Robert F. Kramer (State Bar No. 181706)
Stephanie R. Wood (State Bar No. 242572)
NOVAK DRUCE + QUIGG LLP
555 Mission Street
Thirty-Fourth Floor
San Francisco, CA 94105
Telephone: (415) 814-6161
Facsimile: (415) 814-6165
Email: robert.kramer@novakdruce.com
Email:stephanie.wood@novakdruce.com

Attorneys for Plaintiff
AVAGO TECHNOLOGIES FIBER IP
(SINGAPORE) PTE. LTD.

FILED 2010 JUN 29 P 12:44

E-filing

IN THE UNITED STATES DISTRICT COURT

FOR THE NORTHERN DISTRICT OF CALIFORNIA

SAN FRANCISCO DIVISION

JL

AVAGO TECHNOLOGIES FIBER IP (SINGAPORE) PTE. LTD.,

Plaintiff,

v.

IPTRONICS INC. and IPTRONICS A/S,

Defendants.

CV Case No.: 10 2863

COMPLAINT FOR PATENT INFRINGEMENT

DEMAND FOR JURY TRIAL

Plaintiff Avago Fiber IP (Singapore) Pte. Ltd. ("Avago"), by its undersigned attorneys, alleges in its Complaint for Patent Infringement against Defendants, IPtronics Inc. and IPtronics A/S as follows:

NATURE OF THIS ACTION

1. This civil action arises out of patent infringement under the Patent Laws of the United States, 35 U.S.C. § 1 *et seq*., and, in particular, 35 U.S.C. § 271.

2. Plaintiff seeks relief from Defendants' infringement of Plaintiff's patent rights under United States Patent Nos. 5,359,447 and 6,947,456 as set forth more fully below.

THE PARTIES

3. Plaintiff Avago Fiber IP (Singapore) Pte. Ltd. is a corporation organized and existing under the laws of the Republic of Singapore and having a principal place of doing business at No. 1 Yishun Avenue 7 Singapore 768923.

4. Plaintiff is a subsidiary of Avago Technologies Ltd. Avago Technologies Ltd.'s subsidiary(ies) conduct research and development, and sales and marketing of products covered by the patents asserted herein, and have a place of business within this judicial district at 350 West Trimble Road, Building 90, San Jose, California 95131.

5. Upon information and belief, Defendant IPtronics Inc. is a corporation organized and existing under the laws of the state of Delaware, having its principal place of business at 1370 Willow Road, 2nd Floor, Menlo Park, California 94025, within this judicial district.

6. Upon information and belief, Defendant IPtronics A/S, is a corporation organized and existing under the laws of the Kingdom of Denmark, having its principal place of business at Langebjergvaenget 8B, st. th., DK-4000 Roskilde, Denmark.

7. Upon information and belief, Defendant IPtronics Inc. is a wholly owned subsidiary of Defendant IPtronics A/S.

JURISDICTION

8. This Court has exclusive subject matter jurisdiction over this action pursuant to 28 U.S. C. §§ 1331 and 1338(a).

9. This Court has personal jurisdiction over Defendant IPtronics Inc. which resides within this judicial district, does business within the State of California and within this judicial district, and has committed acts of infringement within this judicial district.

10. This Court has personal jurisdiction over Defendant IPtronics A/S, which does business within the State of California and within this judicial district, and has committed acts of infringement within this judicial district and/or has advertised or otherwise promoted its products and placed its products within the stream of commerce with the expectation and/or knowledge that such products would be purchased by customers and/or used by customers within this judicial district and pursuant to California Code of Civil Procedure § 410.10.

11. Defendant IPtronics A/S maintains a website promoting its laser driver and transimpedance and limiting amplifier products ("the accused products") that is accessible in the United States including in this judicial district.

12. Defendant IPtronics A/S solicits orders for, and/or offers to sell, and/or sells the accused products to, or on behalf of, entities in the United States including entities located within this judicial district.

13. Defendant IPtronics A/S exports, or arranges for and/or directs the export of the accused products to, or on behalf of entities located in the United States including entities located within this judicial district.

14. Defendant IPtronics A/S knows, and/or has the expectation and/or understanding that all of its laser driver products are sold for use in combination with vertical cavity surface emitting lasers ("VCSELs") in United States including at least this judicial district.

15. Defendant IPtronics A/S describes its laser driver products and transimpedance and limiting amplifier products as "complementary chip set[s],"and thus knows, and/or has the expectation and/or understanding that the accused products are sold, and/or used in combination with VCSELs in the United States including at least this judicial district.

16. Upon information and belief, Defendant IPtronics A/S imports laser driver products and/or transimpedance and limiting amplifier products into the United States for sale in the United States.

17. Upon information and belief, the conduct of Defendant IPtronics A/S as alleged herein has been systematic and continuous within the Northern District of California.

18. Upon information and belief, Defendant IPtronics, Inc. offers for sale, sells, imports, sells after importation, and/or arranges for the importation for sale of laser driver products and/or transimpedance and limiting amplifier products based from its location within the Northern District of California.

VENUE

19. Venue is proper in this judicial district at least pursuant to 28 U.S.C. §§ 1391(b) and (d) and 1400(b) because, upon information and belief, various acts and transactions constituting at least a substantial portion of the claims arose in this judicial district. Venue is also proper in this judicial district as to Defendant IPtronics, Inc. because such Defendant is subject to personal jurisdiction in this judicial district pursuant to 28 U.S.C. § 1391(c).

INTRADISTRICT ASSIGNMENT

20. Pursuant to Civil L.R. 3-2(c), this is an Intellectual Property Action and is subject to district-wide assignment.

COUNT ONE: INFRINGEMENT OF U.S. PATENT NO. 5,359,477

21. Plaintiff incorporates by reference Paragraphs 1 through 20 as if fully set forth herein.

22. United States Patent No. 5,359,447 (the "'447 patent"), entitled "Optical Communication with Vertical-Cavity Surface-Emitting Laser Operating in Multiple Transverse Modes," duly and legally issued on October 25, 1994. A true and correct copy of the '447 patent is attached hereto as Exhibit 1.

23. Plaintiff is the owner by assignment of all rights, title and interest in the '447 patent, including the right to sue and recover for past infringement.

24. A vertical cavity surface emitting laser is referred to as a VCSEL.

25. A plurality of VCSELs arranged in rows and/or columns is referred to as a VCSEL array.

26. The '447 patent relates in general terms to an optical communication network which includes a VCSEL, a power supply providing a current such that the VCSEL operates in multiple transverse modes, and a multimode optical medium optically coupled to the VCSEL to carry an optical signal from the VCSEL to a receiver.

27. Within the six-year period preceding the filing of this Complaint, on information and belief, Defendants advertised for sale, offered for sale, imported and/or sold within the United States various driver circuits for VCSELs for use in optical communication networks including, by way of example and not by way of limitation as to infringing products, IPVD12G011 and IPVD3x4 VCSEL drivers.

28. Within the six-year period preceding the filing of this Complaint, on information and belief, Defendants advertised for sale, offered for sale, imported and/or sold within the United States various components for use in optical communication networks including by way of example and not by way of limitation as to infringing products, IPTA12G011 and IPTA3x4 transimpedance and limiting amplifiers.

29. Defendants, in their publication "Parallel Optical Interconnects," instruct how to couple the products identified in the immediately preceding two paragraphs with an optical coupling medium and with VCSELs to provide an optical communication network.

30. Defendants, in their publication "Reference Design," also instruct how to couple the products identified in the preceding paragraphs with an optical coupling medium and with VCSELs to provide an optical communication network.

31. On information and belief, the VCSEL arrays in Defendants' "Reference Design" publication operate in multiple transverse modes, at least when used as instructed by Defendants.

32. An optical communication network using one or more of Defendants' products as described in this Count One literally infringes at least one or more claims of the '447 patent if the VCSEL aperture has a diameter of at least 8 microns.

33. An optical communication network using one or more of Defendants' products as described in this Count One infringes one or more claims of the '447 patent under the doctrine of equivalents if the VCSEL aperture has a diameter of 8 microns or less.

34. Defendants do not advertise or otherwise promote their products identified in this Count One for any use other than in an optical communication network covered by one or more claims of the '447 patent.

35. There is no substantial known use for Defendants' products identified in this Count One other than in an optical communication network covered by one or more claims of the '447 patent.

36. Upon information and belief, customers and/or end users of Defendants' products identified in this Count One directly infringe at least the aforementioned claim(s) of the '447 patent.

37. Upon information and belief, Defendants had knowledge of the '447 patent prior to the filing of this civil action. In the alternative, the filing of this civil action constitutes notice of Plaintiff's patent rights.

38. Defendants' activities as complained of in this Count One contribute to infringement of one or more claims of the '447 patent.

39. Defendants' activities as complained of in this Count One constitutes active inducement of infringement of one or more claims of the '447 patent.

40. Upon information and belief Defendants' infringement of the '447 patent has been willful.

41. The activities of Defendants as complained of in this Count One have injured and been to the detriment of Plaintiff and as a result thereof, Plaintiff is entitled to recover damages adequate to compensate it for the infringement complained of herein, but in no event less than a reasonable royalty.

42. The activities of Defendants as complained of in this Count One have caused and will continued to cause Plaintiff substantial damage and irreparable injury by virtue of their past and

continuing infringement, and Defendants will continue to infringe the '447 patent, causing Plaintiff to suffer further damage and irreparable injury unless and until enjoined by this Court.

COUNT TWO: INFRINGEMENT OF U.S. PATENT NO. 6,947,456

43. Plaintiff incorporates by reference Paragraphs 1 through 42 as if fully set forth herein.

44. United States Patent No. 6,947,456 (the "'456 patent"), entitled "Open-Loop Laser Driver having an Integrated Digital Controller," duly and legally issued on September 20, 2005. A true and correct copy of the '456 patent is attached hereto as Exhibit 2.

45. Plaintiff is the owner by assignment of all rights, title and interest in the '456 patent including the right to sue and recover for past infringement.

46. Within the six-year period preceding the filing of this Complaint, on information and belief, Defendants advertised for sale, offered for sale, imported and/or sold within the United States various laser driver circuits for an array of VCSELs including, by way of example and not by way of limitation to two infringing products, the IPVD12G011 and IPVD3x4 VCSEL drivers, each of which is for an array of VCSELs.

47. A "bit rate" is the speed at which data is transmitted and, with respect to at least Defendants' products identified in this Count Two, may be from about 5 to about 12.5 Gb/s.

48. On information and belief, at least Defendants' laser driver circuits referred to in this Count Two literally infringe one or more claims of the '456 patent, including when operated at bit rates above 5 Gb/s and when used with an array of VCSELs, as instructed by Defendants' "Reference Design" publication referred to above in paragraph 30.

49. Defendants, in their publications referred to herein above, instruct how to connect and use Defendants' laser driver circuits with VCSEL arrays.

50. On information and belief, a laser array using one or more of Defendants' products described in this Count Two literally infringes one or more claims of the '456 patent, including when operated at bit rates above 5 Gb/s.

51. Defendants do not advertise or otherwise promote their products identified in this Count Two for any use other than with an array of VCSELs.

52. There is no substantial known use for Defendants' products, including those identified in this Count Two, other than with an array of VCSELs.

53. Upon information and belief, customers and/or end users of Defendants' products identified in this Count Two literally infringe one or more claims of the '456 patent.

54. Upon information and belief, Defendants had knowledge of the '456 patent prior to the filing of this civil action. In the alternative, the filing of this civil action constitutes notice of Plaintiff's patent rights.

55. Defendants' activities as complained of in this Count Two contribute to infringement of one or more claims of the '456 patent.

56. Defendants' activities as complained of in this Count Two constitutes active inducement of infringement of one or more claims of the '456 patent.

57. Upon information and belief Defendants' infringement of the '456 patent has been willful.

58. The activities of Defendants as complained of in this Count Two have been to the injury and detriment of Plaintiff and as a result thereof, Plaintiff is entitled to recover damages adequate to compensate it for the infringement complained of herein, but in no event less than a reasonable royalty.

59. The activities of Defendants as complained of in this Count Two have caused and will continued to cause Plaintiff substantial damage and irreparable injury by virtue of their past and continuing infringement, and Defendants will continue to infringe the '456 patent, causing Plaintiff to suffer further damage and irreparable injury unless and until Defendants are enjoined by this Court.

DEMAND FOR JURY TRIAL

Plaintiff hereby demands a jury trial of all issues in the above-captioned action which are triable to a jury.

PRAYER FOR RELIEF

WHEREFORE, PLAINTIFF prays for relief against Defendants as follows:

a. Judgment that Defendants have contributorily infringed one or more claims of the '447 patent;

b. Judgment that Defendants have actively induced infringement one or more claims of the '447 patent;

c. Judgment that Defendants have directly infringed one or more claims of the '456 patent;

d. Judgment that Defendants have contributorily infringed one or more claims of the '456 patent;

e. Judgment that Defendants have actively induced infringement of one or more claims of the '456 patent;

f. A preliminary and permanent injunction enjoining Defendants, its officers, agents, servants, employees, representatives, licensees, successors, assigns, and those persons in active concert or participation with any of them, from directly or indirectly infringing the '447 patent;

g. A preliminary and permanent injunction enjoining Defendants, its officers, agents, servants, employees, representatives, licensees, successors, assigns, and those persons in active concert or participation with any of them, from directly or indirectly infringing the '456 patent;

h. Awarding Plaintiff damages adequate to compensate it for the infringement of the '447 patent but in no event less than a reasonable royalty for use of the invention together with interest and costs under 35 U.S.C. § 284;

i. Awarding Plaintiff damages adequate to compensate it for the infringement of the '456 patent but in no event less than a reasonable royalty for use of the invention together with interest and costs under 35 U.S.C. § 284;

j. Awarding pre-judgment and post-judgment interest on the damages assessed;

k. Awarding treble damages on the damages assessed if the infringement is determined to be willful;

l. Awarding to Plaintiff such other and further relief as the Court deems just and proper.

Dated: June 29, 2010

Respectfully submitted,

NOVAK DRUCE + QUIGG LLP

Robert F. Kramer (State Bar No. 181706)
Attorneys for Plaintiff
AVAGO TECHNOLOGIES FIBER IP (SINGAPORE) PTE. LTD.

EXHIBIT 1

US005359447A

United States Patent [19]

Hahn et al.

