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- (71) **Applicant:** ALCATEL LUCENT [FR/FR]; 148/152 route de la Reine, 92100 Boulogne-Billancourt (FR).
- (72) **Inventors:** DEBREGEAS, Hélène; III - V Lab, Campus de Polytechnique, 1 avenue Augustin Fresnel, 91767 Palaiseau (FR). BRENOT, Romain; III - V Lab, Campus de Polytechnique, 1 avenue Augustin Fresnel, 91767 Palaiseau (FR). PROVOST, Jean-Guy; III - V Lab, Campus de Polytechnique, 1 avenue Augustin Fresnel, 91767 Palaiseau (FR). PFEIFFER, Thomas; Alcatel-Lucent Deutschland AG, Lorenzstrasse 10, 70435 Stuttgart (DE).
- (74) **Agent:** BERTHIER, Karine; Alcatel-Lucent International, 148/152 route de la Reine, 92100 Boulogne-Billancourt (FR).
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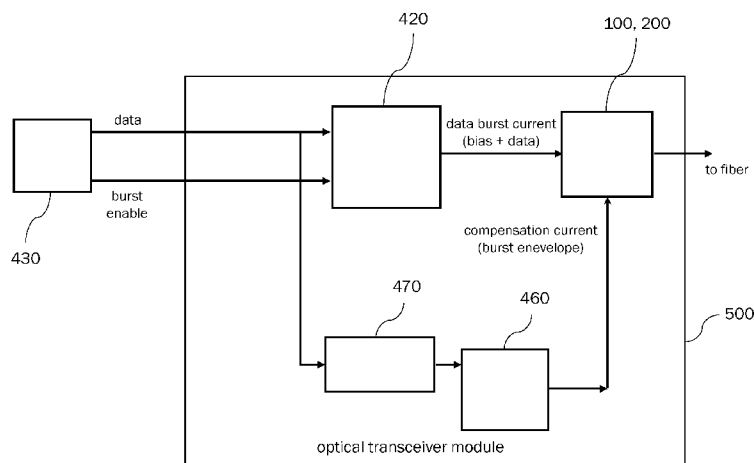


Fig. 5

(57) **Abstract:** This application relates to a laser assembly displaying self-heating mitigation. The laser assembly comprises a semiconductor laser and a drive unit for driving the semiconductor laser. The semiconductor laser comprises: a first semiconductor region for generating or modulating an optical signal in response to a first drive current that is applied to the first semiconductor region, and a heating region that is arranged in proximity to the first semiconductor region and electrically insulated from the first semiconductor region. The drive unit is configured to generate the first drive current and a second drive current, apply the first drive current to the first semiconductor region during respective transmission periods of the semiconductor laser, and apply the second drive current to the heating region in intervals between successive transmission periods. The application further relates to a method for driving a semiconductor laser.



TRANSIENT WAVELENGTH DRIFT REDUCTION IN SEMICONDUCTOR LASERS

Technical Field

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This application relates to laser assemblies (laser modules) comprising semiconductor lasers, particularly for use in burst-mode operation, and to methods for driving semiconductor lasers, particularly in burst-mode operation. The application relates to both laser modules comprising directly modulated lasers (DMLs) and externally modulated lasers (EMLs).

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Background

Directly tunable lasers, such as e.g. distributed feedback (DFB) lasers and to some degree also other laser types such as EMLs suffer from self-heating induced wavelength drifts during burst-mode operation. In signal processing, this drift results in signal degradations when signals generated by these lasers are passed through narrowband wavelength filters at the receive side, e.g. at the optical line termination (OLT) in a time and wavelength division multiplexed passive optical network (TWDM-PON). This leads to unacceptable transmission errors and instabilities in wavelength stabilization schemes based on e.g. received signal strength indication (RSSI) measurements. Thus, without self-heating mitigation, these lasers are not useable in networks with filter widths in the order of 50 GHz or less.

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A number of generic mitigation techniques that are applicable to semiconductor lasers have been proposed so far, e.g. applying accelerated heating, elevated subthreshold bias current or operation at low output powers. However, in order for these mitigation techniques to be efficient, the respective semiconductor laser

would need to be driven in a non-optimal point of operation, resulting in system penalties due to e.g. lower power or degraded eye openings.

Thus, there is a need for improved self-heating mitigation techniques applicable to
5 semiconductor lasers.

Summary

10 In view of this need, the present document proposes a laser assembly and a method of driving a semiconductor laser having the features of the respective independent claims.

An aspect of the disclosure relates to a laser assembly (a laser module). The laser
15 assembly may comprise a semiconductor laser and a drive unit for driving the semiconductor laser. The semiconductor laser may comprise a first semiconductor region for generating or modulating an optical signal in response to a first drive current that is injected (applied) to the first semiconductor region and a heating region that is arranged in proximity to the first semiconductor region and
20 electrically insulated from the first semiconductor region. The drive unit may be configured to generate the first drive current and a second drive current, inject (apply) the first drive current to the first semiconductor region during respective transmission periods (data bursts) of the semiconductor laser, and inject (apply) the second drive current to the heating region in intervals between successive
25 transmission periods (inter burst gaps, IBGs). The heating region may be configured to have characteristics of heat generation that are matched to those of the first semiconductor region, e.g. the heating region and the first semiconductor region may have substantially the same characteristics of heat generation. The heating region may be for example a second semiconductor region, a parallel
30 waveguide or a metallic heater made of resistive material. The heating region may

be configured to not emit any light when injected with the second drive current (i.e. may be optically inactive, e.g. due to including deep electron traps or being appropriately doped otherwise), or to not emit any light that would be coupled into an optical fiber that is attachable to the semiconductor laser to receive the optical
5 signal generated or modulated by the first semiconductor region. This may require optically insulating the heating region from the first semiconductor region. In consequence, the first semiconductor region may be referred to as an active region, whereas the heating region may be referred to as a passive region, or dummy region.

