Thermal Compensation for Burst-Mode Laser Wavelength Drift

BACKGROUND

[0004] Passive optical networks (PONs) have user or customer end devices and operator end devices in communication with each other. PONs may employ time-division multiplexing, in which end users share a wavelength in different time periods to communicate with the operator end (e.g., optical line termination (OLT)) via an upstream link. Accordingly, some transmitters on the user or customer side, such as those in an optical network unit (ONU), may have lasers working in a burst mode. In the burst mode, an ONU transmitter may be assigned a small time period and may send upstream signals only within its own time period. At other times, the ONU transmitter may have a bias current (or voltage) below its threshold current value (e.g., zero bias current), and therefore stay inactive.

[0005] When a burst-mode laser is enabled, it may emit or transmit an optical signal, on which radio frequency (RF) signals may be added. During emission, a temperature of the laser chip may increase slowly, causing the optical wavelength to drift or shift. In a time- and wavelength-

layer has a thickness no more than 300 nanometers to allow efficient heat transfer from the electric heater to the burst-mode laser, and to block current injection from the heating pad to the electrode pad.

[0009] These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] For a more complete understanding of this disclosure, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description, wherein like reference numerals represent like parts.

[0011] FIG. 1A and FIG. 1B are exemplary simulation results of temperature increase and wavelength shift, respectively, for a distributed feedback (DFB) laser within one burst time period without temperature compensation by a heater.

[0012] FIG. 2A shows an exemplary profile of a heating current used in a simulation.

[0013] FIG. 2B shows an exemplary profile of a laser enable voltage used in the same simulation as FIG. 2A.

[0014] FIG. 3 shows exemplary simulation results of temperature changes of a burst-mode laser under three different conditions: (1) heater only, (2) laser only, and (3) both heater and laser turned on.

[0015] FIG. 4A shows another exemplary profile of a heating current.

[0016] FIG. 4B shows an exemplary profile of a laser enable voltage used in the same simulation as FIG. 4A.

[0017] FIG. 5 shows another exemplary simulation results of temperature changes of the burst-mode laser under three different conditions: (1) heater only, (2) laser only, and (3) both heater and laser turned on.

[0018] FIG. 6 shows a perspective view of an embodiment of a laser system.

[0019] FIG. 7A shows a cross-sectional view of the laser system of FIG. 6 along the A-A line.

[0020] FIG. 7B shows a perspective cross-sectional view of the laser system of FIG. 6 along the B-B line.

[0021] FIG. 7C shows a perspective cross-sectional view of a buried heterostructure DFB laser.

[0022] FIGS. 8A-8D show embodiments of four driving circuits, each for generating a heating current that feeds into a heater.

without any RF signal is emitted, e.g., for reference purposes, the wavelength information and/or power of the optical wave may still be considered types of signals. Embodiments disclosed herein may be applied to any suitable type of burst-mode lasers including DFB lasers and distributed Bragg reflector (DBR) lasers. Further, a burst-mode laser disclosed herein may be located anywhere and be used in any suitable system. For example, the burst-mode laser may reside in a transmitter at the user end (e.g., in an ONU) or at the operator end (e.g., in an OLT) of a PON system. In the present disclosure, functioning of the heat compensation may be discussed first, followed by the structures and fabrication details of the heater.

[0028] When an injection current makes a laser emit an optical signal, the current also heats the laser because the laser has an ohmic contact resistance. The heating causes a temperature of the laser to increase. The temperature of some burst-mode laser chips may be regulated via thermal electric control (TEC), in which case a stable temperature gradient may be formed after several hundred microseconds. Nevertheless, the laser chip temperature may still change due to the applied current and the optical signal.