[11] Patent Number: 5,359,447

[45] Date of Patent: Oct. 25, 1994

[54] OPTICAL COMMUNICATION WITH VERTICAL-CAVITY SURFACE-EMITTING LASER OPERATING IN MULTIPLE TRANSVERSE MODES

[75] Inventors: Kenneth H. Hahn, Cupertino; Michael R. T. Tan, Mountain View; Shih-Yuan Wang, Palo Alto, all of Calif.

[73] Assignee: Hewlett-Packard Company, Palo Alto, Calif.

[21] Appl. No.: 83,739

[22] Filed: Jun. 25, 1993

[51] Int. Cl.^{5} H04B 10/00

[52] U.S. Cl. 359/154; 359/173; 372/38

[58] Field of Search 359/154, 161, 173, 180, 359/188, 195; 372/38, 45

[56] References Cited

U.S. PATENT DOCUMENTS

5,025,487	6/1991	Eichen	359/154
5,125,054	6/1992	Ackley et al.	385/49
5,140,452	8/1992	Yamamoto et al.	359/154
5,224,183	6/1993	Dugan	359/161
5,249,245	9/1993	Lebby et al.	385/89

OTHER PUBLICATIONS

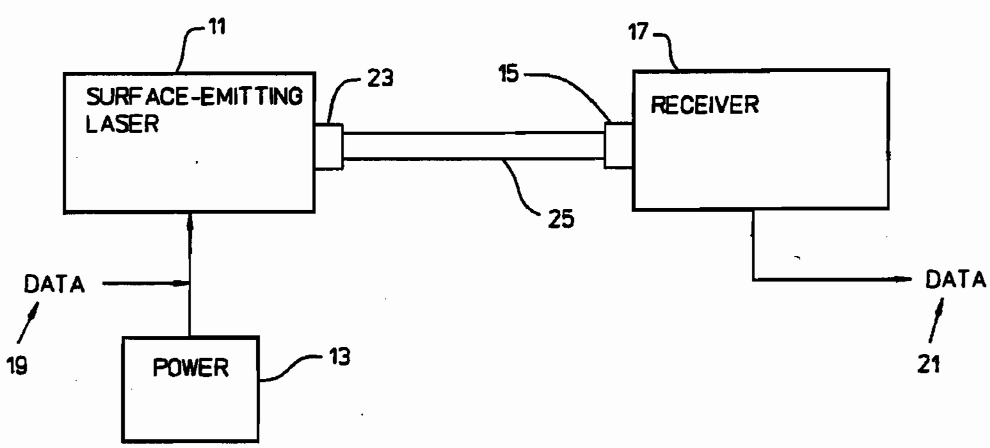
Banwell et al. "VCSE Laser Transmitters for Parallel Data Lines", IEEE Journal of Quantum Electronics, vol. 29, No. 2, Feb. 1993.

Primary Examiner—Richard E. Chilcot, Jr.
Assistant Examiner—Kinfe-Michael Negash

[57] ABSTRACT

An optical communication system using a relatively large-area vertical-cavity surface-emitting laser. The laser has an opening larger than about eight micrometers and is coupled to a multimode optical fiber. The laser is driven into multiple transverse mode operation, which includes multiple filamentation as well as operation in a single cavity.

6 Claims, 2 Drawing Sheets



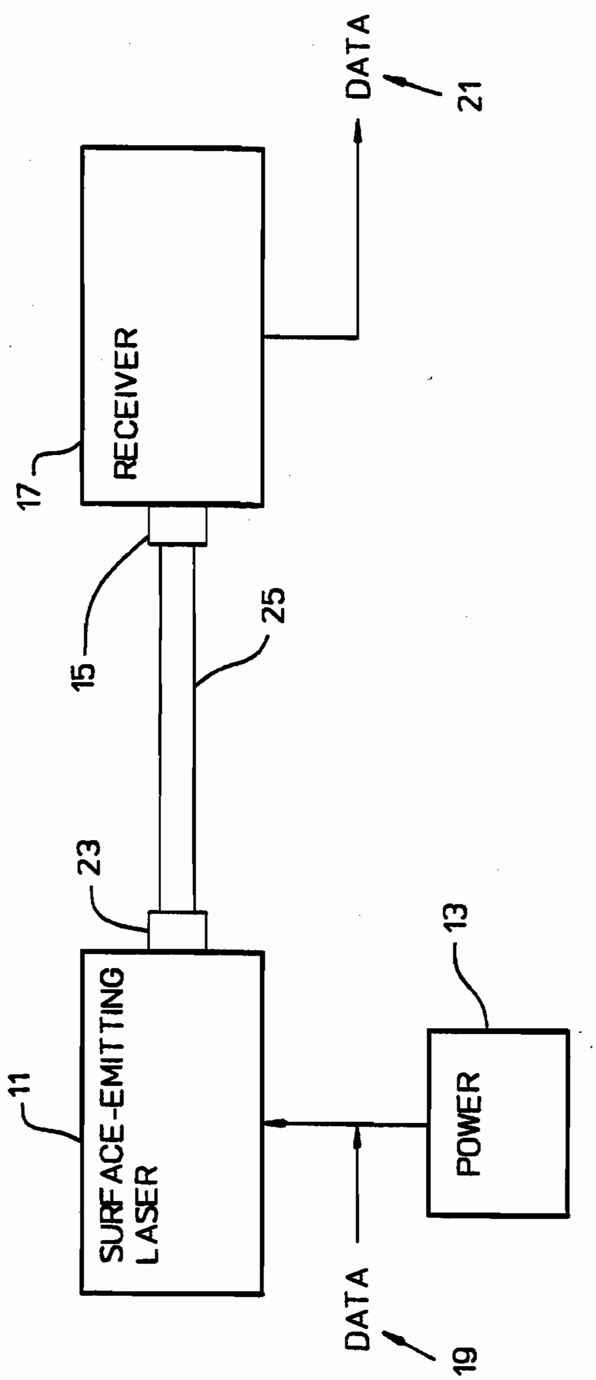

DATA
21
RECEIVER
17
15
25
23
13
11
SURFACE-EMITTING
LASER
POWER
DATA
19

FIG. 1

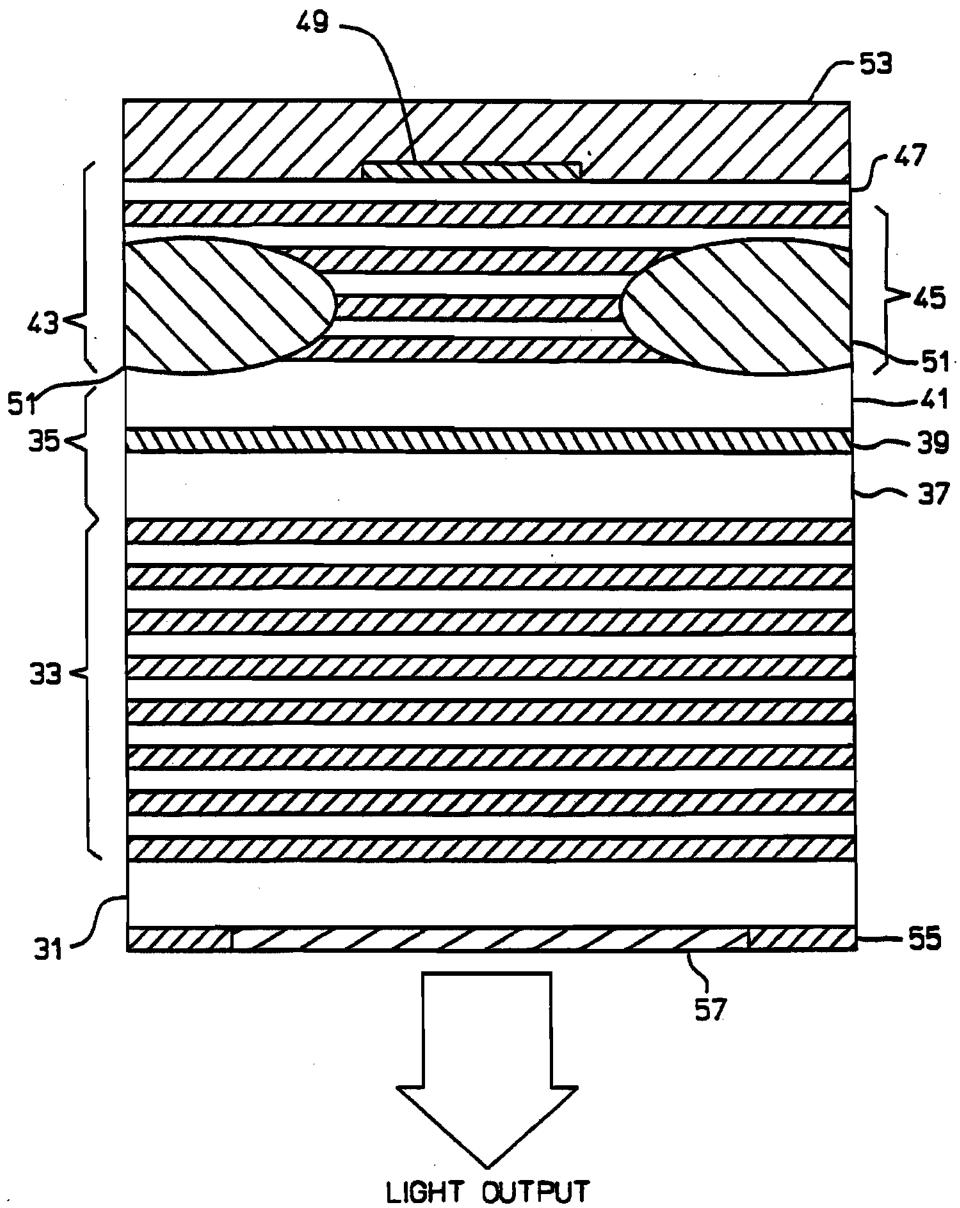


FIG. 2

OPTICAL COMMUNICATION WITH VERTICAL-CAVITY SURFACE-EMITTING LASER OPERATING IN MULTIPLE TRANSVERSE MODES

BACKGROUND OF THE INVENTION

The present invention relates generally to optical transmission of signals and more particularly to an optical communication network of the kind having a multimode optical fiber that receives a multiple mode beam of light from a vertical-cavity, surface-emitting laser being operated in multiple modes or multiple filamentation.

Optical communication systems are used to carry information from one location to another. One of the advantages of optical systems is that they have extremely wide bandwidths. This means that optical systems can carry much more information than can other kinds of communication systems such as radio or microwave. For example, nearly all long-distance telephone calls are carried by optical communication systems because a single optical fiber can carry thousands of conversations at the same time. Optical systems also offer the potential of carrying large quantities of digital data for high-speed computers more efficiently and economically than other communication systems.

Every optical communication system includes, at a minimum, three elements: a transmitter that generates a beam of light and modulates the beam with data to be transmitted, a receiver that receives the beam of light and recovers the data from it, and a medium such as an optical fiber that carries the beam of light from the transmitter to the receiver. Typically the transmitter uses a laser or a light-emitting diode ("LED") to generate the light beam. The receiver uses photodetectors or the like to receive the beam. The medium may be an optical waveguide or the like instead of an optical fiber.

Light may travel through an optical medium in single mode or multiple modes. In general, a "mode" of an electromagnetic wave can be defined as a stationary pattern of the wave. In the special case of a beam of light (which may be thought of as an electromagnetic wave in the optical portion of the spectrum), a mode is a wave pattern that does not change the shape of its transverse field distribution as it propagates through the medium.

A given optical medium may be capable of supporting many modes or only a single mode. This is determined by physical parameters such as—in the case of an optical fiber—the diameter of the fiber and the difference between the indices of refraction of the core and the cladding.

Likewise, many lasers can be caused to operate in single mode or in multiple modes. This can be done by a suitable choice of device structure and drive conditions. Multiple mode operation has generally been understood to consist of multiple modes in one laser cavity. However, studies have shown that multiple mode laser operation can occur with filamentation due to non-uniform gain or loss. This is especially true for lasers with large transverse dimensions compared with the wavelength. For convenience, the terms "multiple mode" and "multimode" as used herein to describe the operation of a laser will include both multiple modes in a single laser cavity and multiple filamentation.

Optical communication systems are subject to various kinds of losses and limitations. Among these are intermodal dispersion, chromatic dispersion and mode selective losses. All of these have the effect of decreasing the signal-to-noise ratio, and therefore it is desirable to eliminate or minimize them as much as possible.

Intermodal dispersion becomes worse as the length of the fiber increases. Intermodal dispersion only affects multimode fibers, and therefore single mode fibers are preferred for communication over long distances. As used herein, a "long" distance means a distance that is more than a few hundred meters and a "short" distance is one that is less than a few hundred meters. Of course, it should be understood that this is an approximation; multimode fibers up to a few kilometers in length have been used successfully, but usually when the required length of the fiber exceeds a couple of hundred meters a single mode fiber will be used.

Chromatic dispersion also becomes more severe as the length of the fiber increases but, unlike intermodal dispersion, chromatic dispersion affects both single mode and multimode fibers. The adverse effects of chromatic dispersion can be minimized by using a highly coherent laser because such a laser produces a light beam of very narrow spectral width. Accordingly, highly coherent lasers have been preferred for most optical communication systems, especially for communication over long distances.

Of course, single mode optical fibers can also be used over short distances (less than a few hundred meters), for example to carry digital data from one computer to another in a local network or even to carry data between points less than a meter apart within a single computer. However, multimode optical fibers are preferred for short-distance optical communication systems because their relative ease of packaging and alignment makes them considerably less expensive than single mode fibers.

A drawback of multimode optical media has been that these media are subject to mode selective losses. A mode selective loss may be characterized as a physical condition that affects the optical characteristics of the medium. These losses may be, for example, splices in the medium, power splitters and other devices that are connected to the medium, and physical defects such as poor quality connections and misalignment of components. Although such physical conditions can be reduced by careful design and construction, in practice it is rarely possible to produce a system that is totally free of them. Therefore, all practically realizable multimode optical communication systems will be subject to at least some mode selective losses.

The actual mechanism by which physical discontinuities produce mode selective losses will now be briefly discussed. Interference between different modes in a multimode medium carrying a coherent light beam produces a speckle pattern. Ideally this speckle pattern would remain stationary, but in practice it moves about within the medium. Speckle pattern movement may be caused by physical jostling or other movement of the fiber itself (relatively slow movement) or by laser mode partitioning and the like (relatively fast movement). Movement of the speckle pattern in a system having mode selective losses results in power variations in the received signal. These variations are caused by the mode selective losses and result in a degradation of the signal-to-noise ratio. In digital systems, a degradation of the signal-to-noise ratio manifests itself as an increased bit error rate.