10

Configured as above, heat is generated in the heating region during the IBGs and transferred to the first semiconductor region. Thereby, a temperature drop in the first semiconductor region during IBGs may be avoided, or at least mitigated. A difference between the temperature of the first semiconductor region at the
15 beginning of each transmission period and a temperature of the first semiconductor region at the end of the respective transmission period thus vanishes or is at least reduced. Since the drift in emission wavelength depends on the rise of temperature of the first semiconductor region between the beginning of an IBG and the end of the respective IBG, the drift in emission wavelength is
20 altogether avoided or at least mitigated in the above laser assembly. This makes the above the laser assembly a perfect candidate for use e.g. in TWDM-PONs with filter widths of 50 GHz or less, such as a NG-PON2 network.

In embodiments, the first semiconductor region may be one of an active region of a
25 laser section of a semiconductor laser (e.g. a DML or an EML), an active region of an external modulator section of a semiconductor laser (e.g. an EML), or an active region of a semiconductor optical amplifier (SOA). Further, the first semiconductor region may be an active region of any other section of a semiconductor laser that generates heat due to current injection.

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In embodiments, the heating region may have a high frequency response (time response) substantially identical (or at least, similar) to a high frequency response of the first semiconductor region. Likewise, circuitry for driving the heating region (including wiring and wire bonding; e.g. a circuit path) may have a high frequency response (time response) substantially identical (or at least, similar) to a high frequency response of circuitry for driving the first semiconductor region, i.e. both may be equally (or at least similarly) suitable for high frequency operation.

In embodiments, the heating region may have substantially the same shape and material composition (e.g. the same doping profile) as the first semiconductor region.

Thereby, if a second semiconductor region has been chosen to be the heating region, the second semiconductor region with appropriate characteristics of heat generation may be provided in a particularly simple manner, without extensive simulations of heat generation. Moreover, manufacturing of the semiconductor laser is particularly simple since merely the steps that lead to creation of the first semiconductor region need to be repeated.

In embodiments, the heating region may be arranged relative to the first semiconductor region so that heat generated by the heating region may diffuse to the first semiconductor region and heat up the first semiconductor region. Further, the characteristics of heat generation of the heating region may be chosen in such a manner that a heat transfer from the heating region to the first semiconductor region during the intervals between successive transmission periods is dimensioned so that a temperature of the first semiconductor region during the intervals between successive periods of transmission is kept at the same level as during the transmission periods. This translates into the requirement that heat losses of the first semiconductor region during intervals between transmission periods are compensated for by heat transfer from the heating region to the first

semiconductor region. More specifically, the second drive current and the characteristics of heat generation of the heating region may be chosen to attain this goal. Thereby, the temperature of the first semiconductor region may be kept substantially constant across the transmission periods and the intervals there
5 between.

Configured as above, a drift of the emission wavelength is effectively removed.

In embodiments, the semiconductor laser may further comprise another heating
10 region that is electrically insulated from the first semiconductor region and arranged in proximity to the first semiconductor region such that the first semiconductor region is sandwiched between the heating region and the another heating region. The drive unit may be further configured to apply a third drive current to the another heating region in the intervals between successive
15 transmission periods. The third drive current may be identical to the second drive current. The another heating region may be configured to have characteristics of heat generation that are matched to those of the first semiconductor region. The another heating region may be for example a third semiconductor region, another parallel waveguide or another metallic heater made of resistive material. The
20 another heating region may be configured to not emit any light when injected with the drive current (i.e. may be optically inactive, e.g. due to including deep electron traps or being appropriately doped otherwise), or to not emit any light that would be coupled into an optical fiber that is attachable to the semiconductor laser to receive the optical signal generated or modulated by the first semiconductor
25 region. This may require optically insulating the another heating region from the first semiconductor region. In consequence, also the another heating region may be referred to as a passive region, or dummy region.

By providing two passive heating regions sandwiching the first semiconductor region, the first semiconductor region may be more uniformly heated and compensation of the drift of the emission wavelength may be further improved.

- 5 In embodiments, the another heating region may be arranged relative to the first semiconductor region so that heat generated by the another heating region may diffuse to the first semiconductor region and heat up the first semiconductor region. Further, the characteristics of heat generation of the heating region and the another heating region may be chosen in such a manner that a heat transfer from
- 10 the heating region and the another heating region to the first semiconductor region during the intervals between successive transmission periods is dimensioned such that a temperature of the first semiconductor region during the intervals between successive periods of transmission is kept at the same level as during the transmission periods. This translates into the requirement that heat
- 15 losses of the first semiconductor region during intervals between transmission periods are compensated for by heat transfer from the heating region and the another heating region to the first semiconductor region. More specifically, the second and third drive currents and the characteristics of heat generation of the heating region and the another heating region may be chosen to attain this goal.
- 20 Thereby, the temperature of the first semiconductor region may be kept substantially constant across the transmission periods and the intervals there between.

- In embodiments, the another heating region may have a high frequency response
- 25 (time response) substantially identical (or at least, similar) to a high frequency response of the first semiconductor region. Likewise, circuitry for driving the another heating region (including wiring and wire bonding; e.g. a circuit path) may have a high frequency response (time response) substantially identical (or at least, similar) to a high frequency response of circuitry for driving the first semiconductor

region, i.e. both may be equally (or at least similarly) suitable for high frequency operation.

In embodiments, the drive unit is configured to generate the second drive current
5 such that the second drive current is different from zero during at least a portion of
each of the intervals between successive transmission periods. For example, the
second drive current may relate to a sequence of current pulses that each extend
over the full length of a respective interval between successive transmission
periods. The same may apply to the third drive current. For example, the third drive
10 current may be identical to the second drive current.

