diode frequency. FIG. **25**A depicts a high-power laser diode **370** having HR coating on the back facet and very low reflectivity AR coating on the front facet. The external cavity of the laser diode **370** may be formed by a VBG element **371** positioned after a collimating lens **379**. A QPM crystal **378** may be placed between the VBG element **371** and the front facet of the laser diode **370**, and between a lens pair **376**, **379** that focuses the light into the QPM crystal **378**. By having the QPM crystal **378** positioned inside the external cavity of the laser diode **370**, the power of the fundamental harmonic of the laser diode **370** can be increased, thus increasing the conversion efficiency from the fundamental to the second harmonic. A window **374** with AR coating for the fundamental harmonic and HR coating for the second harmonic can be placed between the front facet of the laser diode **370** and the QPM crystal **378** in order to increase the total power of the second harmonic emitted by this device. The QPM crystal **378** preferably has AR coating for the fundamental and the second harmonic on both facets.

As shown in FIG. **25**B, the laser diode **370** may abut a QPM nonlinear waveguide **388**. Preferably, the waveguide **388** has AR coating for the fundamental harmonic of light emitted by the laser diode **370** and HR coating for the second harmonic on its front facet (i.e., the one facing the laser diode **370**). The back facet of the QPM nonlinear waveguide **388** preferably has AR coating for both the fundamental and the second harmonic.

Thus, there have been described example embodiments of apparatus and methods for conditioning laser characteristics using volume Bragg grating elements. It will be appreciated that modifications may be made to the disclosed embodiments without departing from the spirit of the invention. The scope of protection, therefore, is defined by the following claims.

What is claimed:

1. Apparatus for altering a characteristic of a light-emitting device, the apparatus comprising:

a light-emitting device having an emission spectrum;

a cylindrical microlens that receives light emitted by the light-emitting device; and

a three-dimensional optical element comprising a bulk of optical material and having a Bragg grating recorded in the bulk of optical material,

wherein the three-dimensional optical element receives light directed from the microlens, the light received by the optical element having a first bandwidth, and redirects only a narrowband portion of the light received from the microlens, the redirected narrowband portion having a second bandwidth that is narrower than the first bandwidth, such that the redirected narrowband portion is fed back optically into the light-emitting device as a narrow-wavelength seed that causes a narrowing of the emission spectrum of the light-emitting device, and wherein the light emitting device has a fast axis and a slow axis, and wherein the microlens collimates the light emitted by the light-emitting device along the fast axis of the light-emitting device.

2. Apparatus according to claim **1**, wherein the light emitting device has a fast axis and a slow axis, and wherein the microlens reduces divergence of the light emitted by the light-emitting device along the fast axis of the light-emitting device.

3. Apparatus according to claim **1**, wherein the three-dimensional optical element provides external feedback to the light-emitting device.

4. Apparatus according to claim **1**, wherein the lens has a focal length in the range of about 0.05 mm to about 3.0 mm.

5. Apparatus according to claim **1**, wherein the three-dimensional optical element has a thickness in a range from about 0.2 mm to about 3.0 mm, and a reflectivity in a range from about 5 percent to about 60 percent.

6. Apparatus according to claim **1**, wherein the three-dimensional optical element is positioned at a distance behind the microlens, the distance being in a range from about 0 mm to about 10 mm.

7. Apparatus according to claim **1**, wherein the microlens is formed on or attached to a surface of the three-dimensional optical element thus forming an integral optical element.

8. Apparatus according to claim **1**, wherein the light emitting device has a fast axis and a slow axis, and wherein the microlens does not collimate the light emitted by the light-emitting device along the slow axis of the light-emitting device.

9. Apparatus according to claim **1**, wherein the microlens does not collimate the light emitted by the light-emitting device along the slow axis of the light-emitting device.

10. Apparatus according to claim 9, further comprising a second microlens that collimates the light emitted by the light-emitting device along the slow axis of the light-emitting device.

11. Apparatus for altering a characteristic of a light-emitting device, the apparatus comprising:

a laser having a laser cavity and an emission spectrum;

a cylindrical microlens that receives laser light emitted by the laser, the emitted laser light having a first bandwidth; and

a light-conditioning element comprising a three-dimensional Bragg grating element having a holographic Bragg grating recorded therein,

wherein the light-conditioning element receives laser light directed from the microlens, and

wherein the laser operates above threshold in the absence of the feedback, and the Bragg grating is adapted to redirect a portion of the laser light received from the microlens, the redirected portion of the laser light having a second bandwidth that is narrower than the first bandwidth, such that the redirected portion is fed back optically into the laser cavity as a narrow wavelength seed that causes a narrowing of the emission spectrum of the laser.

12. Apparatus according to claim 11, wherein the light emitting device has a fast axis and a slow axis, and wherein the microlens collimates the light emitted by the light-emitting device along the fast axis of the light-emitting device.

13. Apparatus according to claim 11, wherein the light emitting device has a fast axis and a slow axis, and wherein the microlens reduces divergence of the light emitted by the light-emitting device along the fast axis of the light-emitting device.

14. Apparatus according to claim 11, wherein the three-dimensional optical element provides external feedback to the light-emitting device.

15. Apparatus according to claim 11, wherein the microlens is formed on or attached to a surface of the three-dimensional optical element thus forming an integral optical element.

16. Apparatus according to claim 11, wherein the light emitting device has a fast axis and a slow axis, and wherein the microlens does not collimate the light emitted by the light-emitting device along the slow axis of the light-emitting device.

17. Apparatus according to claim 11, wherein the light emitting device has a fast axis and a slow axis, and wherein the microlens does not collimate the light emitted by the light-emitting device along the fast axis of the light-emitting device.

18. Apparatus according to claim 12, wherein the microlens does not collimate the light emitted by the light-emitting device along the slow axis of the light-emitting device.

19. Apparatus according to claim 11, further comprising a second microlens that collimates the light emitted by the light-emitting device along the slow axis of the light-emitting device.

* * * * *