Mode selective losses are described in more detail in such references as Epsworth, R. E., "The Phenomenon of Modal Noise in Analogue and Digital Optical Fibre Systems", *Proceedings of the 4th European Conference on Optical Communications*, Genoa, September, 1978, pp. 492–501, and in Kanada, T., "Evaluation of Modal Noise in Multimode Fiber-Optic Systems", *IEEE Journal of Lightwave Technology*, 1984, LT-2, pp. 11–18.

Mode selective losses can be avoided by using a relatively low-coherence light source such as an LED or a self-pulsating laser diode ("SPLD") rather than a highly coherent laser. The use of LEDs in optical communication systems is described in Soderstrom, R., et al., "Low Cost High Performance Components of Computer Optical Data Links", *Proceedings of the IEEE Laser and Electrooptics Society Meeting*, Orlando, Fla. 1989. A disadvantage of using LEDs in optical communication systems is that the coupling efficiency between an LED and an optical fiber is very low. In addition, LEDs are inherently slow, which limits the maximum data rate.

SPLDs have been used in such systems as the Hewlett-Packard HOLC-0266 Mbaud Fiber Channel multimode fiber data link, manufactured by the assignee hereof; this is described in Bates, R. J. S., "Multimode Waveguide Computer Data Links with Self-Pulsating Laser Diodes", *Proceedings of the International Topical Meeting on Optical Computing*, Kobe, Japan, April, 1990, pp. 89–90. The coupling efficiency between an SPLD and an optical fiber is better than that between an LED and an optical fiber, but still is not optimal. In addition, the maximum data rate that can be achieved with an SPLD is limited. Neither SPLD nor LED systems have been able to achieve reliable data rates as high as 1 gigabit per second

From the foregoing it will be apparent that there remains a need for a reliable and economical way to carry data at rates exceeding one gigabit per second by means of optical communication systems operating over short distances.

SUMMARY OF THE INVENTION

The present invention provides an optical communication system that can transmit data reliably and economically by means of multimode optical media at any rate up to and exceeding one gigabit per second.

Briefly and in general terms, the invention is embodied in an optical communication system having a vertical-cavity, surface-emitting laser ("SEL"). A multimode optical medium such as an optical fiber is coupled to the SEL. A power supply provides a bias current that drives the SEL into multiple transverse mode operation, preferably in more than two distinct modes. The SEL generates a beam of light that has a lower coherence than that provided by a single-mode laser. This beam of light is modulated with data carried by an incoming signal. The SEL preferably has an aperture larger than about eight micrometers ("μm") through which the modulated light beam is emitted.

The optical medium carries the modulated beam of light from the SEL to a receiver at a remote location. The receiver, which may be closer than a meter or farther away than 100 meters, recovers the data from the light beam.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a preferred embodiment of an optical communication system according to the invention; and

FIG. 2 is a cross-sectional view of a vertical-cavity, surface-emitting laser of the kind used in the communication system shown in FIG. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENT

As shown in the drawings for purposes of illustration, the invention is embodied in a novel optical communication system having a vertical-cavity, surface-emitting laser ("SEL") driven into multiple transverse mode operation to provide a light beam that carries data reliably and efficiently over a multimode optical medium. To avoid the expense of single mode fibers for communicating over distances of less than a few hundred meters, existing optical communication systems have used multimode fibers, but such systems have been subject to unacceptably high mode selection losses or have used low-coherence light sources such as LEDs and SPLDs that have not been able to achieve sufficiently high data rates.

A communication system according to the invention uses an SEL operating in multiple transverse modes. The SEL provides a beam of light that has lower coherence than the highly-coherent light beams typically used in single mode systems but higher coherence than the low-coherence beams provided by LEDs and self-pulsating lasers. A multimode optical medium carries the beam from the SEL to a receiver which may be less than a meter away or 100 meters or more distant. The system can transmit data at any rate up to and exceeding 1.5 gigabits per second with a negligible bit error rate. The system provides all the benefits, such as easy alignment, simple packaging and low cost, usually associated with multimode optical media.

A preferred embodiment of the invention will now be discussed in more detail. As shown in FIG. 1, the invention is embodied in an optical communication network that includes an SEL 11, a power supply 13 that provides a bias current to drive the SEL into multiple transverse mode operation, and a multimode optical medium 15 optically coupled to the SEL to carry the optical signal from the SEL to a remotely-located receiver 17. The SEL is responsive to a signal carrying data (designated generally as 19) to provide an optical signal modulated with the data. The receiver 17, which is optically coupled to the optical medium 15, receives the modulated optical signal and recovers the data (designated generally as 21) therefrom.

Various kinds of multimode optical media such as optical fibers and waveguides may be used for the medium 15. The SEL 11 and the receiver 17 are coupled to the medium 15 through suitable couplings 23 and 25. As will be discussed in more detail presently, the SEL 11 is preferably driven in more than two distinct transverse modes; as noted previously, this may comprise multiple filamentation.

A preferred method of fabricating the SEL 11 is illustrated in FIG. 2. The SEL is grown on an n+GaAs (gallium arsenide) substrate 31. A bottom output mirror, for example 18.5 pairs of n-doped GaAs/AlAs (gallium arsenide/aluminum arsenide) quarter-wave layers (generally designated 33 in the drawing), is epitaxially grown on the substrate 31. The interface between the layers is graded using an AlAs/GaAs/Al(0.3)Ga(0.7)As variable duty cycle short period superlattice ("SPSL"). The SPSL reduces any heterojunction band discontinuities at the GaAs/AlAs interface. The doping level is $1\times10^{18}cm^{-3}$ in uniform regions and $3\times10^{18}cm^{-3}$ in graded regions. For simplicity only a few of the 18.5 pairs of layers are shown in the figure. The reflectivity of the bottom mirror **33** is 98.9%.

Next an optical cavity structure **35** is grown. The cavity structure includes an n-cladding layer **37**, a quantum well **39**, and a p-cladding layer **41**. The cladding layers **37** and **41** comprise Al(0.3)Ga(0.7)As doped to $1\times10^{18}cm^{-3}$, reduced to $5\times10^{17}cm^{-3}$ adjacent the quantum well **39**. The quantum well **39** comprises 3 MQW of strained In(0.2)Ga(0.8)As (indium gallium arsenide) having a thickness of about 80 Å (Å=Angstrom), with GaAs barriers having a thickness of 100 Å.

Above the quantum well **35** is a highly-reflective top mirror **43**. The reflectivity of the top mirror is greater than 99.96%. The top mirror **43** comprises, for example, 15 pairs of GaAs/AlAs quarter wave layers (generally designated **45**), a phase matching layer **47**, and an Au (gold) layer **49**. A proton isolation region **51** surrounds the perimeter of the quarter wave layers **45**. As with the bottom mirror **33**, only a few of the quarter wave layers **45** are actually shown in FIG. 2. The interfaces between the quarter wave layers are graded in a manner generally similar to the grading of the interfaces in the bottom mirror **33**. The doping levels are $1\times10^{18}cm^{-3}$ in uniform regions and $5\times10^{18}cm^{-3}$ in graded regions.

The phase matching layer **47**, which is GaAs, compensates for phase delays that result from finite penetration of the optical field into the Au layer.

The Au layer **49** is about 2000 Å thick and is fabricated, after MBE growth of the underlying structure, as follows. First a 2000 Å layer of Au is deposited on the GaAs phase matching layer **47**. Then a thick (more than 10 μm) Au button is plated on top to serve as a mask for proton isolation. The wafer is then proton implanted. Crystal structure damage that results from the proton implantation provides for current confinement and therefore gain guiding. Then another thick Au button **53** with a diameter of about 300 μm is plated on top. This button **53** is used for solder/die attachment of the completed device to a heat sink. The wafer is then lapped and polished to a diameter of 125 μm and an annular electrode **55** is patterned on the bottom. A quarter-wave anti-reflection coating **57** of SiO_2 (silicon dioxide) is deposited in the open region of the electrode **55**.

An optical communication system embodying the principles of the invention was constructed using a relatively large-area SEL with a 25 μm opening coupled to an optical fiber. A physical discontinuity was deliberately introduced into the fiber; this discontinuity was a gap of several millimeters. The gap was adjustable to cause between 3 dB and 16 dB of loss. The length of the fiber between the SEL and the gap was 16 meters; this portion of the fiber was agitated with a shaker to simulate the effect of fiber movement. The bit error rate ("BER") was measured for gaps of various widths; the measured BERs were less than $10^{31\ 11}$ for losses up to 10 dB.

In the tests described herein, a wavelength of about 970 nanometers ("nm") was used. It will be apparent that the principles of the invention are equally applicable to devices that are operated at other wavelengths, and that the physical dimensions will change accordingly.

In another test the performance of the large-area SEL was compared with that of a smaller SEL having a 12 μm opening. The threshold currents were about 6.5 milliamps (mA) for the large SEL and 4.2 mA for the smaller. The threshold voltages were 2.7 and 4.5 volts, respectively. The output power at twice the threshold current was 3.6 milliwatts (mW) for the larger SEL and 2.8 mW for the smaller. The emission wavelength was about 970 nm.

The SELs were modulated directly by a 1 gigabit-per-second, non-return-to-zero ("NRZ") signal at a maximum of 2 volt amplitude and with a $2^{15}-1$ pseudorandom bit sequence through a bias-T. The bias levels were several times the respective threshold currents. The SELs were directly coupled into 50/125 graded index multimode fiber. The length of the fiber between the SEL and the gap was 16 meters, and the gap was adjusted for a 10 dB loss. An optical attenuator was inserted between the gap and the receiver to keep the optical power incident on the receiver at 6 dB above the receiver sensitivity.

The receiver was a Hewlett-Packard model 83442A receiver modified for multimode use with a 60 μm InGaAs detector and a multimode FC/PC input connector. The receiver had a −3 dB bandwidth of 0.9 GHz. The AC-coupled receiver output was amplified to 2.0 volts before detection. The sensitivity of the receiver was −23 dBm for a receiver noise-limited BER of 10^{-9}.

In this test configuration, the 25 μm SEL was operated for 16 hours without an error, resulting in a BER of less than 10^{-13}. In other tests, the length of the fiber between the SEL and the gap (the gap was adjusted to a 10 dB loss) was varied between six and 406 meters and in every such instance the BER was less that 10^{-11}. The 12 μm SEL was also able to achieve a BER of less than 10^{-11} with the gap adjusted to about a 4 dB loss.

A strongly-driven SEL with a relatively large surface area ("large surface area" means a surface opening larger than about eight μm) will operate in multiple, high-order transverse modes that are at slightly different wavelengths. As the size of the opening increases, so does the maximum number of transverse modes that can be obtained. Thus, an SEL with a 25 μm opening can be operated in significantly more transverse modes than an SEL with a 12 μm opening.

As the number of transverse modes increases, the optical bandwidth of the light produced by the laser also increases and the coherence of the light decreases. Speckle visibility measurements have shown that the speckle visibility from a large-area SEL is smaller than that of smaller SELs.

Despite operating in multiple transverse modes, the large-area SEL operates in a stable, single longitudinal mode. Longitudinal mode partition noise, which results from multiple longitudinal modes, is therefore not a significant problem with large-area SELs.

In one test, a 25 μm SEL was found to be operating in at least six distinct transverse modes at a drive current of 2.3 times the threshold current. The spectral width was $\Delta\lambda=0.75$ nm. When the drive current was reduced sufficiently to cause the laser to go into single mode operation, the spectral width was $\Delta\lambda<0.08$ nm; this measurement was limited by the resolution of the optical spectrum analyzer that was used for the test. In contrast, a 12 μm SEL was found to be operating in single mode at a drive current 1.5 times the threshold and in two transverse modes at a drive current 2.5 times the threshold.

From the foregoing it will be apparent that an optical communication system according to the invention is capable of carrying digital data at rates up to and exceeding 1.5 gigabits per second with very low bit error rates. The invention also offers the advantages, such as easy alignment, simple packaging and low cost, that are associated with systems using multimode optical media. In addition, SELs are expected to be easier and less expensive to manufacture than other kinds of lasers.

Although a specific embodiment of the invention has been described and illustrated, the invention is not to be limited to the specific forms or arrangements of parts so described and illustrated, and various modifications and changes can be made without departing from the scope and spirit of the invention. Within the scope of the appended claims, therefore, the invention may be practiced otherwise than as specifically described and illustrated.

We claim:

1. An optical communication network comprising:

a vertical-cavity, surface-emitting semiconductor laser structure having an aperture larger than eight micrometers through which an optical signal may be emitted;

a power supply that provides a bias current to drive the laser into a multiple transverse mode of Operation in which the laser is responsive to a signal carrying data to provide an optical signal modulated with the data and to emit the optical signal through the aperture; and

a multimode Optical medium optically coupled to the laser to carry the optical signal from the laser to a remotely-located receiver.

2. A network as in claim 1 and further comprising a receiver, optically coupled to the optical medium, that receives the modulated optical signal and recovers the data therefrom.

3. A network as in claim 1 wherein the multiple transverse mode of operation comprises more than two distinct transverse modes.