In embodiments, the drive unit may be configured to generate the first drive
current on the basis of an input signal comprising a data signal indicative of data to
be transmitted by means of the optical signal. The drive unit may be further
15 configured to generate the second drive current on the basis of the first drive
current or the input signal.

Thereby, synchronicity between the second drive current and the IBGs can be
ensured. Moreover, the second drive current can be specifically adapted to
20 compensate for the heat loss of the first semiconductor region during the IBGs. The
reason is that said heat loss depends, among others, on the temperature of the first
semiconductor region at the end of the respective transmission period, and said
temperature in turn depends on the data transmitted during the respective
transmission period, i.e. on the input data.

25

Another aspect of the disclosure relates to a method of driving a semiconductor
laser. The semiconductor laser may comprise a first semiconductor region for
generating or modulating an optical signal in response to a first drive current that is
applied to the first semiconductor region, and a heating region that is arranged in
30 proximity to the first semiconductor region and electrically insulated from the first

semiconductor region. The heating region may be configured to have characteristics of heat generation that are matched to those of the first semiconductor region, e.g. the heating region and the first semiconductor region may have substantially the same characteristics of heat generation. The heating region may be for example a second semiconductor region, a parallel waveguide or a metallic heater made of resistive material. The heating region may be configured to not emit any light when injected with the second drive current (i.e. may be optically inactive, e.g. due to including deep electron traps or being appropriately doped otherwise), or to not emit any light that would be coupled into an optical fiber attachable to the semiconductor laser to receive the optical signal generated or modulated by the first semiconductor region. This may require optically insulating the heating region from the first semiconductor region. In consequence, the first semiconductor region may be referred to as an active region, whereas the heating region may be referred to as a passive region, or dummy region. If a second semiconductor region has been chosen to be the heating region, each semiconductor region may correspond to a semiconductor layer or part of a semiconductor layer. The method may comprise applying the first drive current to the first semiconductor region during respective transmission periods of the semiconductor laser. The method may further comprise applying a second drive current to the heating region in intervals between successive transmission periods.

In embodiments, the semiconductor laser may further comprise another heating region that is electrically insulated from the first semiconductor region and arranged in proximity to the first semiconductor region such that the first semiconductor region is sandwiched between the heating region and the another heating region. The method may further comprise applying a third drive current to the another heating region in the intervals between successive transmission periods. The third drive current may be identical to the second drive current. The another heating region may be configured to have characteristics of heat generation that are matched to those of the first semiconductor region. The

another heating region may be for example a third semiconductor region, another parallel waveguide or another metallic heater made of resistive material. The another heating region may be configured to not emit any light when injected with the drive current (i.e. may be optically inactive, e.g. due to including deep electron
5 traps or being appropriately doped otherwise), or to not emit any light that would be coupled into an optical fiber that is attachable to the semiconductor laser to receive the optical signal generated or modulated by the first semiconductor region. This may require optically insulating the another heating region from the first semiconductor region. In consequence, also the another heating region may
10 be referred to as a passive region, or dummy region.

In embodiments, the second drive current may be different from zero during at least a portion of each of the intervals between successive transmission periods. For example, the second drive current may relate to a sequence of current pulses
15 that each extend over the full length of a respective interval between successive transmission periods. The same may apply to the third drive current. For example, the third drive current may be identical to the second drive current.

In embodiments, the method may further comprise generating the first drive
20 current on the basis of an input signal comprising a data signal indicative of data to be transmitted by means of the optical signal, and generating the second drive current on the basis of the first drive current or the input signal.

It will be appreciated that method steps and apparatus features may be
25 interchanged in many ways. In particular, the details of the disclosed apparatus can be implemented as a method, as the skilled person will appreciate.

Brief Description of the Figures

Embodiments of the disclosure are explained below in an exemplary manner with reference to the accompanying drawings, wherein

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Fig. 1 schematically illustrates an example of a semiconductor laser according to embodiments of the disclosure;

Fig. 2 schematically illustrates another example of a semiconductor laser according to embodiments of the disclosure;

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Fig. 3 schematically illustrates another example of a semiconductor laser according to embodiments of the disclosure;

Fig. 4 and **Fig. 5** schematically illustrate examples of laser assemblies according to embodiments of the disclosure;

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Fig. 6 is a schematic timing diagram of time-dependent quantities related to operation of the laser assemblies illustrated in **Fig. 4** and **Fig. 5**;

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Fig. 7 and **Fig. 8** schematically illustrate further examples of laser assemblies according to embodiments of the disclosure;

Fig. 9 is a schematic timing diagram of time-dependent quantities related to operation of the laser assemblies illustrated in **Fig. 7** and **Fig. 8**;

25

Fig. 10 schematically illustrates a facet of a semiconductor laser device according to one embodiment of the disclosure;

Fig. 11 is a schematic set-up to demonstrate the effectiveness of the semiconductor laser device illustrated in **Fig. 10** according to one embodiment of the disclosure; and

- 5 **Fig. 12** is a schematic timing diagram of time-dependent quantities related to the effectiveness of the semiconductor laser device illustrated in **Fig. 10** using the demonstrating set-up of **Fig. 11** according to one embodiment of the disclosure.

10 Detailed Description

The basic idea in this disclosure consists in maintaining the temperature constant in the area of the laser waveguide, whether the laser is turned on or off. During data bursts, laser temperature is increased by ΔT due to self-heating. When the laser is
15 turned off at the end of a data burst, a heating region or a heating parallel device positioned along the laser waveguide is synchronously heated in order to locally heat the laser by the same ΔT . Therefore, the laser is always at a temperature equal to thermoelectric cooler controller (TEC) temperature + ΔT . ΔT is obtained by the laser self-heating during data bursts, and by the heating region or the parallel
20 heating device between data bursts. Due to the proximity between the laser waveguide and the heating region or parallel heating device, the laser heating by the heating device or the heating region is almost instantaneous. Thus, the temperature is kept constant and there is no flux of heat towards the submount and Peltier control. The heating region or the parallel heating device can be for
25 example a semiconductor region, a parallel fake waveguide, or a metallic heater made of resistive material, e.g. Chromium (Cr), Platinum (Pt) or others.