[0029] FIG. 1A and FIG. 1B are exemplary simulation results of temperature increase and wavelength shift, respectively, for a DFB laser within a burst time period of 125 μs without thermal compensation by a heater. Specifically, FIG. 1A shows the temperature increase with time in an active area of a DFB laser during the burst period with the x-axis being time and the y-axis being the laser active region temperature. FIG. 1B shows the wavelength increase (i.e., red drift) of an optical signal emitted by the DFB laser during the burst period with the x-axis being time and the y-axis being the amount of laser wavelength drift. An average temperature increase for laser optical confinement area may be about 1 Kelvin (K) to 1.5 K over a burst period of about 125 μs, where the temperature increase may also depend on an average output optical power of the laser. FIG. 1A further shows that, at the beginning of burst period, the temperature change is relatively faster, and that, toward the later part of the burst mode period, temperature change may enter into a near-saturation region and vary at a slower slope. The laser temperature change results in an optical wavelength shift. As shown in FIG. 1B, around the working ambient temperature of about 30 degrees Celsius (^{o}C) (or 303 degrees K), 1 K in laser temperature increase may cause the optical wavelength to shift about 0.105 nanometer (nm). Accordingly, an empirical formula may be concluded from the simulation:

$$d\lambda = 0.105 \text{ nm/k} * dT, \quad (1)$$

where $d\lambda$ denotes wavelength shift and dT denotes temperature change. However, these values are only intended as examples, as temperature increase and wavelength shift may also depend on more factors such as an output power level of the laser.

[0030] In order to reduce the wavelength drift when a laser operates in a burst mode and thus stabilize the wavelength, an active area temperature of the laser may be stabilized to reduce temperature change. In an embodiment, a heater may be fabricated on the top of an anode electrode pad for the burst-mode laser. Therefore, the heater resides right on top of the laser active region so that it may heat the laser active area quickly and efficiently. For example, as shown in FIG. 3 (further described below), with application of heat the laser temperature may rise $1^{o}C$ within about 1 μs.

[0031] Various embodiments of heat application dynamically based on a burst enable signal are disclosed herein. In a first embodiment, a burst enable signal (e.g., an ONU transmitter enable signal) and a heating current are applied simultaneously. In other words, the heater starts heating when the laser enabling signal turns on. The burst enable signal may be implemented as any suitable signal (e.g., voltage or current). The burst enable signal controls timing of a burst period and indicates the start of the burst period. The burst-mode laser may start emitting optical signal shortly (e.g., one μs) after the burst enable signal turns from a logic low to a logic high. A heating current for the heater may be designed to have any suitable profile. FIG. 2A shows an exemplary profile of a heating current used in a simulation, and FIG. 2B shows an exemplary profile of a laser enable voltage used in the same simulation.

[0032] As shown in FIG. 2A, the heating current profile has three temporal portions associated with three different steps. The first step is from a start of the burst period to about 1 μs, where the current is set to a maximal level (e.g., about 56 milliampere (mA)). The second step is from about 1 μs to about 10 μs, where the current is reduced to an intermediate or lower level (e.g., about 18.8 mA). The third and last step is from about 10 μs to the end of the burst period, where the heater is turned off with zero current. As shown in FIG. 2B, the burst enable signal stays high throughout the burst period, and turns low at about 125 μs to end the burst period. The laser may start emitting the optical signal with at least one wavelength shortly (e.g., 1 μs) after the burst enable signal turns high (the laser warms up).

[0033] FIG. 3 shows exemplary simulation results of temperature changes of a burst-mode laser under three different conditions. Condition (1), represented by square markers, has the heater

turned on with a current profile shown in FIG. 2A, and has the laser turned off. Condition (2), represented by triangle markers, has the laser turned on with a burst enable voltage profile shown in FIG. 2B, and has the heater turned off. Condition (3), represented by diamond markers, has both the heater and the laser turned on according to the profile in FIG. 2A and FIG. 2B, respectively. As shown in FIG. 2A, the heating current is first set to a maximal level for a short period (e.g., about 1 μs). As shown for condition (1) of FIG. 3, the maximal heating current heats the laser active area quickly, causing an average temperature to rise for about one degree Celsius (e.g., from about 303 K to about 304.1 K) in the first microsecond. After the first microsecond, the heating current may decrease to stop the laser temperature from continuing to increase. As shown in FIG. 2A, the heating current may be lowered (e.g., from about 56 mA to about 18.8 mA) for another short period (e.g., about 10 μs). As shown for condition (1) of FIG. 3, the lower current causes the laser chip temperature to vary or fluctuate over this period (e.g., between about 303.8 K and about 304.2 K). After about 10 μs, the hearting current is turned off, and the laser temperature may naturally decrease over the rest of the burst period (e.g., from about 303.9 K to about 303.1 K).