4. A network as in claim 1 wherein the multiple transverse mode of operation comprises multiple filamentation.

5. A network as in claim 1 wherein the multi-mode optical medium comprises an optical fiber.

6. A network as in claim 1 wherein the multi-mode optical medium comprises an optical waveguide.

* * * * *

EXHIBIT 2

US006947456B2

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

(10) **Patent No.: US 6,947,456 B2**
(45) **Date of Patent: Sep. 20, 2005**

(54) **OPEN-LOOP LASER DRIVER HAVING AN INTEGRATED DIGITAL CONTROLLER**

(75) Inventors: **Jesse Chin**, Hillsborough, CA (US); **Miaobin Gao**, San Jose, CA (US); **Robert Elsheimer**, San Jose, CA (US); **Matthew Scott Abrams**, Santa Clara, CA (US); **Heng-ju Cheng**, Mountain View, CA (US); **Takashi Hidai**, Palo Alto, CA (US); **Myunghee Lee**, San Jose, CA (US); **Song Liu**, San Jose, CA (US)

(73) Assignee: **Agilent Technologies, Inc.**, Palo Alto, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/735,315**

(22) Filed: **Dec. 12, 2000**

(65) **Prior Publication Data**

US 2002/0105982 A1 Aug. 8, 2002

(51) **Int. Cl.**[7] **H01S 3/00**; H01S 3/30; H01S 3/13

(52) **U.S. Cl.** **372/38.02**; 372/8; 372/38.1; 372/38.01; 372/38.08; 372/29.01

(58) **Field of Search** 372/8, 29.01, 29.011, 372/29.014, 29.02, 38.1, 38.02, 38.08, 38.01, 43, 29.015, 34, 38.07

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,952,949	A		8/1990	Uebbing	346/154
4,982,203	A		1/1991	Uebbing et al.	346/107 R
5,016,027	A		5/1991	Uebbing	326/107 R
5,018,154	A		5/1991	Ohashi	
5,019,769	A		5/1991	Levinson	
5,383,208	A		1/1995	Queniat et al.	
5,623,355	A	*	4/1997	Olsen	398/162
5,638,390	A		6/1997	Gilliland et al.	372/38
5,734,672	A		3/1998	McMinn et al.	
5,844,928	A	*	12/1998	Shastri et al.	372/38.02
6,195,370	B1		2/2001	Haneda et al.	
6,272,164	B1		8/2001	McMinn et al.	
2002/0064193	A1	*	5/2002	Diaz et al.	372/26
2002/0094000	A1	*	7/2002	Heilman et al.	372/38.02

OTHER PUBLICATIONS

Data sheet entitled "S7011 1.0/1.25 Gbps VCSEL Driver", Revision 3, Jun. 7, 1999, by Applied Micro Circuits Corporation (AMCC) of San Diego, California.

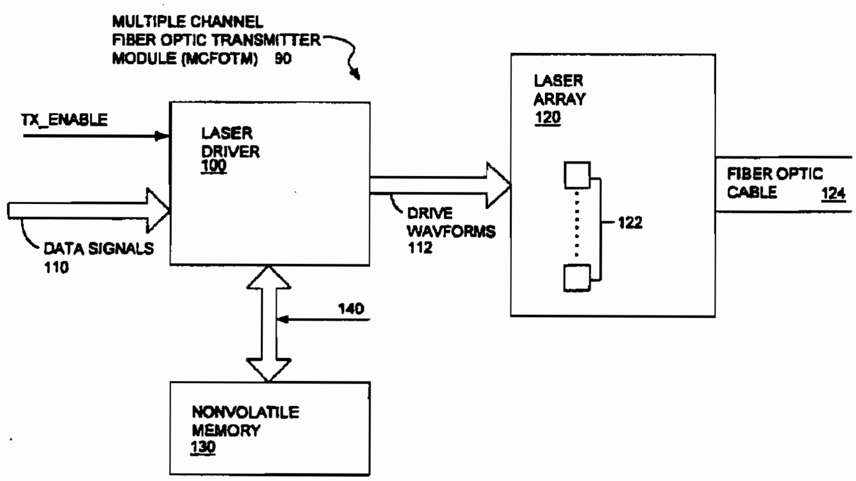
* cited by examiner

Primary Examiner—Minsun Oh Harvey
Assistant Examiner—Armando Rodriguez

(57) **ABSTRACT**

A laser driver for generating drive waveforms that are suitable for driving a single VCSEL or an array of VCSELs. A digital controller is integrated into the laser driver and is utilized to initially program and selectively adjust during the operation of the driver one or more of the following VCSEL drive waveform parameters: (1) bias current, (2) modulation current, (3) negative peaking depth, and (4) negative peaking duration. The laser driver has an aging compensation mechanism for monitoring the age of the laser and for selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the aging of the laser. The laser driver also has a temperature compensation mechanism for monitoring the temperature of the driver IC and selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the changes in temperature.

20 Claims, 7 Drawing Sheets



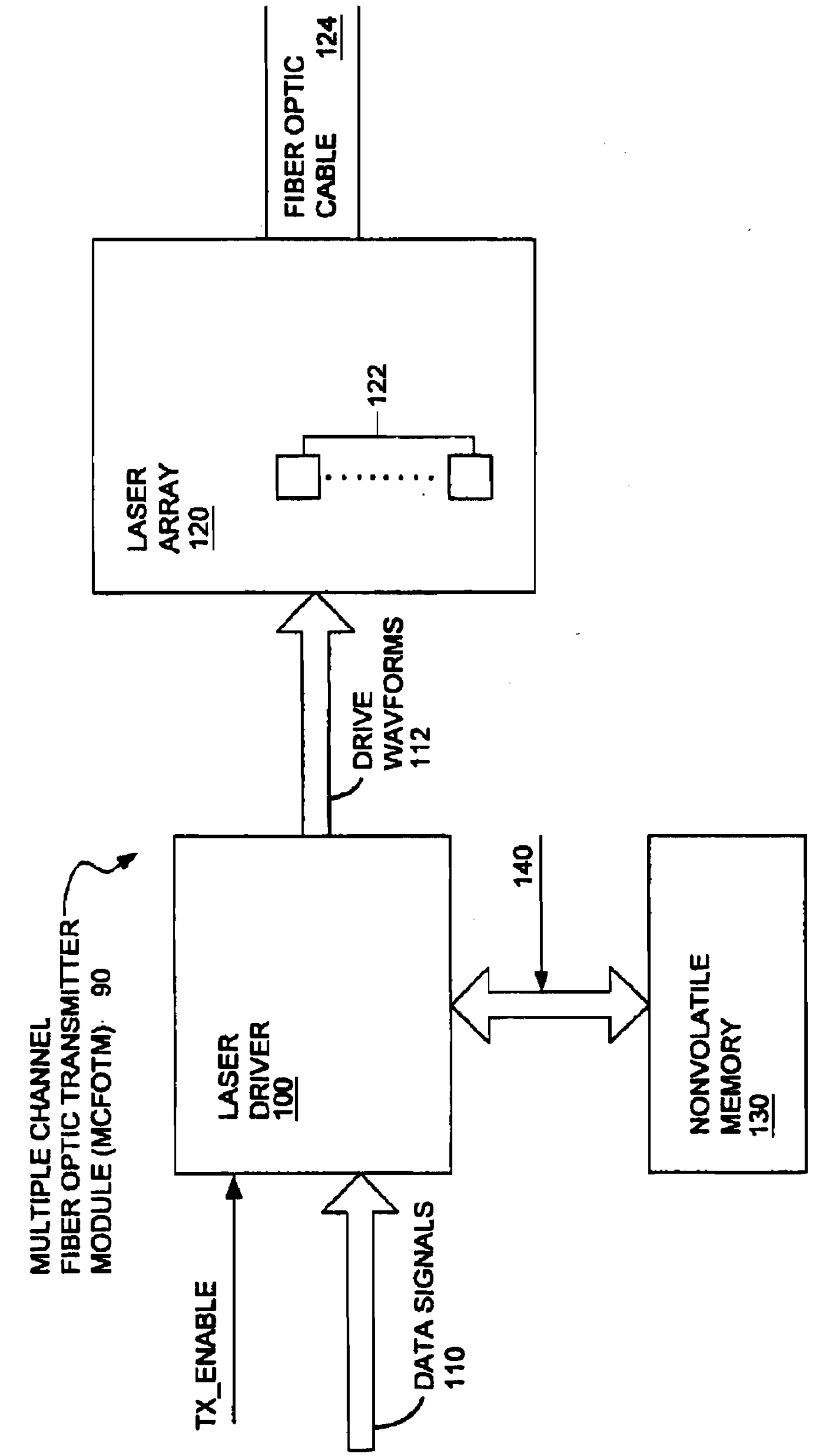

FIBER OPTIC CABLE 124
LASER ARRAY 120
122
DRIVE WAVFORMS 112
MULTIPLE CHANNEL FIBER OPTIC TRANSMITTER MODULE (MCFOTM) 90
LASER DRIVER 100
140
NONVOLATILE MEMORY 130
TX_ENABLE
DATA SIGNALS 110

FIG. 1

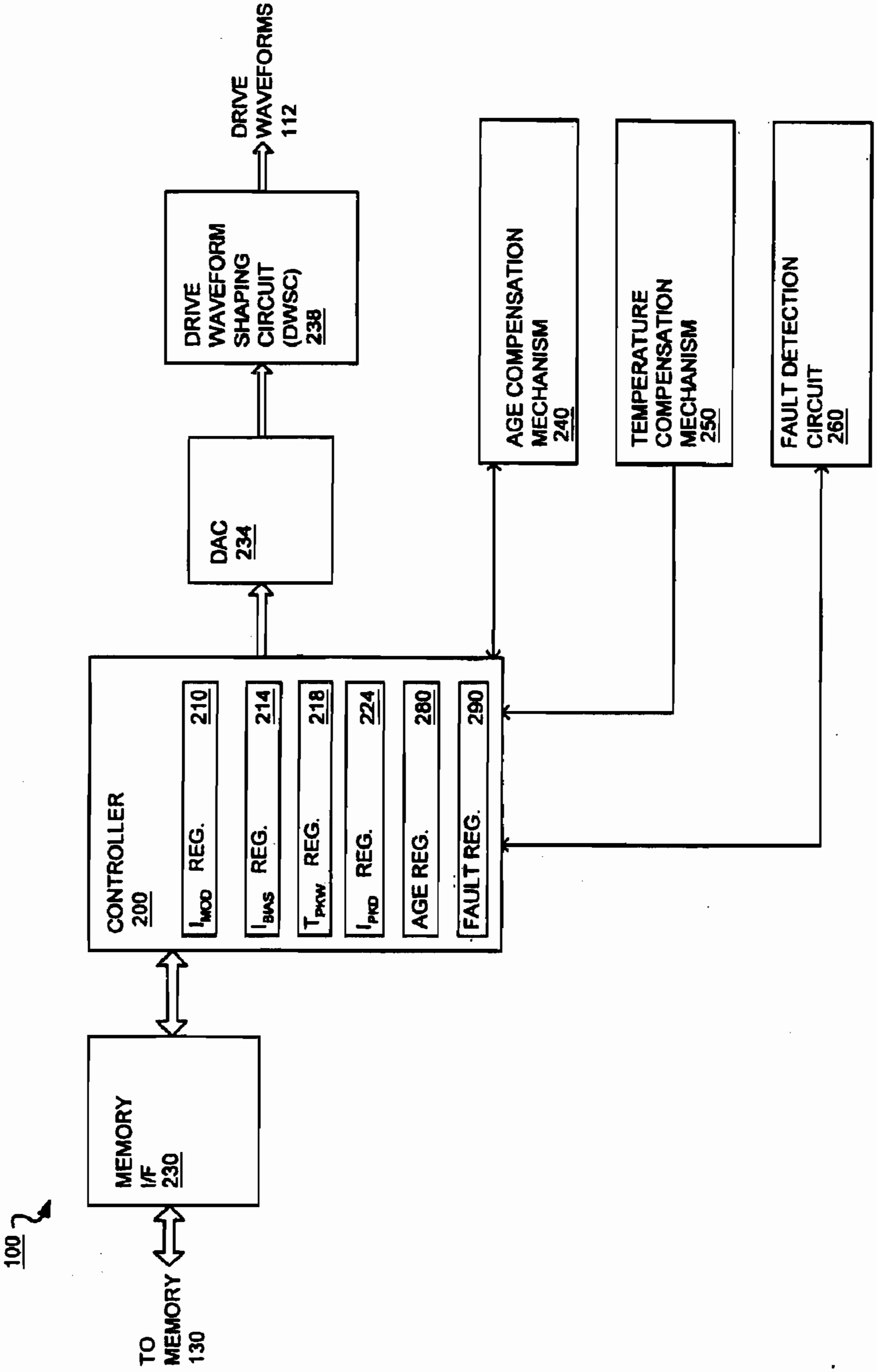

100
TO MEMORY 130
MEMORY I/F 230
CONTROLLER 200
I_{MOD} REG. 210
I_{BIAS} REG. 214
T_{PKW} REG. 218
I_{PKD} REG. 224
AGE REG. 280
FAULT REG. 290
DAC 234
DRIVE WAVEFORM SHAPING CIRCUIT (DWSC) 238
DRIVE WAVEFORMS 112
AGE COMPENSATION MECHANISM 240
TEMPERATURE COMPENSATION MECHANISM 250
FAULT DETECTION CIRCUIT 260