In a directly modulated laser, such as a DFB laser, the injection current (first drive current) modulates the gain in the DFB section (active section/stripe, gain section/stripe, or first semiconductor region) of the laser. Almost the entire
30 electrical energy is converted into heat, leading to the observed wavelength-drift

over time during short data bursts. To prevent occurrence of these wavelength transients during data bursts (during transmission periods) it is proposed to implement an additional dummy section (a heating region) close to the active section of the laser which is electrically driven during the gaps between data bursts (inter-burst-gaps, IGBs, or intervals between successive transmission periods), thus
5 generating heat even when no optical signals are generated. For instance, a dummy stripe may be provided in parallel to the active stripe.

Then, due to this constant generation of heat in the semiconductor laser during
10 both data bursts and IGBs there will be no more variation of the emission wavelength during the generation of optical signals during data bursts.

The heat (and correspondingly, the temperature) in the active section of the laser should remain constant over time, irrespective of whether or not optical data is
15 generated. In order to accomplish this, the dummy stripe should be positioned (arranged) close to the active stripe (typically only a few micrometers apart) and preferably have a shape and material composition very similar (e.g. substantially identical) to the active stripe.

20 However, care must be taken not to generate additional light during the IGBs, or alternatively, to prevent such light that is generated during the IGBs from being coupled into the optical fiber that receives the optical signal output from the semiconductor laser. This may be ensured by an appropriate design of the laser structure and optionally by an appropriate treatment of the dummy section, e.g. by
25 introducing deep level electronic traps into the dummy section for reducing the radiative electron-hole recombination rate or by otherwise doping the dummy section to prevent emission of light.

Fig. 1 schematically illustrates an example of a semiconductor laser 100 according
30 to embodiments of the disclosure. The semiconductor laser 100 comprises a

semiconductor material 110, 120, a first semiconductor region (active region, active stripe) 130 for generating or modulating an optical signal in response to a first drive current that is applied to the first semiconductor region 130 during transmission periods (but not during IBGs), and a second semiconductor region (dummy region, dummy stripe) 140 as heating region. The second semiconductor region 140 may be arranged in proximity to the first semiconductor region such that heat generated in the second semiconductor region 140 may diffuse to the first semiconductor region 130. The second semiconductor region 140 may be arranged in parallel to the first semiconductor region 130. Further, the second semiconductor region 140 may be electrically insulated from the first semiconductor region 130. This may be achieved e.g. by providing an appropriate doping profile between the first semiconductor region 130 and the second semiconductor region 140 (i.e. by providing an insulation layer), or by providing an air-filled gap between the first semiconductor region 130 and the second semiconductor region 140. Moreover, the second semiconductor region 140 may be optically inactive and/or be optically insulated from the first semiconductor region 130, as indicated above.

The above reference to a directly modulated laser, such as a DFB laser, is understood to indicate an example, without intended limitation of the present disclosure. In general, the first semiconductor region may be one of an active region of a laser section of a semiconductor laser (e.g. a DML or an EML), an active region of an external modulator section of a semiconductor laser (e.g. an EML), or an active region of an SOA. Further, the first semiconductor region may be an active region of any other section of a semiconductor laser that generates heat due to current injection.

The second semiconductor region 140 may be electrically driven by a second drive current during the IBGs, but not during the transmission periods. The second drive current may relate e.g. to a single current pulse lasting over the entire duration of the IBG or to a sequence of current pulses representing a sequence of dummy data

(e.g. a "1010" sequence) during the IBG. In the former case the second semiconductor region 140 needs to handle lower electrical bandwidths (typically few MHz) as compared to the latter case (few GHz) and may therefore be the preferred case. Notably, there is freedom in the choice of the signal structure of the second drive current, as long as requirements described further below are met.

The second semiconductor region 140 may have characteristics of heat generation (e.g. indicative of a time dependence of heat generation and an amount of heat generation in dependence on an injected drive current) matched to those of the first semiconductor region 130. For instance, the characteristics of heat generation of the second semiconductor region may be substantially identical to those of the first semiconductor region 130. This may be achieved by providing the second semiconductor region with the same shape and material composition (e.g. same doping profile) as the first semiconductor region 130.

In most general terms, the requirements for the structure of the second drive current and for the characteristics of heat generation of the second semiconductor region 140 are that the amount of heat generated by the second semiconductor region 140 driven by the second drive current and arriving in the first semiconductor region 130 during the IGBs must be identical to the heat generated by the first semiconductor region 130 during the real data bursts. Said heat generated by the second semiconductor region 140 depends on both the second drive current and the characteristics of heat generation of the second semiconductor region 140. It may be further required to also take into account time constants and losses in the heat transfer between the second semiconductor region 140 and the first semiconductor region 130, which may depend on the relative arrangement of the first and second semiconductor regions 130, 140.

In other words, the characteristics of heat generation of the second semiconductor region 140 and the second drive current need to be chosen in such a manner that a

heat transfer from the second semiconductor region 140 to the first semiconductor region 130 during the IBGs is dimensioned so that a temperature of the first semiconductor region 130 during the IBGs is kept at the same level as during the transmission periods, i.e. so that the temperature of the first semiconductor region 130 is kept substantially constant across transmission periods and IBGs during operation in burst mode.