[0034] Condition (2) of FIG. 3 is similar to FIG. 1B, where the laser temperature increases as a result of its bias and modulation current. Combining conditions (1) and (2) for condition (3) in FIG. 3, it is clear that the decreasing temperature of the heater can compensate for the increasing temperature of the laser, resulting in a largely stabilized temperature profile. Under condition (3), the heater current and the laser enable signal are turned on simultaneously, causing the laser temperature to stay between about 303.9 K and about 304.2 K throughout the burst period. As temperature variation is reduced from about 1 K to less than about 0.3 K, wavelength shift is reduced accordingly. Applying equation (1), $d\lambda = 0.105$ nm * dT, and assuming a temperature change dT of 0.3 K, the wavelength shift would be substantially stable with a shifting range within about 0.0315 nm. The corresponding frequency shift would be within the range of 5 gigahertz (GHz). More generally, when a duration of the burst period is about 125 microseconds, the temperature of the burst-mode laser may be controlled to change no more than about $\pm 0.2^{o}$C, and the wavelength shift of the optical signal may be no more than about ±0.02 nm.

[0035] In a second embodiment of applying heat to a laser based on a burst enable signal, the heat may be applied prior to the start of the burst period. FIG. 4A shows an exemplary profile of a heating current used in a simulation of the second embodiment, FIG. 4B shows an exemplary profile of a laser enable voltage used in the same simulation, and FIG. 5 shows exemplary

diode 814 (denoted as LED2-1) and a resistor 816 (denoted as R2-1); and (3) a current modulator 820 formed with a control input voltage (Vctrl) 822, a transistor (Q2-2) 824 and a resistor (R2-2) 826. Exemplary values for some of the components are given in FIG. 8A.

[0043] In the constant current source 810, the forward voltages of LED2-1 814 may be 1.5 volts (V), and the emitter-base voltage (Veb) of Q2-1 812 may be 0.6 V. Further, both voltages may vary with temperature following a similar voltage-temperature curve. As a result, a difference between the two voltages, which may be applied onto R2-1 816, may be insensitive to (or substantially independent of) the ambient temperature. Consequently, R2-1 816 may be able to produce a constant current substantially independent of the ambient temperature of the driving circuit. In other words, the current may be relatively stable when the temperature changes. Further, the value of R2-1 816 may be selected such that the current is sufficient for heating the laser as discussed above.

[0044] In the current modulator 820, if Vctrl 822 is set to a low value or zero, no current may flow through Q2-2 824. In this case, the heater 802 may accept all the current provided by the constant current source 810. Otherwise, If Vctrl 822 is set higher (e.g., higher than the turn-on threshold voltage for Q2-2 824), at least part of the current from the constant current source 810 may bypass through Q2-2 824 and R2-2 826, thereby reducing a current going through the heater 802. Thus, current modulation may be achieved by controlling a value of Vctrl 822. The response time of the current modulator 820 may be designed to be short (e.g., about 1 nanosecond (ns)) to ensure fast switching or modulation.

[0045] One of ordinary skill in the art would recognize that the driving circuits 830, 860, and 890 shown in FIGS. 8B-8D are largely similar to the driving circuit 800 in FIG. 8A. Thus, similarities are not further discussed. The driving circuit 830 in FIG. 8B may receive the output of a timing circuit 832, which may control the timing of each stage in a current profile (e.g., how long a current stays at a maximal level, a medium level, and zero). The output current of the driving circuit 830 can be preset to a certain value by adjusting the value of a potentiometer 834 (denoted as RV3). The driving circuit 830 may work at an on/off mode. The rising/falling time of the output current (e.g., the time of reaching from the zero level to the maximal level) may be no more than a few ns (e.g., about 1 ns).

[0046] The driving circuit 860 in FIG. 8C and the driving circuit 890 in FIG. 8D may each be precisely controlled with a digital-to-analog (DA) converter, which may be 12 or 16 bits in depth.