FIG. 2

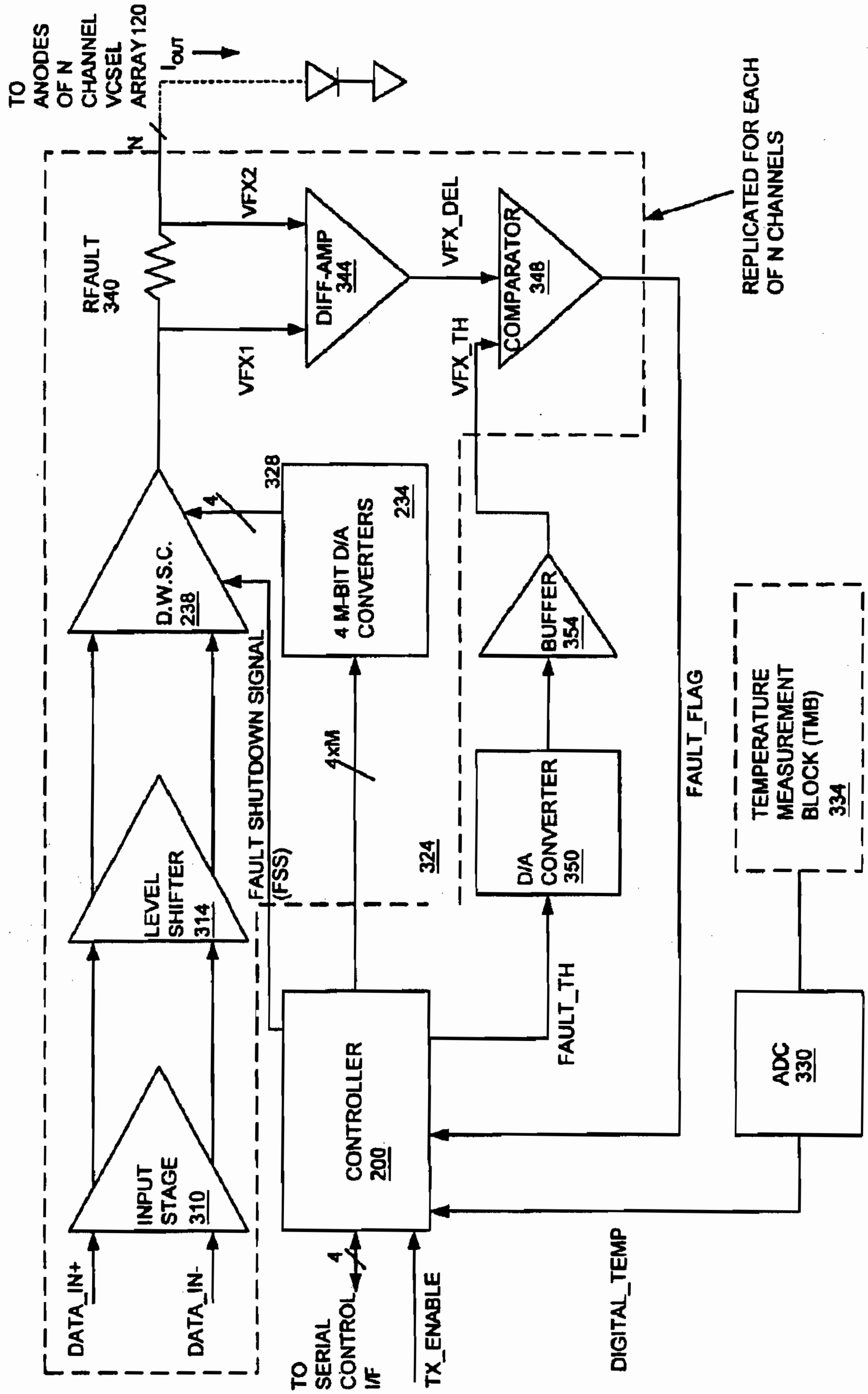

TO ANODES OF N CHANNEL VCSEL ARRAY 120
I_{OUT}
N
RFAULT 340
VFX2
VFX1
DIFF-AMP 344
VFX_DEL
COMPARATOR 348
VFX_TH
REPLICATED FOR EACH OF N CHANNELS
D.W.S.C. 238
4
328
4 M-BIT D/A CONVERTERS 234
BUFFER 354
LEVEL SHIFTER 314
FAULT SHUTDOWN SIGNAL (FSS)
4xM
324
D/A CONVERTER 350
FAULT_FLAG
TEMPERATURE MEASUREMENT BLOCK (TMB) 334
INPUT STAGE 310
CONTROLLER 200
FAULT_TH
ADC 330
DATA_IN+
DATA_IN-
4
TO SERIAL CONTROL I/F
TX_ENABLE
DIGITAL_TEMP

FIG. 3

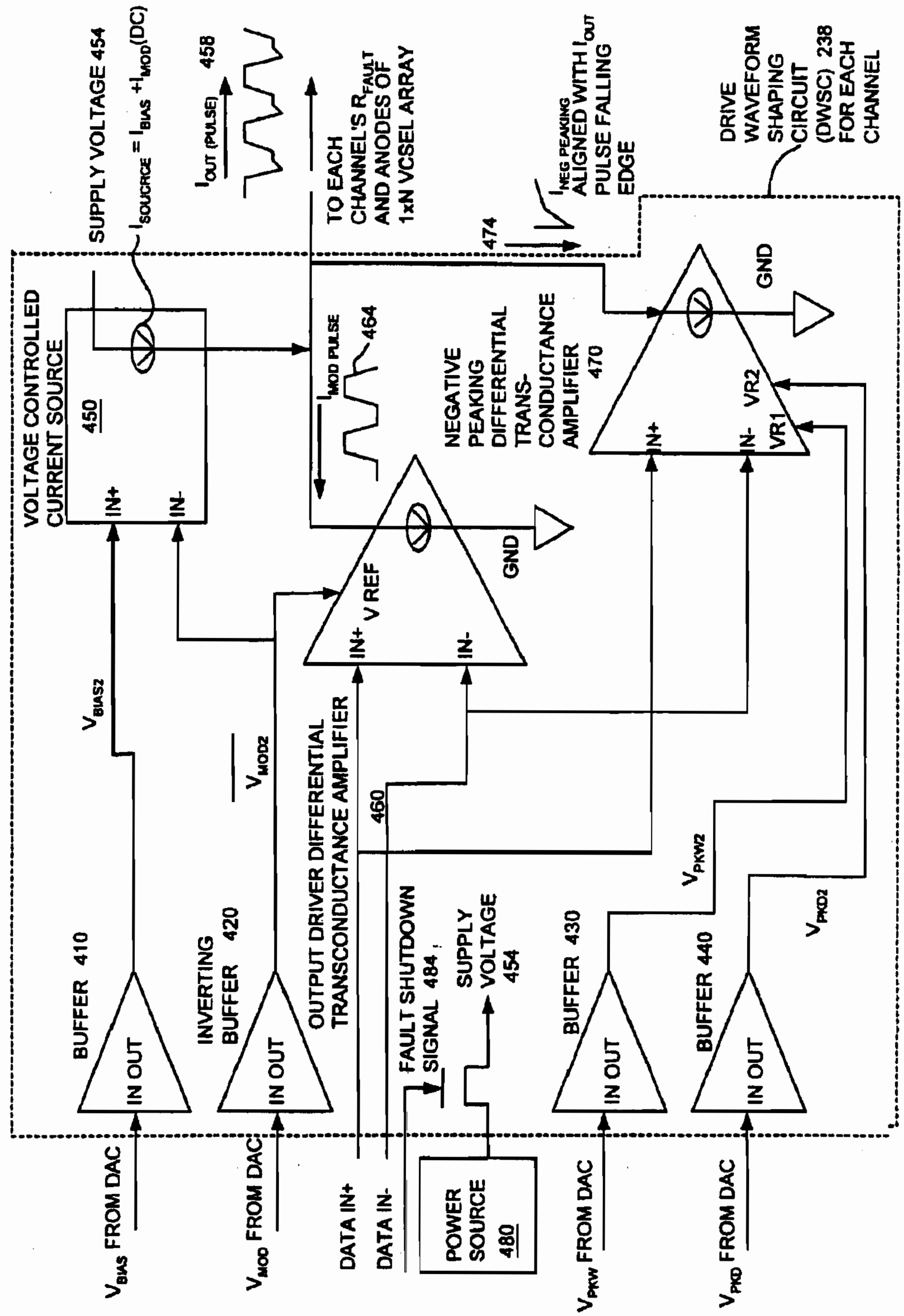

SUPPLY VOLTAGE 454
$I_{SOUCRCE} = I_{BIAS} + I_{MOD}(DC)$
$I_{OUT\ (PULSE)}$ 458
TO EACH CHANNEL'S R_{FAULT} AND ANODES OF 1xN VCSEL ARRAY
474
$I_{NEG\ PEAKING}$ ALIGNED WITH I_{OUT} PULSE FALLING EDGE
DRIVE WAVEFORM SHAPING CIRCUIT (DWSC) 238 FOR EACH CHANNEL
VOLTAGE CONTROLLED CURRENT SOURCE
450
IN+
IN-
$I_{MOD\ PULSE}$ 464
NEGATIVE PEAKING DIFFERENTIAL TRANS-CONDUCTANCE AMPLIFIER 470
GND
IN+
IN-
VR2
VR1
V REF
GND
IN+
IN-
V_{BIAS2}
$\overline{V_{MOD2}}$
OUTPUT DRIVER DIFFERENTIAL TRANSCONDUCTANCE AMPLIFIER
460
V_{PKW2}
V_{PKD2}
BUFFER 410
IN OUT
INVERTING BUFFER 420
IN OUT
FAULT SHUTDOWN SIGNAL 484
SUPPLY VOLTAGE 454
BUFFER 430
IN OUT
BUFFER 440
IN OUT
V_{BIAS} FROM DAC
V_{MOD} FROM DAC
DATA IN+
DATA IN-
POWER SOURCE 480
V_{PKW} FROM DAC
V_{PKD} FROM DAC

FIG. 4

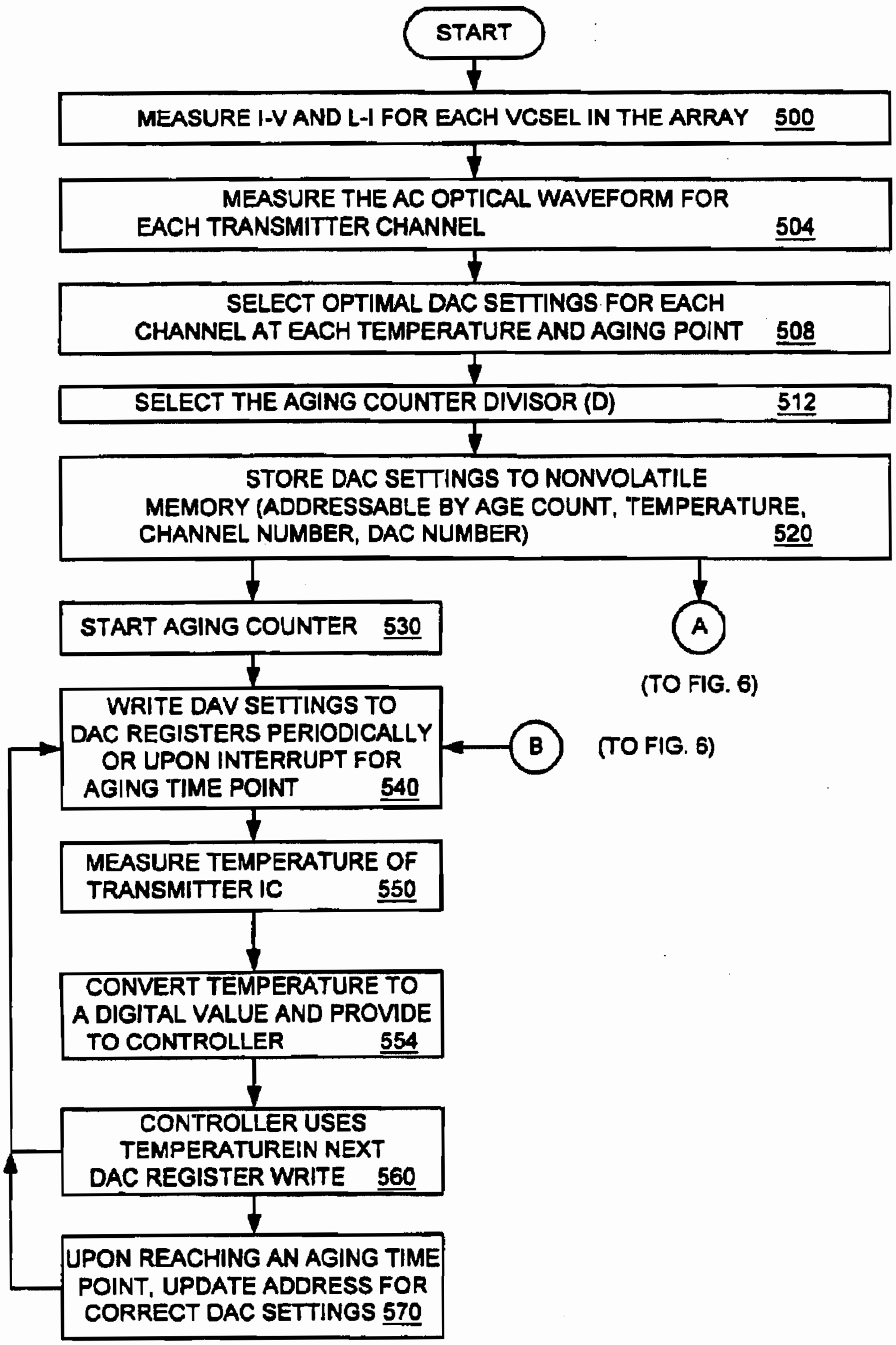

START
MEASURE I-V AND L-I FOR EACH VCSEL IN THE ARRAY 500
MEASURE THE AC OPTICAL WAVEFORM FOR EACH TRANSMITTER CHANNEL 504
SELECT OPTIMAL DAC SETTINGS FOR EACH CHANNEL AT EACH TEMPERATURE AND AGING POINT 508
SELECT THE AGING COUNTER DIVISOR (D) 512
STORE DAC SETTINGS TO NONVOLATILE MEMORY (ADDRESSABLE BY AGE COUNT, TEMPERATURE, CHANNEL NUMBER, DAC NUMBER) 520
START AGING COUNTER 530
A
(TO FIG. 6)
WRITE DAV SETTINGS TO DAC REGISTERS PERIODICALLY OR UPON INTERRUPT FOR AGING TIME POINT 540
B
(TO FIG. 6)
MEASURE TEMPERATURE OF TRANSMITTER IC 550
CONVERT TEMPERATURE TO A DIGITAL VALUE AND PROVIDE TO CONTROLLER 554
CONTROLLER USES TEMPERATUREIN NEXT DAC REGISTER WRITE 560
UPON REACHING AN AGING TIME POINT, UPDATE ADDRESS FOR CORRECT DAC SETTINGS 570