In embodiments, two dummy sections may be implemented, one on either side of the active stripe. This situation is illustrated in **Fig. 2**. The semiconductor laser 200 illustrated in **Fig. 2** comprises the regions described above in connection with **Fig. 1**, and additionally a third semiconductor region (dummy region, dummy section, dummy stripe) 150 as another heating region. The second and third semiconductor regions 140, 150 are sandwiching the first semiconductor region 130. The third semiconductor region 150 may be arranged in proximity to the first semiconductor region such that heat generated in the third semiconductor region 150 may diffuse to the first semiconductor region 130. The third semiconductor region 150 may be arranged in parallel to the first semiconductor region 130. Further, the third semiconductor region 150 may be electrically insulated from the first semiconductor region 130. This may be achieved e.g. by providing an appropriate doping profile between the first semiconductor region 130 and the third semiconductor region 150 (i.e. by providing an insulation layer), or by providing an air-filled gap between the first semiconductor region 130 and the third semiconductor region 150. Moreover, the third semiconductor region 150 may be optically inactive and/or be optically insulated from the first semiconductor region 130. This may be achieved in the same manner as described above in connection with the second semiconductor region 140.

The third semiconductor region 150 may be electrically driven by a third drive current during the IGBs, but not during the transmission periods. Similar to the second drive current, the third drive current may relate e.g. to a single current pulse

lasting over the entire duration of the IBG or to a sequence of current pulses representing a sequence of dummy data (e.g. a "1010" sequence) during the IBG. For simplicity, the third drive current may be identical to the second drive current.

- 5 The third semiconductor region 150 may have characteristics of heat generation (e.g. indicative of a time dependence of heat generation and an amount of heat generation in dependence on an injected drive current) matched to those of the first semiconductor region 130. For instance, the characteristics of heat generation of the third semiconductor region 150 may be substantially identical to those of the
10 first semiconductor region 130.

In any case, the characteristics of heat generation of the third semiconductor region 150 and the third drive current need to be chosen in such a manner that a heat transfer from the third semiconductor region 150 to the first semiconductor region 130 during the IBGs is dimensioned so that a temperature of the first
15 semiconductor region 130 during the IBGs is kept at the same level as during the transmission periods. More precisely, the characteristics of heat generation of the second and third semiconductor regions 140, 150 and the second and third drive currents need to be chosen in such a manner that a heat transfer from the second
20 and third semiconductor regions 140, 150 to the first semiconductor region 130 during the IBGs is dimensioned so that a temperature of the first semiconductor region 130 during the IBGs is kept at the same level as during the transmission periods.

- 25 **Fig. 10** illustrates a front scheme of the structure of a semiconductor laser device according to one embodiment of the disclosure, where a scheme of a facet of the semiconductor laser device cut in the middle of laser waveguide is shown. The semiconductor laser device 1000 comprises a semiconductor material 1010, which may be for example a Indium Phosphide (InP) chip, a laser waveguide 1030 for
30 generating or modulating an optical signal in response to a first drive current that is

applied thereto during transmission periods, e.g. data bursts, and a heating region or a parallel heating device 1040, which may be for example a Nickel-Chromium (NiCr) resisting stripe. The heating region or the parallel heating device 1040 may be located on the top of the semiconductor material 1010, aside the laser waveguide 1030. The NiCr resistance is controlled by injecting electrical current or applying a voltage between two electrodes positioned at the extremities. In this semiconductor laser device, the heating region or the parallel heating device 1040 serving as a heater is e.g. 20µm away from the laser waveguide 1030. The electrical current injected to the heater 1040 corresponding to a second drive current may be obtained from the voltage applied to the heater 1040. For further improvement, the heater 1040 could be brought even closer to the laser waveguide 1030. When the laser is turned on during data bursts, or when a voltage is applied to the heater 1040 at the end of the data burst, heat is generated locally around the laser waveguide 1030. Owing to the proximity between the heater 1040 and the laser waveguide 1030 (e.g. ~20µm) compared to the InP chip thickness (e.g. ~120µm), temperature at the bottom of the InP chip remains almost constant when switching from laser self-heating to heater operation and there is no variation of heat flux towards the InP chip bottom.

Fig. 4 and **Fig. 5** schematically illustrate examples of laser assemblies (laser modules) 400, 500 according to embodiments of the disclosure, which may comprise each of the above-described semiconductor lasers.

Both laser assemblies 400, 500 comprise a semiconductor laser 100, 200 as described above, and a drive circuit (laser driver) 420 for driving the first semiconductor region 130 of the semiconductor laser 100, 200, i.e. for generating the first drive current for the semiconductor laser 100, 200. The laser assembly 400, 500 receives an input signal from a logic circuit (e.g. a PON logic) 430 that is fed to the drive circuit 420. The laser assemblies 400, 500 further comprise a pulse

generation circuit (pulse generator) 460. The laser assembly 500 in **Fig. 5** further comprises an averaging circuit (averager) 470.

The input signal generated by the logic circuit 430 may comprise a burst enable
5 signal (a sequence of rectangular pulses, each rectangular pulse corresponding to a respective transmission period) indicating transmission periods of the semiconductor laser 100, 200 and biasing the semiconductor laser 100, 200 at its operation point, and a data signal indicating actual data to be transmitted by means of optical emission by the semiconductor laser 100, 200. The burst enable
10 signal and the data signal are fed to the drive circuit 420. The drive circuit 420 generates the first drive current that is applied to the first semiconductor region 130 of the semiconductor laser 100, 200 on the basis of the input signal, i.e. on the basis of the burst enable signal and/or the data signal. The first drive current is zero during the IBGs, i.e. a drive current is not applied to the first semiconductor region
15 130 during the IBGs.