What is claimed is:

1. An apparatus comprising:

a burst-mode laser comprising an active layer and configured to emit an optical signal during a burst period, wherein a temperature change of the burst-mode laser causes the optical signal to shift in wavelength; and

a heater thermally coupled to the active layer and configured to:

reduce a wavelength shift of the optical signal during the burst period by applying heat to the active layer based on timing of the burst period;

apply the heat to the active layer before a start of the burst period such that a temperature of the burst-mode laser is substantially stabilized during the burst period; and

receive an electric current for generating the heat,

wherein the electric current reaches a maximal level for a first period before the burst period starts, decreases to an intermediate level for a second period after the start of the burst period, and further decreases to zero during a third period after the second period.

2. The apparatus of claim 1, wherein a duration of the burst period is about 125 microseconds (μs), wherein the temperature of the burst-mode laser varies no more than about 0.2 degrees Celsius (°C.) during the burst period, and wherein the wavelength shift of the optical signal is no more than about 0.02 nanometers (nm) during the burst period.

3. The apparatus of claim 1, wherein the electric current is dedicated to the heater.

4. An apparatus comprising:

a burst-mode laser comprising an active layer and configured to emit an optical signal during a burst period, wherein a temperature change of the burst-mode laser causes the optical signal to shift in wavelength; and

a heater thermally coupled to the active layer and configured to:

reduce a wavelength shift of the optical signal during the burst period by applying heat to the active layer based on timing of the burst period; receive an electric current for generating the heat, wherein the electric current reaches at least three levels during the burst period; and apply the heat to the active layer at a start of the burst period, wherein the electric current reaches a maximal level no later than a start of an emission of the optical signal and then decreases from the maximal level.

5. The apparatus of claim 4, wherein the electric current reaches the maximal level from zero in no more than about 2 nanoseconds (ns), wherein the electric current stays at the maximal level for no more than about 1 microsecond (μs) and then decreases to an intermediate level, and wherein the electric current stays at the intermediate level for no more than about 10 μs and then further decreases to zero for the rest of the burst period.

6. The apparatus of claim 4, wherein the electric current continuously decreases from the maximal level to zero following an exponential curve.

7. A method for temperature compensation during operation of a burst-mode laser that is thermally coupled to a heater, the method comprising:

receiving a burst enable signal indicating a start of a burst period; emitting an optical signal with at least one wavelength during the burst period;

substantially maintaining a temperature of the burst-mode laser throughout an emission of the optical signal to reduce wavelength shift of the optical signal, wherein substantially maintaining the temperature comprises applying, using the heater, heat to the burst-mode laser based on the burst enable signal; and

supplying an electric current to the heater for generating at least the heat applied to the burst-mode laser, wherein the electric current reaches a maximal level no later than the start of the emission of the optical signal and then decreases from the maximal level thereafter.

8. The method of claim 7, wherein the heat is applied to the burst-mode laser prior to the start of the burst period, and wherein the heat is not applied to the burst-mode laser at least during a latter portion of the burst period.

9. The method of claim 8, wherein the electric current reaches the maximal level at least about 4 microseconds (μs) before the start of the burst period, and wherein the electric current decreases to an intermediate level for a first portion of the burst period until the electric current is turned off during the latter portion of the burst period.

10. The method of claim 8, wherein a duration of the burst period is about 125 microseconds (μs), wherein the temperature of the burst-mode laser varies no more than about 0.2 degrees Celsius (°C.) during the burst period, and wherein the wavelength shift of the optical signal is no more than about 0.02 nanometers (nm) during the burst period.

11. The method of claim 7, wherein the electric current and the burst enable signal are received simultaneously at the start of the burst period.

12. The method of claim 11, wherein the electric current reaches the maximal level from zero in no more than about 2 nanoseconds (ns), wherein the electric current stays at the maximal level for no more than about 1 microsecond (μs) and then decreases to an intermediate level, and wherein the electric current stays at the intermediate level for no more than about 10 μs and then further decreases to a zero level for the rest of the burst period.