FIG. 5

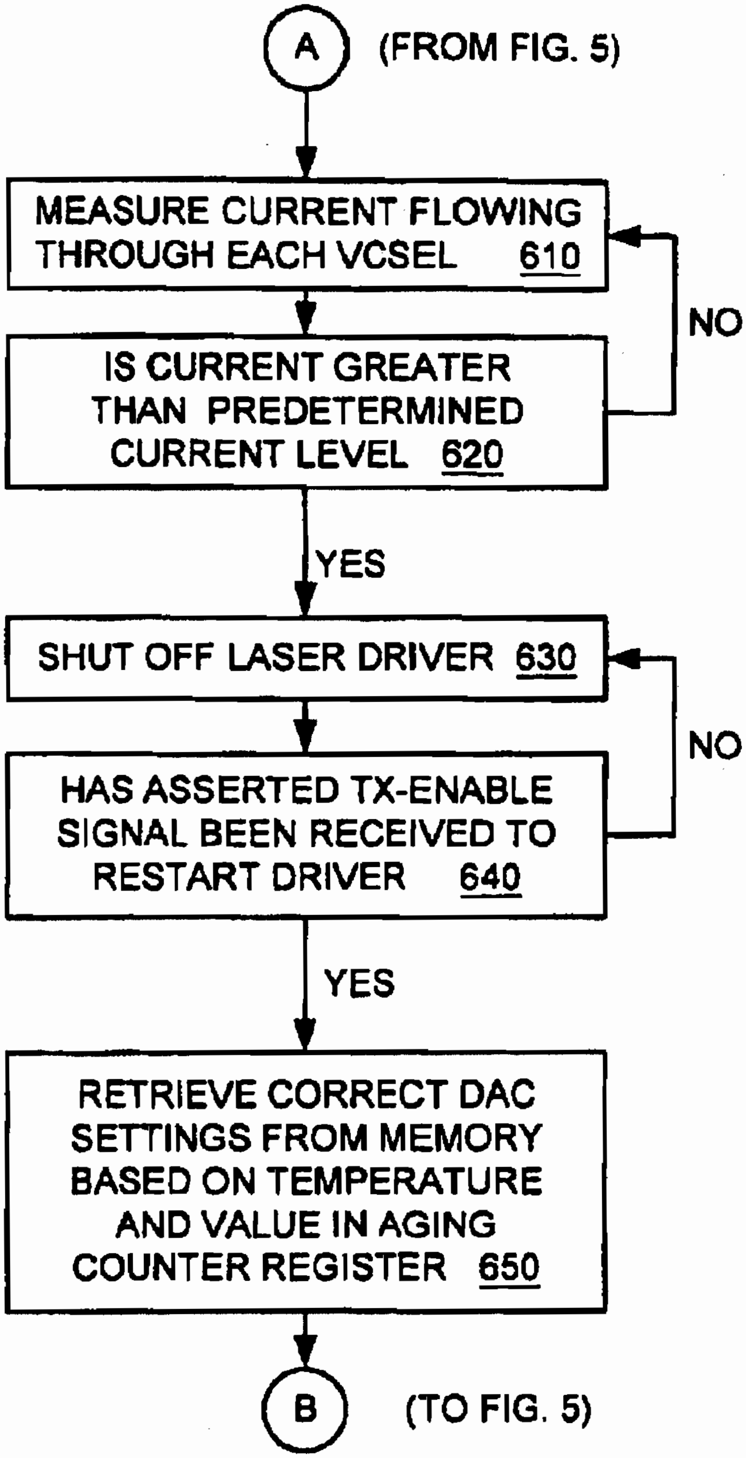

A
(FROM FIG. 5)
MEASURE CURRENT FLOWING THROUGH EACH VCSEL 610
IS CURRENT GREATER THAN PREDETERMINED CURRENT LEVEL 620
NO
YES
SHUT OFF LASER DRIVER 630
HAS ASSERTED TX-ENABLE SIGNAL BEEN RECEIVED TO RESTART DRIVER 640
NO
YES
RETRIEVE CORRECT DAC SETTINGS FROM MEMORY BASED ON TEMPERATURE AND VALUE IN AGING COUNTER REGISTER 650
B
(TO FIG. 5)

FIG. 6

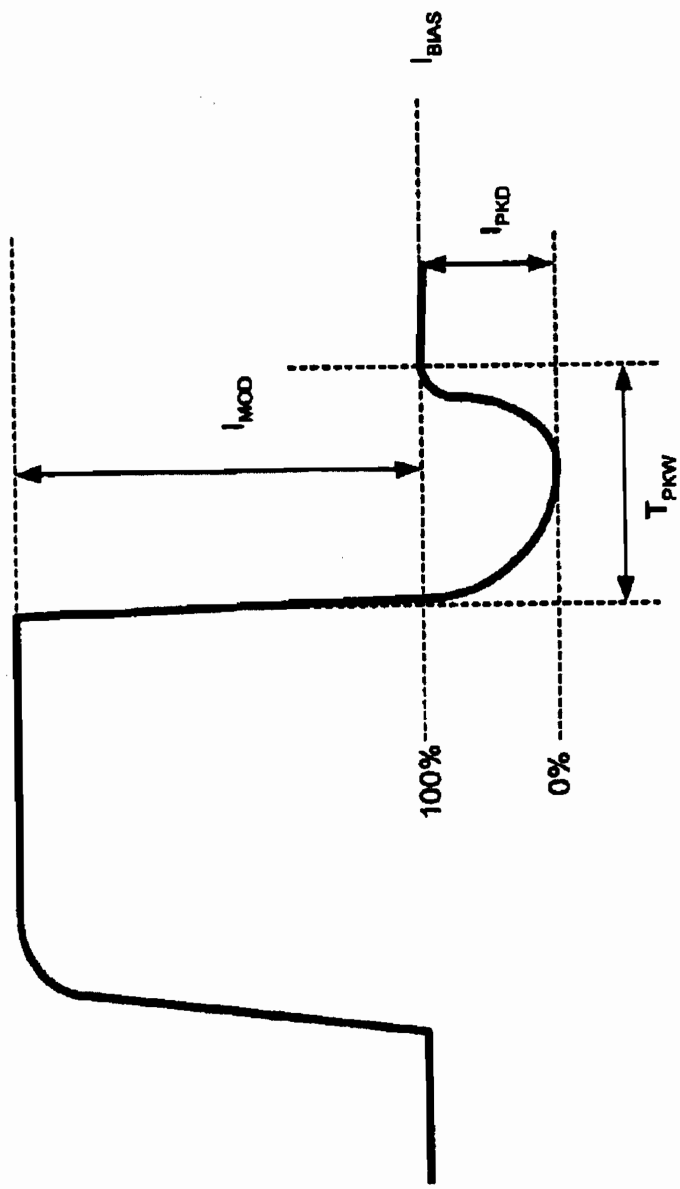


FIG. 7

OPEN-LOOP LASER DRIVER HAVING AN INTEGRATED DIGITAL CONTROLLER

FIELD OF THE INVENTION

The present invention relates generally to semiconductor lasers, and more particularly, to an open-loop laser driver having an integrated digital controller for providing drive waveforms to lasers.

BACKGROUND OF THE INVENTION

An optical transmitter module is an important component in networking systems. The purpose of an optical transmitter module is to convert data signals in electrical form into corresponding data signals in optical form. In this manner, the data can be communicated as light to another module (e.g., an optical receiver module) through a light-conducting medium, such as a fiber optic cable.

The optical transmitter module typically employs a laser to convert the electrical data signals into the light data signals. One commonly utilized semiconductor laser is the vertical cavity surface emitting laser (VCSEL). However, the VCSEL is configured to operate only with input signals (e.g., drive waveforms) that conform to particular predetermined electrical properties. The drive waveforms can have both dc operating parameters and ac operating parameters. For example, the dc operating parameters may include bias current to obtain either average or low state output power. The ac operating parameters may include modulation current, peaking current, and time constant parameters associated with pulsed waveforms. The data signals typically do not have these predetermined electrical characteristics (e.g., specific dc and ac operating parameters). Consequently, a circuit is needed for accepting the data signals, and responsive thereto, for generating corresponding VCSEL drive signals (e.g., a drive waveform) with the electrical characteristics that are suitable to drive the VCSEL. This circuit is commonly referred to as a VCSEL driver.

Furthermore, the VCSEL driver programs or sets the drive waveform with particular dc and ac parameters in order to optimize the bit error rate (BER) of the fiber optic link using the transmitter. The bit error rate is simply a measure of the number of bit errors caused by the transmitter module. A bit error is simply a data error when a data "1" is transmitted as a data "0" or when a data "0" is transmitted as a data "1".

There are two main approaches in the design of prior art laser drivers. The first approach employs a closed loop (i.e., uses optical feedback to adjust the light output power) to program the drive waveforms. The second approach employs an open loop (i.e., does not use optical feedback to adjust the light output power) to program the drive waveforms. These prior art approaches with their attendant disadvantages are described hereinafter.

Closed-Loop Approaches

U.S. Pat. No. 5,638,390 describes an exemplary closed-loop approach embodied in a laser output power stabilizing circuit. The laser output power stabilizing circuit uses a photodiode to monitor the laser's optical power. The photodiode output is compared to a reference voltage from a digital potentiometer, to obtain the correct dc bias current for the laser. At the time of the transmitter's manufacture, the digital potentiometer is set to optimize the laser's dc bias current. During operation of the transmitter, the laser's bias current is adjusted when any change in photodiode output occurs.

Unfortunately, these closed-loop approaches suffer from several disadvantages. First, the use of the photodiode increases the cost of the optical transmitter. Second, the requirement of the photodiode introduces packaging concerns related to the mounting of the photodiodes in such a manner as to be optimally aligned with the VCSEL. Third, the closed-loop approaches require complex feedback circuits that need to be replicated for each VCSEL, thereby further increasing costs and manufacturing complexity.

Open-Loop Approaches

The data sheet for the AMCC S7011 transmitter integrated circuit (IC) that is available from Applied Micro Circuits Corporation (AMCC) describes an exemplary open-loop approach. The S7011 IC appears to be capable of adjusting the laser drive waveform parameters Imod and Ibias, given input from an external source (e.g., a microprocessor), or input from external resistors and voltage references. Unfortunately, the prior art open-loop approaches, including the AMCC approach, fail to provide or provide very limited mechanisms to adjust the drive waveform based on changes in age and temperature of the laser. These prior art open-loop approaches also fail to allow programming of the transitional aspects of the VCSEL drive waveform (e.g. negative peaking).

VCSEL Arrays

Recently, there has been interest in moving from a single VCSEL to an array of VCSELs, which for example, can be a plurality of VCSELs that are arranged in a row. As can be appreciated, an array of VCSELs can be employed to transmit more data through multi-channel fiber optic cable than a single VCSEL can transmit through a fiber optic cable having a single channel. Unfortunately, one of the engineering challenges for implementing the array of VCSELS is that optical waveform uniformity across the VCSEL array needs to be maintained in order to optimize the BER of the fiber optic link.

Consequently, correct settings for the dc and ac parameters of the drive waveforms are particularly critical for fiber optic transmitters using an array of VCSELs. The parameters must be set to maintain optical waveform uniformity across the VCSEL array. The setting of these properties needs to occur at the beginning of operation and also at periodic intervals during the product's lifetime.

Semiconductor electrical to optical transmitters often require a scheme to program the optical de and ac operating characteristics of the light-emitting device. Preferably, the programming is performed at the beginning of product use, and periodically programmed throughout the lifetime of the transmitter. Unfortunately, the prior art approaches that do periodically program the waveforms during the lifetime of the transmitter are costly, complex to implement, and limited to dc parameters. Those prior art approaches that address some of the ac issues, such as modulation current, are limited to programming only at the beginning of product use. Consequently, if the product requires programming during the operating life of the driver, these prior art approaches are unable to perform this type of programming.

Age Dependence of Light Output

Ideally, the laser's performance in terms of light output remains constant throughout the operating life of the laser. If this were the case, the drive waveforms can be programmed once by the laser driver and would require no further changes or re-programming. Unfortunately, in reality, VCSEL light output tends to degrade over the operating life of the laser. Consequently, it would be desirable to have a mechanism in the VCSEL driver for periodically adjusting the VCSEL drive waveform parameters to compensate for the degradation. Regrettably, the prior art approaches that employ an open-loop approach, such as the AMCC approach, are limited to programming the waveform parameters at the beginning of the product life and do not have a mechanism for periodically adjusting the VCSEL drive waveform parameters to compensate for the degradation.

Temperature Dependence of Light Output

Moreover, in an ideal situation, the laser's light output would be independent of operating temperature. If this were the case, the drive waveform would not require adjustment as the operating temperature changes. Unfortunately, in reality, the laser's light output is dependent on operating temperature. Accordingly, it would be desirable to have a mechanism that adjusts the drive waveforms as the operating temperature changes. By so doing, optimum VCSEL optical waveform characteristics can be maintained. Regrettably, the prior art approaches do not offer any mechanism for periodically adjusting the VCSEL drive waveform parameters to compensate for changing operating temperatures.

Based on the foregoing, there remains a need for a digital control method and apparatus for semiconductor lasers that overcomes the disadvantages set forth previously.

SUMMARY OF THE INVENTION

According to one embodiment, the laser driver of the present invention includes an integrated digital controller for programming the dc and ac parameters of the drive waveform that drives a single VCSEL or an array of VCSELs for use in a fiber optic transmitter. The digital controller is integrated into the driver IC and is utilized to program one or more of the following VCSEL drive waveform parameters: (1) bias current, (2) modulation current, (3) negative peaking depth, and (4) negative peaking duration.

In one embodiment, the laser driver includes an aging compensation mechanism for monitoring the age of the laser and for selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the aging of the laser. Preferably, a timer is employed to monitor the age of the laser.

In another embodiment, the laser driver includes a temperature compensation mechanism for monitoring the temperature of the driver IC and selectively adjusting the dc and ac parameters of the VCSEL drive waveform to compensate for the changes in temperature. Preferably, a temperature sensor is employed to monitor the temperature of the driver IC.

As described previously, the optimization of VCSEL optical waveform characteristics in a multi-channel fiber optic transmitter can pose a difficult challenge. The laser driver of the present invention separately programs each channel's VCSEL drive waveform parameters initially and during operation of the transmitter in order to maintain optimum optical waveforms for each channel. By updating of VCSEL drive parameters during transmitter operation, the laser driver of the present invention compensates for aging of the laser and temperature changes.

According to another embodiment of the present invention, a design methodology for the programming of the VCSEL drive waveform is provided.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements.

FIG. 1 is a block diagram of an exemplary multiple channel fiber optic transmitter module in which the laser driver of the present invention can be implemented.

FIG. 2 illustrates in greater detail the laser driver of FIG. 1 according to one embodiment of the present invention.

FIG. 3 is a block diagram illustrates in greater detail the laser driver of FIG. 1 according to one embodiment of the present invention.

FIG. 4 illustrates in greater detail the drive waveform shaping circuit of FIG. 3 according to one embodiment of the present invention.

FIG. 5 is a flowchart illustrating the steps performed by the controller of FIG. 2. according to one embodiment of the present invention.

FIG. 6 is a flowchart illustrating the steps performed by the controller of FIG. 2. according to one embodiment of the present invention.

FIG. 7 illustrates an exemplary drive waveform that is generated by the laser driver of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

An open-loop laser driver having an integrated digital controller and programming method are described. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to avoid unnecessarily obscuring the present invention.

The laser driver of the present invention integrates a digital controller, data storage/retrieval facilities, and the needed mechanisms to initially set and periodically adjust the parameters of the VCSEL drive waveform for each channel to effectively compensate for aging and operating temperature changes.