In the laser assembly 400 in **Fig. 4**, the burst enable signal is additionally fed to the pulse generation circuit 460. The pulse generation circuit 460 generates, on the basis of the burst enable signal, the second drive current that is applied to the
20 heating region, e.g. the second semiconductor region 140 and, if present, also to the another heating region, e.g. the third semiconductor region 150. For example, the second drive current may be generated to be proportional to the inverted burst enable signal, or to correspond to a dummy sequence during the IBGs (i.e. when the burst enable signal is zero). The second drive current is zero during the
25 transmission periods, i.e. a drive current is not applied to the second semiconductor region 140 (and the third semiconductor region 150) during transmission periods.

In the laser assembly 500 in **Fig. 5**, the data signal is fed to the averaging circuit
30 470. The averaging circuit 470 may be implemented by a suitable low pass filter.

The averaging circuit 470 generates an envelope of the data signal e.g. by averaging the data signal. The generated envelope is fed to the pulse generation circuit 460. The pulse generation circuit 460 generates, on the basis of the envelope of the data signal, the second drive current that is applied to the second semiconductor region 140 and, if present, also to the third semiconductor region 150. For example, the second drive current may be generated to be proportional to the inverted envelope of the data signal, or to correspond to a dummy sequence during the IBGs (i.e. when the envelope of the data signal is zero).

10 In the above, the drive circuit 420 and the pulse generation circuit 460 in the case of **Fig. 4** and the drive circuit 420, the pulse generation circuit 460, and the averaging circuit 470 in the case of **Fig. 5** may be said to form a drive unit for driving the semiconductor laser 100, 200. The drive unit generates the first and second drive currents. The drive unit further applies the first drive current to the first semiconductor region 130, and the second drive current to the second semiconductor region 140 (and the third semiconductor region 150, if present). The (non-zero) first drive current is applied to the first semiconductor region 130 during the transmission periods, and the (non-zero) second drive current is applied to the second semiconductor region 140 (and the third semiconductor region 150, if present) during the IBGs.

Fig. 6 is an exemplary schematic timing diagram of time-dependent quantities related to operation of the laser assemblies 400 and 500 illustrated in **Fig. 4** and **Fig. 5**. The topmost diagram 610 indicates an example of the first drive current output by the drive circuit 420 and injected to the first semiconductor region 130 of the semiconductor laser 100, 200, and the output optical power of the semiconductor laser 100, 200. In this schematic representation, the first drive current and the output optical power are illustrated to have qualitatively the same variation in time. The second diagram 620 from the top indicates an example of the laser temperature within the first semiconductor region 130 and the emission

wavelength of the optical signal output by the semiconductor laser 100, 200 during data bursts, both for a case in which the self-heating mitigation technique according to the disclosure is not applied. Also the laser temperature and the emission wavelength are schematically illustrated to have qualitatively the same variation in time. Needless to say, the emission wavelength is understood to be zero during intervals between data bursts. The third diagram 630 from the top indicates an example of the second drive current that is applied to the heating region, e.g. the second semiconductor region 140 (and the another heating region, e.g. the third semiconductor region 150, if present). The fourth diagram 640 from the top indicates an example of the temperature of the first semiconductor region 130 induced by heat generated in the second semiconductor region 140 (and the third semiconductor region 150, if present), ignoring any heat generated by the first semiconductor region 130 during transmission periods. The lowermost diagram 650 indicates an example of the net temperature of the first semiconductor region 130 and the emission wavelength of the optical signal output by the semiconductor laser 100, 200 during data bursts for the case in which the self-heating mitigation technique according to the disclosure is applied. Also the net temperature and the emission wavelength are schematically illustrated to have qualitatively the same variation in time.

20

As can be seen from **Fig. 6**, without applied self-heating mitigation technique, the laser temperature rises during data bursts, and the emission wavelength of the optical signal increases proportionally to the temperature increase. The second drive current has a constant level during the IBGs, and is zero during the transmission periods. Further, the heat transferred to the first semiconductor region 130 during the IBGs prevents a cooling off of the first semiconductor region 130 during the IBGs and keeps constant the temperature of the first semiconductor region 130 across periods of transmission and IBGs. Accordingly, if the self-heating mitigation technique according to the disclosure is applied, the emission

wavelength of the optical signal is substantially constant over time during data bursts.

The above considerations are easily adapted to other than directly modulated laser structures. For example, in case of an externally modulated laser (EML), the transient heat generation occurs in the electrical absorption modulator (EAM) as well as in the gain section, if the laser section is activated only during bursts. If an additional on-chip SOA is used, e.g. for power levelling or for boosting the output power, then also this element will generate heat bursts on the chip. In all these cases additional dummy heating sections will help keep the temperature of the active stripe constant over time, thus preventing wavelength drifts. A dummy section can be specially designed to compensate for the net effect of all the transient heat generation in the different sections of the semiconductor laser. This requires thermal modelling of the laser structure. A dummy section used as a heating region can be for example a semiconductor region, a parallel fake waveguide, or a metallic heater made of resistive material. If a semiconductor region is chosen to be the dummy heating section, an alternate and possibly simpler approach is to just copy the respective heat generating sections of the laser structure and place them as dummy elements next to the original elements and drive them during the IBGs with appropriate electrical currents, as discussed above.

Fig. 3 schematically illustrates another example of a semiconductor laser 300 according to embodiments of the disclosure, which is an EML. The semiconductor laser 300 comprises a laser section (left-hand side) and an external modulator section (right-hand side). The externally modulated optical signal is emitted from the semiconductor laser 300 in a direction pointing to the right in **Fig. 3**. The laser section comprises a first semiconductor region 330 which is an active section for generating an optical signal as well as second and third semiconductor regions 340, 350, which are dummy sections used as heating regions. Either one of the second and third semiconductor regions 340, 350 may be omitted. The external modulator

section comprises a first semiconductor region 335, which is an active section for modulating the optical signal generated by the first semiconductor region 330 of the laser section, as well as second and third semiconductor regions 345, 355, which are dummy sections. Either one of the second or third semiconductor regions 345, 355 of the external modulation section may be omitted. The first semiconductor region 330 of the laser section is driven by a first drive current for the laser section, and the second and third semiconductor regions 340, 350 of the laser section are driven by a second drive current for the laser section. The first semiconductor region 335 of the external modulator section is driven by a first drive current for the external modulator section, and the second and third semiconductor regions 345, 355 of the external modulator section are driven by a second drive current for the external modulator section. It is understood that any statements made earlier with respect to the second and third semiconductor regions and respective drive currents also apply to the configuration illustrated in **Fig. 3**.

By providing the second and/or third semiconductor region 345, 355 of the external modulator section, an amount of heat generated by the external modulator section can be kept constant across transmission periods and IBGs. Accordingly, an amount of heat transferred to the laser section is constant over time and will not cause a drift of the emission wavelength of the first semiconductor region of the laser section. In other words, operating the external modulator section in burst mode does not cause a drift of the emission wavelength of the laser section.

Likewise, one or more dummy regions may be provided as heating regions for any other active region of a semiconductor laser that generates heat due to current injection, such as the active region of an SOA. Thereby, an amount of heat that is transferred to the laser section is kept constant over time and will not cause a drift of the emission wavelength of the laser section of the semiconductor laser.

Fig. 7 and **Fig. 8** schematically illustrate further examples of laser assemblies (laser modules) 700, 800 according to embodiments of the disclosure, which may comprise the semiconductor laser 300 described with reference to **Fig. 3**. Unless indicated otherwise, statements analogous to those made earlier with respect to
5 corresponding components of the respective laser assemblies in **Fig. 4** and **Fig. 5** are understood to apply also here.

Both laser assemblies 700, 800 comprise a semiconductor laser 300 as described above, and a drive circuit (laser driver) 720 for driving the first semiconductor
10 regions 330, 335 of the laser section and the external modulator section of the semiconductor laser 300, i.e. for generating the first drive current for the laser section and the first drive current for the external modulator section of the semiconductor laser 300. The laser assembly 700, 800 receives an input signal from a logic circuit (e.g. a PON logic) 730 that is fed to the drive circuit 720. The laser
15 assemblies 700, 800 further comprise a pulse generation circuit (pulse generator) 760. The laser assembly 800 in **Fig. 8** further comprises an averaging circuit (averager) 770.

The input signal generated by the logic circuit 730 corresponds to that described
20 above with reference to **Fig. 4** and **Fig. 5** and may comprise a burst enable signal and a data signal. The burst enable signal and the data signal are fed to the drive circuit 720. The drive circuit 720 generates the first drive current for the laser section that is applied to the first semiconductor region 330 of the laser section of the semiconductor laser 300 on the basis of the input signal, i.e. on the basis of the
25 burst enable signal and/or the data signal. The drive circuit 720 further generates the first drive current for the external modulator section that is applied to the first semiconductor region 335 of the external modulator section of the semiconductor laser 300 on the basis of the input signal, i.e. on the basis of the burst enable signal and/or the data signal.

30

In the laser assembly 700 in **Fig. 7**, the burst enable signal is additionally fed to the pulse generation circuit 760. The pulse generation circuit 760 generates, on the basis of the burst enable signal, the second drive current for the laser section that is applied to the heating region, e.g. the second semiconductor region 340 and, if present, also to the another heating region, e.g. the third semiconductor region 350 of the laser section of the semiconductor laser 300. Further, the pulse generation circuit 760 generates, on the basis of the burst enable signal, the second drive current for the external modulator section that is applied to the heating region, e.g. the second semiconductor region 345 and, if present, also to the another heating region, e.g. the third semiconductor region 355 of the external modulator section of the semiconductor laser 300.

In the laser assembly 800 in **Fig. 8**, the data signal is fed to the averaging circuit 770. The averaging circuit 770 generates an envelope of the data signal e.g. by averaging the data signal. The generated envelope is fed to the pulse generation circuit 760. The pulse generation circuit 760 generates, on the basis of the envelope of the data signal, the second drive current for the laser section of the semiconductor laser 300 that is applied to the heating region, e.g. the second semiconductor region 340 and, if present, also to the another heating region, e.g. the third semiconductor region 350 of the laser section of the semiconductor laser 300. The pulse generation circuit 760 further generates, on the basis of the envelope of the data signal, the second drive current for the external modulator section of the semiconductor laser 300 that is applied to the heating region, e.g. the second semiconductor region 345 and, if present, also to the another heating region, e.g. the third semiconductor region 355 of the external modulator section of the semiconductor laser 300.

In the above, the drive circuit 720 and the pulse generation circuit 760 in the case of **Fig. 7** and the drive circuit 720, the pulse generation circuit 760, and the averaging circuit 770 in the case of **Fig. 8** may be said to form a drive unit for driving the

semiconductor laser 300. The drive unit generates the first and second drive currents. The drive unit further applies the first drive currents to respective first semiconductor regions 330, 335, and applies the second drive currents to respective second semiconductor regions 340, 345 (and respective third semiconductor regions 350, 355, if present).