Multiple Channel Fiber Optic Transmitter Module **90**

FIG. 1 is a block diagram of an exemplary multiple channel fiber optic transmitter module (MCFOTM) **90** in which the laser driver of the present invention can be implemented. For example, the multiple channel fiber optic transmitter module (MCFOTM) **90** can be a 12-channel transmitter module. The multiple channel fiber optic transmitter module **90** includes a laser driver **100** for receiving data signals **110** and responsive thereto for generating drive waveforms **112**, a laser array **120** that has a plurality of lasers **122** (e.g., VCSELs), and a nonvolatile memory **130** for storing drive waveform parameters. A fiber optic cable **124** is coupled to the laser array **120** in order to receive light launched therein by the lasers **122**.

The drive current waveform associated with each channel's VCSEL diode is programmed by the laser driver **100** and the non-volatile memory **130**. In one embodiment, the MCFOTM **90** includes a VCSEL driver, a 1×N VCSEL array, and an EEPROM. As described in greater detail hereinafter, the laser driver **100** includes a digital controller for programming and data retrieval.

In one embodiment, there are 2*N signal lines interposed between the laser driver **100** and the VCSEL array **120**, where N signal lines are coupled to the anodes of the VCSELs, and N lines that are coupled to either a ground plane or to the cathodes of the VCSELs depending on the type of VCSEL and configuration of the laser driver **100**. It is noted that N is the number of channels incorporated into the multiple channel fiber optic transmitter module **90**.

An access point **140** is provided for reading and writing data into the memory **130** and the laser driver **100**. As will be described in greater detail hereinafter, the access point **140** can be used to communicate test signals and data to the laser driver **100** and the memory **130**.

Laser Driver **100**

FIG. **2** illustrates in greater detail the laser driver **100** of FIG. **1** according to one embodiment of the present invention. The laser driver **100** includes a controller **200**, a plurality of drive parameter registers (**210, 214, 218, 224**) for storing drive parameters, an age compensation mechanism **240**, a temperature compensation mechanism **250**, a fault determination circuit **260**, a plurality of digital-to-analog converters (DACs) **234**, a drive waveform shaping circuit **238**, an age register **280** for storing an age value, and a fault register **290** for storing a predetermined fault value.

Integrated Digital Controller **200** in the VCSEL Driver IC

One aspect of the present invention is the integration of a digital controller **200** in the laser driver **100**. The laser driver **100** of the present invention employs the controller **200** to digitally program the dc and ac properties of the VCSEL drive waveform for a single laser die or for a 1×N array of laser die.

The laser driver **100** of the present invention provides a mechanism for individually programming the parameters (e.g., dc and ac parameters) for each laser die in an array in order to obtain uniformity in the optical waveforms across the array.

Programming the Driver Waveform Parameters

For example, the laser driver **100** can digitally program the VCSEL bias for an optical logic zero by using the integrated controller **200** and the digital-to-analog converters (DACs) **234**. Furthermore, the laser driver **100** can digitally program the VCSEL drive waveform for modulating an optical zero to one transition by using the integrated controller **200** and the DACs **234**.

One feature of the laser driver of the present invention is the programmability of the ac characteristics, such as negative peaking depth and duration, of the VCSEL drive waveform. Negative peaking refers to peaking of the VCSEL drive waveform during the logic one to logic zero falling transition. I_{pkd} is the negative peaking depth. T_{pkw} is the negative peaking duration.

The laser driver **100** can digitally program a negative peaking depth on the VCSEL drive waveform for use during an optical one to zero transition. The negative peaking is used to decrease the optical fall time during a one to zero transition. Also, the laser driver **100** can digitally program a negative peaking duration on the VCSEL drive waveform for use during an optical one to zero transition.

As described in greater detail hereinafter, the laser driver **100** of the present invention can also use the digital controller **200** to implement a timer function for periodically adjusting the VCSEL drive waveform to compensate for aging.

Furthermore, as described in greater detail hereinafter, the laser driver **100** of the present invention can use an integrated digital control loop to monitor die temperature and adjust the dc and ac parameters of the VCSEL drive waveforms to compensate for changes in temperature.

Age Compensation Mechanism **240**

As described previously, the VCSEL light output tends to degrade over the operating life of the laser. In this regard, the VCSEL drive waveform parameters need to be adjusted periodically to compensate for the degradation. In one embodiment, the laser driver of the present invention includes a programmable timer that in cooperation with in the digital controller periodically adjusts each VCSEL's drive waveform parameters to compensate for aging.

A further aspect of the laser driver of the present invention is the integration of a timer function into the digital controller to enable the compensation of light output due to VCSEL aging. The timer allows periodic adjustment of the VCSEL drive waveform dc and ac parameters to compensate for aging.

In one embodiment, the age compensation mechanism **240** can be implemented by using an on-chip 10 Mhz clock, a programmable divisor (D) for the clock, a 31 bit counter (herein referred to as a low order aging counter) in the controller **200**, and a 16 bit counter (herein referred to as a high order aging counter in the non-volatile memory **130**. The clock divisor D combined with the 10 MHz clock period determine how often (in seconds or minutes) the high order aging counter is incremented. The controller **200** updates the DAC settings when the four MSB of the high order aging counter are incremented. For example, when D is equal to 32, and 10 Mhz clock period is equal to 100 ns, then the low order aging counter be incremented every 114.5 minutes, and the high order aging counter's 4 MSB is be incremented every 325 days.

If power to the transmitter is interrupted, the EEPROM stores the last counter setting in multiple registers (e.g., three registers). Once power resumes, the counter setting in each of the registers is compared with the counter values in the other two registers for accuracy. The counter setting found in at least two registers is chosen as the correct setting.

Temperature Compensation Mechanism **250**

As described previously, as the operating temperature of the transmitter module changes, the VCSEL drive waveform parameters require adjustment in order to maintain optimum VCSEL optical waveform characteristics. In one embodiment, the laser driver of the present invention includes an integrated temperature monitor and feedback system for adjusting the VCSEL drive waveform parameters after a temperature change.

Another aspect of the laser driver of the present invention is the integration of a temperature sensing and feedback circuitry onto the driver IC.

The laser driver **100** also includes a non-volatile memory interface **230** for communicating with the nonvolatile memory **130**. The nonvolatile memory **130** stores the DAC settings for I_{mod}, I_{bias}, T_{pkw}, and I_{pkd} in a lookup table format. Each DAC setting can be referenced (e.g., accessed by a read operation) by employing an address that has the following format: AAAATTTTTCCCCXX. The "A"s represent the four most significant bits (MSB) of the aging counter. The "T"s represent five bits that represent the temperature of the laser driver **100**. The "C"s represent the channel number, and the "X"s represent the DAC number. It is noted that the DACs for the I_{mod}, I_{bias}, T_{pkw}, I_{pkd} parameters each has a different number associated therewith.

FIG. **3** illustrates an exemplary implementation of the temperature compensation mechanism **250** and the fault determination circuit **260** of FIG. **2**. For each channel, differential input data flows from Data_in+ and Data_in− through the input stage **310** and level shift stage **314** to the drive waveform shaping circuit **238**. The drive waveform shaping circuit **238** generates a current pulse (i.e., a drive waveform) for each data pulse to drive a laser **122** in the laser array **120**.

The VCSEL current pulse shape is optimized by the drive waveform shaping circuit **238** in terms of I_{mod}, I_{bias}, T_{pkw}, and I_{pkd} as shown in FIG. 7. Each channel's output current I_{out} is sent to one of the lasers **122** in the VCSEL array **120**. An exemplary embodiment of the drive waveform shaping circuit **238** is described in greater detail hereinafter with reference to FIG. 4.

Temperature Measurement Block **334**

As the VCSEL operating parameters need to change over time or temperature, the controller **200** updates the drive parameters in real time. For example, adjustments for temperature can occur periodically (e.g., in intervals of 30 milliseconds). In one embodiment, the temperature compensation mechanism **250** can be implemented in part by a temperature measurement block (TMB) **334** and an analog to digital converter **330**. The temperature measurement block (TMB) **334** is a sensor that measures the die substrate temperature. The measured data is then converted to a digital format by the analog-to-digital converter (ADC) **330** and then provided to the controller **200** as the digital temp_ signal. The controller **200** then retrieves (from the EEPROM **130**) new DAC settings for I_{mod}, I_{bias}, T_{pkw}, I_{pkd} based upon the temperature. The new DAC settings are stored in registers (e.g., I_{mod} register **210**, I_{bias} register **214**, T_{pkw} register **218**, I_{pkd} register **224**). Preferably, the registers (herein referred to also as DAC registers) are disposed inside the DACs **234**. The DACs **234** use the current DAC values in these registers (**210, 214, 218, 224**) to set the VCSEL drive waveform parameters.

Similarly, when an aging time point is reached as determined by the aging counter (e.g., the low order aging counter and the high order aging counter), the new DAC settings for I_{mod}, I_{bias}, T_{pkw}, and I_{pkd} are retrieved from the EEPROM, and written to the DAC registers. The VCSEL drive waveform parameters are then adjusted.

Fault Detection Circuit **260**

According to one embodiment, the fault detection circuit **260** includes a resistor (Rfault) **340**, a differential amplifier **344**, a comparator **348**, a DAC **350**, and a buffer **354**. The fault detection circuit **260** determines when the average amount of current flowing through each VCSEL is above a predetermined safety limit. The amount of average VCSEL current is determined by measuring the voltage difference (vfx_del) across the Rfault resistor **340**. The voltage difference across the Rfault resistor **340** is then compared to a predetermined fault threshold vfx_th. The fault threshold vfx_th is programmable by the user and may be stored in the EEPROM **130** and a fault register **290** in the controller **200** as fault_th.

If vfx_del is higher than vfx_th, the comparator **348** changes the state of the fault_flag. A change in state of the fault_flag signal for any channel interrupts the controller **200**. The controller **200** then sets the DAC values for I_{mod}, I_{bias}, T_{pkw}, and I_{pkd} for all N channels, to all zeroes, which in turn changes each channel's VCSEL current to zero milliamperes.

The state of the tx_enable line is toggled for the laser driver **100** to resume operation. Once operation is resumed, the controller **200** retrieves the correct DAC settings based upon temperature and the value in the aging counter. As described previously, the age value may be stored in multiple registers (e.g., age register **280**) in the controller **200**.

Data Waveform Shaping Circuit **238**

FIG. **4** illustrates in greater detail the drive waveform shaping circuit (DWSC) **238** of FIG. **3** according to one embodiment of the present invention. For the sake of brevity, the drive waveform shaping circuit **238** for a single channel is illustrated in FIG. **4** and described hereinafter. It is noted that the drive waveform shaping circuit **238** can be replicated to match the specific number of channels in a particular application.

In this embodiment, the drive waveform shaping circuit **238** includes inputs for receiving differential data signals (DataIn+and DataIn−) and inputs for receiving the output voltage signals from the DAC **234**. Specifically, the drive waveform shaping circuit **238** further includes an input for receiving V_{bias} from the DAC **234**, an input for receiving V_{mod} from the DAC **234**, an input for receiving V_{pkw} from the DAC **234**, and an input for receiving V_{pkd} from the DAC **234**. As described previously, the output voltage signals of the DAC **234** are generated based on drive waveform dc and ac parameters associated with the current age and temperature conditions. Based on these inputs, the drive waveform shaping circuit **238** generates a drive waveform (e.g., the I_{out}) that is provided to an anode of a laser (e.g., an anode of the VCSEL **122**). An example of this drive waveform that has a negative peaking portion is shown in FIG. **7**.

The DWSC **238** includes a plurality of input buffers (**410, 420, 430**, and **440**) for buffering the output voltage signals received from the DAC **234** before providing the voltage signals to the other blocks of the DWSC **238**. It is noted that buffer **420** is an inverting buffer that receives V_{mod} and generates an inverted V_{mod} signal.

The DWSC **238** further includes a voltage controlled current source (VCCS) **450**, an output driver differential transconductance amplifier (ODDTA) **460** that is coupled to the voltage controlled current source **450**, and a negative peaking differential transconductance amplifier (NPDTA) **470** that is also coupled to the voltage controlled current source **450**. The VCCS **450**, ODDTA **460**, and NPDTA **470** selectively shape the drive waveform (I_{out}) based on the input data signals and input voltage signals.

The voltage controlled current source (VCCS) **450** includes an input for receiving the V_{bias2} signal, an input for receiving the inverted V_{mod2} signal, and an input coupled to a supply voltage **454**. Based on these inputs, the VCCS **450** generates I_{source}, which is a dc current sum of I_{bias} and I_{mod}. The logic 1 level of the drive waveform (I_{out}) is equal to I_{source}. A data pulse into the ODDTA **460** causes $I_{modpulse}$ to be subtracted from I_{source} to leave $I_{out}=I_{bias}$ for logic 0 data bits and $I_{out}=I_{bias}+I_{mod}$ for logic 1 data bits.

A power source **480** is coupled to the VCCS **450** through a switch **484** (e.g., a FET switch). The switch **484** selectively opens and closes in response to the fault shutdown signal. When the switch **484** is closed, the supply voltage signal **454** is provided to the VCCS **450**.

The ODDTA **460** includes inputs for receiving the differential data signals (DataIn+and DataIn−) and an input for receiving the inverted V_{mod2} signal. Based on these inputs, the ODDTA **460** produces a current pulse **464** (i.e., $I_{modpulse}$) for every input data pulse. The amplitude of $I_{modpulse}$ is set by a reference voltage provided to the V_{ref} input. Since the reference voltage in this case is equal to the inverted V_{mod2} signal, the amplitude of the current pulses is equal to the amplitude of the I_{mod} signal.

The NPDTA **470** includes inputs for receiving the differential data signals (DataIn+and DataIn−), an input for receiving the V_{pkw2} signal, and an input for receiving the V_{pkd2} signal. Based on these inputs, the NPDTA **470** generates a negative peaking current transient **474** ($I_{negpeaking}$ or I_{np}) for every logic 1 to logic 0 transition observed on the DataIn pulses It is noted that the negative peaking current $I_{negpeaking}$ is aligned with the falling edge of the I_{out} pulse. The negative peaking current transients ($I_{negpeaking}$) are also denoted herein as I_{np}. The negative peaking transient ($I_{negpeaking}$) has current amplitude (depth) and decay time (width) equal to I_{pkd} and T_{pkw}, respectively. The NPDTA **470** employs the V_{pkw2} signal to set the decay time for the negative peaking transient, and the V_{pkd2} signal to set the current amplitude for the negative peaking transient.

In summary, the current sunk by ODDTA **460** is denoted as $I_{modpulse}$, and the current sunk by NPDTA **470** is denoted as $I_{negpeaking}$ or I_{np}. The following expression provides the value of the output current:

$$I_{out}=I_{source}-I_{modpulse}-I_{np}$$

A data pulse causes $I_{modpulse}$ to subtract I_{mod} from I_{source} to leave $I_{out}=I_{bias}$ for logic 0 data bits, and leave $I_{out}=I_{bias}+I_{mod}$ for logic 1 data bits. A 1 to 0 transition causes an I_{np} transient to be subtracted from I_{source} in phase with the 1 to 0 transition.

Methodology

FIG. **5** is a flowchart illustrating the steps performed by the laser driver **100** of FIG. **1** to set and control the VCSEL drive parameters according to one embodiment of the present invention. Each VCSEL **122** in the VCSEL array **120** is characterized and the resulting data is saved. The lasers are then assembled into the MCFOTM **90**. Each transmit channel in the assembled unit is characterized over temperature, and the resulting data is also saved. Then, the saved data is downloaded into the non-volatile memory **130**. Each VCSEL is then independently programmed using the stored parameters. The programming is performed initially upon "power-up" (e.g., when the module is initially installed into a network device, such as a router or switch) and also periodically during operation as described hereinafter.

In step **500**, the voltage versus current (V-I) and VCSEL light output versus current (L-I) are measured for each laser (e.g., VCSEL) **122** in the array **120**. Preferably, these measurements are performed prior to assembly. Test equipment, such as Agilent 4145 Semiconductor Parameter Analyzer and Agilent 8153A Lightwave Multimeter, that are available from Agilent Technologies, Inc. can be employed to make the measurements.

TABLE I sets forth exemplary VCSEL V-I data and L-I data. This data is used by a production test system to determine the DAC settings to use during I_{bias}, I_{mod}, I_{pkd}, and T_{pkw} optimization. The V-I data shows the maximum current range for a given VCSEL so as not to exceed a maximum VCSEL voltage allowed for correct circuit operation. Once the VCSEL current maximum is known, the L-I data is used to calculate the minimum VCSEL current for light output and the VCSEL slope efficiency (i.e., the change in light output with respect to a change in current). The allowable VCSEL current range and VCSEL slope efficiency, determined previously, are then used to calculate starting points for I_{bias}, I_{mod}, I_{pkd}, and T_{pkw} during optimization.

TABLE I

VCSEL Voltage (V)	VCSEL Current (mA)	VCSEL Light Output (mW)
1.49	1.0	0.012
1.67	5.0	1.59

TABLE I-continued

VCSEL Voltage (V)	VCSEL Current (mA)	VCSEL Light Output (mW)
1.80	10.0	4.32
1.92	15.0	6.84

In step **504**, the AC optical waveform for each transmitter channel is measured. Preferably, during production test, the AC optical waveform of each channel is measured and optimized for performance factors by a tester. These performance factors can include, but is not limited to, extinction ratio (i.e., the ratio of logic 1 optical power to logic 0 optical power), rise/fall times, overshoot, jitter, and mask margin. Optimization of the AC optical waveform utilizes the previously recorded VCSEL optical parameters.

AC optical waveform properties are measured for each VCSEL in the transmitter. The I_{bias}, I_{mod}, I_{pkd}, and T_{pkw} DAC settings are varied around the starting points until the AC optical waveform properties are optimized. Preferably, the optimization is performed at a few temperatures. The AC optical waveform properties can include, but is not limited to, extinction ratio (ER), which is the optical power ratio of a logic 1 bit to a logic 0 bit, rise time, fall time, overshoot, and jitter.

The optimum DAC settings for I_{bias}, I_{mod}, I_{pkd}, and T_{pkw} are then calculated for each allowed temperature and aging time point and written to the nonvolatile memory **130**. The nonvolatile memory (e.g., an EEPROM) **130** stores all of the DAC settings for I_{bias}, I_{mod}, I_{pkd}, and T_{pkw}, referenced by temperature and aging time point. These addressable DAC settings are then used to program each VCSEL's current drive waveform during operation. For example, the I_{bias} DAC register stores a number from 0 to 2^M (for an M bit DAC), which is used to generate a voltage V_{bias} on the DAC output. V_{bias} is used by the drive waveform shaping circuit **238** to set the I_{bias} parameter of the VCSEL drive current waveform. Similarly, V_{mod}, V_{pkw}, and V_{pkd} are generated by the other DACs.

In step **508**, DAC settings for each channel are optimized at each temperature and aging point. The DACs **234** are used to convert the drive parameters into an analog signals that are utilized by the drive waveform shaping circuit (DWSC) **238** to generate the drive waveforms.

In one embodiment, the DACs **234** are integrated into the laser driver **100** and are M bits wide. The number of bits M is chosen to provide adequate resolution for each of the parameters. For example, M may be chosen to be 6 bits for typical implementations.

In step **512**, an aging counter divisor (D) is selected. In step **520**, the DAC settings (i.e., drive parameters) are downloaded into the non-volatile memory from a test system, for example. The DAC settings are stored in such a manner as to allow the retrieval of the DAC settings by aging count, temperature, channel number, and DAC number (i.e., the DAC settings in the non-volatile memory are addressable by aging count, temperature, channel number, and DAC number).

In step **530**, the aging counter is started. In step **540**, drive parameters are loaded into the drive registers (**210**, **214**, **218**, and **224**) from the non-volatile memory **130** upon a predetermined condition. The predetermined condition can be, but is not limited to, the passage of time (e.g., every 30 milliseconds) or an interrupt for an aging time point. It is noted that step **540** occurs during the operation of the transmitter module **90**.

In step **550**, the temperature of the laser driver integrated circuit is measured by the temperature measurement block

(TMB) 334. In step 554, the measured temperature is converted into a digital form (e.g., a digital_temp signal) and provided to the controller 200. In step 560, the controller 200 employs the measured temperature as one of the input parameters in a subsequent DAC register write cycle for updating the drive parameter registers (210, 214, 218, and 224).

In step 570, the controller 200 updates a read address for retrieving values for the drive parameters. Processing then proceeds to step 540 where the drive parameter registers are written with values read from the non-volatile memory 130 at the address that may be modified in step 570.

Handling Unsafe Current Conditions

FIG. 6 is a flowchart illustrating the steps performed by the laser driver 100 of FIG. 1 to detect and manage unsafe current conditions according to one embodiment of the present invention. After step 520 of FIG. 5, the steps, described below for detecting and managing unsafe current conditions are performed. In step 610, the current flowing through each VCSEL is measured. In decision block 620, a determination is made whether the measured current is greater than a predetermined safe current. When the measured current is greater than a predetermined safe current, the output current of the laser driver 100 is maintained at a constant minimum current equal to a minimum I_{bias} plus a minimum I_{mod}. Otherwise, when the measured current is not greater than a predetermined safe current, processing loops back to step 610.

In decision block 640, a determination is made whether a valid restart signal (e.g., a tx_enable signal) has been received by the laser driver 100. When a valid restart signal (e.g., a tx_enable signal) has been received by the laser driver 100, the processing proceeds to step 650. In step 650, the TMB 334 and the age register 280 are employed to generate an address based on a temperature value and age value. As noted previously, the nonvolatile memory 130 is addressable by aging count, temperature, channel number, and DAC number. Processing then proceeds to step 540 of FIG. 5, where the drive parameter registers are loaded with the values read from the non-volatile memory 130.

Otherwise, when a valid restart signal (e.g., a Tx_enable signal) has not been received by the laser driver 100, the processing proceeds to step 630 where the laser driver 100 remains in the minimum output current state.

The digital control method and apparatus for driving semiconductor lasers of the present invention has been described in connection with a VCSEL array. However, it is noted that the digital control method and apparatus for driving semiconductor lasers is useful for other applications whenever drive current is needed for driving any type of semi-conductor laser. The digital control method and apparatus for semiconductor lasers of the present invention are especially useful for applications that have temperature fluctuations across array elements, and yet require an even performance across elements in the array. The digital control method and apparatus for semiconductor lasers of the present invention are also useful for applications whose light output tends to degrade over its operating life. The digital control method and apparatus for semiconductor lasers of the present invention are especially useful for applications that can benefit from programming of AC parameters.

In the foregoing specification, the invention has been described with reference to specific embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader scope of the invention. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

1. An optical transmitter comprising:

an array having at least one semiconductor laser;

a memory for storing a plurality of drive waveform parameters;

a driver circuit, coupled to the memory and the array, for receiving data signals and at least one drive waveform parameter, and responsive thereto, for generating at least one drive waveform to drive the semiconductor laser; wherein the drive waveform includes a negative peak portion;

wherein the drive waveform parameters includes at least one parameter for affecting the negative peak portion of the drive waveform.

2. The optical transmitter of claim 1 wherein the array includes a plurality of semiconductor lasers, each of the plurality of semiconductors lasers associated with its own set of drive waveform parameters;

wherein the driver circuit generates an individual drive waveform for each semiconductor laser based on the set of drive waveform parameters associated with that semiconductor laser increasing the uniformity in the resulting optical waveforms of the semiconductor lasers; and

wherein the driver circuit updates at least one drive waveform parameter during the operation of the transmitter based on one of an aging factor of the array and a temperature factor of the array and generates an updated drive waveform based on the updated drive waveform parameter.

3. The optical transmitter of claim 1 wherein the memory stores the dc properties and the ac properties for each semiconductor laser in the array for different age factors and temperature factors; and wherein the driver circuit generates a drive waveform for each semiconductor laser based on the dc properties and ac properties for that semiconductor laser.

4. The optical transmitter of claim 1 wherein the driver circuit includes an integrated digital controller and a temperature sensor for sensing the temperature of the driver circuit; and wherein the integrated digital controller selectively updates the drive waveform parameters based on the temperature of the driver circuit.

5. The optical transmitter of claim 1 wherein the driver circuit includes and integrated digital controller having a timer function for periodically adjusting at least one drive waveform parameter to compensate for aging of the semiconductor laser.

6. The optical transmitter of claim 1 wherein the array includes a 1×N array semiconductor lasers.

7. The optical transmitter of claim 6 wherein the semiconductor laser is a vertical cavity emitting laser (VCSEL).

8. A laser driver for generating drive waveforms that drives an array having at least one semiconductor laser comprising:

a storage for storing a plurality of drive waveform parameters;

a digital controller coupled to the storage for initially accessing a first set of drive waveform parameters that correspond to a first semiconductor laser and subsequently accessing the storage for other sets of drive waveform parameters corresponding to the first semiconductor laser based on one of an age factor and a temperature factor; and

a waveform shaping circuit coupled to the digital controller for receiving the set of drive waveform parameters and responsive thereto for generating a drive waveform that is dependent on the set of drive waveform parameters; wherein the waveform includes a negative peaking portion; and wherein the drive waveform parameters includes at least one parameter for affecting the negative peaking portion of the drive waveform.

9. The laser driver of claim 8 further comprising:

an aging compensation mechanism for monitoring the age of the laser and for providing an age factor for use in selecting a set of drive waveform parameters from the storage to be utilized in generating a drive waveform that compensates for the aging of the laser.

10. The laser driver of claim 8 further comprising:

a temperature compensation mechanism for monitoring the temperature of the driver and for providing a temperature factor for use in selecting a set of drive waveform parameters from the storage to be utilized in generating a drive waveform that compensates for the changes in temperature of the laser.

11. The laser driver of claim 8 wherein the drive waveform parameters includes

at least one dc parameter and at least one ac parameter.

12. The laser driver of claim 8 wherein the drive waveform parameters associated with the drive waveform include one of

bias current, modulation current, negative peaking depth, and negative peaking duration.

13. The laser driver of claim 8 further comprising:

a digital to analog converter for receiving the drive waveform parameters in digital form and responsive thereto for generating corresponding drive waveform parameters in analog form; and

wherein the drive waveform parameters in analog form are provided to the waveform shaping circuit.

14. The laser driver of claim 8 wherein the laser driver is suitable for driving a single vertical cavity surface emitting laser (VCSEL) or an array of vertical cavity surface emitting lasers (VCSELs).

15. A method for providing a drive waveform that includes ac characteristics for at least one semiconductor laser in a laser driver, the laser driver including an integrated digital controller and a storage for storing a plurality of drive waveform parameters, the method comprising the steps of:

employing the digital controller to access from the storage a first set of drive waveform parameters for a first laser; and

generating a drive waveform for driving the first laser based on the first set of waveform parameters;

employing the digital controller to access from the storage a second set of drive waveform parameters during the operation of the laser driver based on one of a temperature factor and an aging factor; and

generating an updated drive waveform for driving the first laser based on the second set of drive waveform parameters;

wherein the waveform includes a negative peaking portion; and

wherein the drive waveform parameters includes at least one parameter for affecting the negative peaking portion of the drive waveform.

16. The method of claim 15 wherein the drive waveform parameters in the storage are organized by laser, temperature factor, and age factor; and wherein adjusting the parameter during the operation of the laser driver includes retrieving at least one updated drive waveform parameter from the storage based on the operating temperature of the semiconductor laser.

17. The method of claim 15 wherein the drive waveform parameters in the storage are organized by laser, temperature factor, and age factor; and wherein adjusting the parameter during the operation of the laser driver includes periodically retrieving at least one updated drive waveform parameter from the storage based on the age of the semiconductor laser.

18. The method of claim 15 wherein employing the digital controller to access from the storage a first set drive waveform parameters for a first laser includes one of:

prior to operation of the first laser,

digital programming of a bias current parameter;

digital programming of a modulation current parameter;

digital programming of a negative peaking depth parameter during an optical one to optical zero transition; and

digital programming of a negative peaking duration parameter during an optical one to optical zero transition.

19. The method of claim 15 wherein employing the digital controller to access from the storage a second set of drive waveform parameters during the operation of the laser driver based on one of a temperature factor and an aging factor includes one of:

digital programming of an updated bias current parameter;

digital programming of an updated modulation current parameter;

digital programming of an updated negative peaking depth parameter during an optical one to optical zero transition; and

digital programming of an updated negative peaking duration parameter during an optical one to optical zero transition.

20. The optical transmitter of claim 1 wherein the drive waveform parameters include a bias current parameter, a modulation current paramerer, a negative peaking depth paramerer, and a negative peaking duration parameter for each semiconductor laser in the array.

* * * * *