Fig. 9 is a schematic timing diagram of time-dependent quantities related to operation of the laser assemblies illustrated in **Fig. 7** and **Fig. 8**. The topmost diagrams 910, 915 indicate an example of the first drive current for the laser section of the semiconductor laser output by the drive circuit 720 and injected to the first semiconductor region 330 of the laser section of the semiconductor laser 300 (left diagram) and an example of the first drive current for the external modulator section of the semiconductor laser output by the drive circuit 720 and injected to the first semiconductor region 335 of the external modulator section of the semiconductor laser 300 and the output optical power of the semiconductor laser 300 (right diagram). In this schematic representation, the first drive current for the external modulator section and the output optical power are illustrated to have qualitatively the same variation in time. The second diagram 920 from the top indicates an example of the laser temperature within the first semiconductor region 330 of the laser section and the emission wavelength of the optical signal output by the semiconductor laser 300 during data bursts, both for a case in which the self-heating mitigation technique according to the disclosure is not applied. Also the laser temperature and the emission wavelength are schematically illustrated to have qualitatively the same variation in time. Needless to say, the emission wavelength is understood to be zero during intervals between data bursts. The third diagrams 930, 935 from the top indicate an example of the second drive current for the laser section that is applied to the heating region, e.g. the second semiconductor region 340 (and the another heating region, e.g. the third semiconductor region 350, if present) of the laser section (left diagram) and an example of the second drive current for the external modulator section that is

applied to the heating region, e.g. the second semiconductor region 345 (and the another heating region, e.g. the third semiconductor region 355, if present) of the external modulator section (right diagram). The fourth diagram 940 from the top indicates an example of the temperature of the first semiconductor region 330 of the laser section, ignoring any heat generated by the first semiconductor regions 330, 335 during transmission periods. The lowermost diagram 950 indicates an example of the net temperature of the first semiconductor region 330 of the semiconductor laser 300 and the emission wavelength of the optical signal output by the semiconductor laser 300 during data bursts for the case in which the self-heating mitigation technique according to the disclosure is applied. Also the net temperature and the emission wavelength are schematically illustrated to have qualitatively the same variation in time.

As can be seen from the topmost left diagram 910 of **Fig. 9**, the laser section is driven only during transmission periods. Alternatively, the laser section could be driven continuously. This case is not reflected in the remaining diagrams.

As can be further seen from **Fig. 9**, without applied self-heating mitigation technique, the laser temperature rises during data bursts, and the emission wavelength increases proportionally to the temperature increase. The second drive currents have a constant level during the IBGs, and are zero during the transmission periods. Further, the heat that is transferred to the first semiconductor regions 330, 335 during the IBGs prevents a cooling off of the first semiconductor regions 330, 335 during the IBGs and keeps constant the temperature of the first semiconductor regions 330, 335 across periods of transmission and IBGs. Accordingly, if the self-heating mitigation technique according to the disclosure is applied, there is no cooling off of the first semiconductor regions 330, 335 between data bursts and the emission wavelength of the optical signal is substantially constant over time during data bursts.

Fig. 11 schematically illustrates a set-up to demonstrate the effectiveness of the semiconductor laser device 1000 in **Fig. 10** according to one embodiment of the disclosure. A laser module (not shown) similar to laser assemblies 400, 500 comprises a directly modulated laser (DML) with a heater 1100. Current sequences 1130 of 1ms are applied to the laser waveguide 1030, while opposite voltage steps 1140 are synchronously applied to the heater 1040. The DML output is then transmitted through a 0.25nm (~30GHz) narrow-band filter 1110. By positioning a filter edge on the laser emission wavelength, wavelength modulation is transferred into amplitude modulation. The output signal 1150 is then visualized on an oscilloscope 1120.

Fig. 12 shows the resulting signals on the oscilloscope 1120 in **Fig. 11** for increasing heater counter-modulation voltages, i.e. operating a heater 1040 with 0V (no heating) during laser on-states and with voltages ranging from 0 to 3V during laser off-states. The result of **Fig. 12(a)** corresponds to laser modulation current between 60 and 100mA for a sequence period of 1ms. The result of **Fig. 12(b)** corresponds to laser modulation current between 0 and 80mA for a sequence period of 40ms. When the heater 1040 is not modulated (heater off), the signal slowly shifts during the laser on-state due to laser self-heating 1200, 1220, indicating that wavelength is not stabilized, even after 20ms. When the heater voltage during laser off-states is increased, the signal variation decreases until becoming stable, which corresponds to the heater voltage exactly compensating for laser self-heating. This heater voltage depends on laser modulation currents. For laser modulation current between 60 and 100mA, the optimum heater counter-modulation is 0V/2.15V, represented by the curve 1210, while for laser modulation current between 0 and 80mA, the optimum heater counter-modulation is 0V/2.6V, represented by the curve 1230. In that situation, the wavelength is clearly stabilized after only a few μ s.

It should be noted that the apparatus features described above correspond to respective method features that are however not explicitly described, for reasons of conciseness. The disclosure of the present document is considered to extend also to such method features.

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It should be further noted that the description and drawings merely illustrate the principles of the proposed apparatus. Those skilled in the art will be able to implement various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples and embodiment outlined in the present document are principally intended expressly to be only for explanatory purposes to help the reader in understanding the principles of the proposed apparatus. Furthermore, all statements herein providing principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass equivalents thereof.

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Claims

1. A laser assembly comprising a semiconductor laser and a drive unit for driving the semiconductor laser,
- 5 wherein the semiconductor laser comprises:
- a first semiconductor region for generating or modulating an optical signal in response to a first drive current that is applied to the first semiconductor region;
 - a heating region that is arranged in proximity to the first semiconductor region and electrically insulated from the first semiconductor region,
- 10 wherein the drive unit is configured to generate the first drive current and a second drive current, apply the first drive current to the first semiconductor region during respective transmission periods of the semiconductor laser, and apply the second drive current to the heating region in intervals between successive transmission periods.
- 15 wherein the drive unit is configured to generate the first drive current on the basis of an input signal comprising a data signal indicative of data to be transmitted by means of the optical signal; and
- wherein the drive unit comprises:
- a drive circuit for generating the first drive current based on the data
- 20 signal;
- an averaging circuit for generating an envelope of the data signal; and
 - a pulse generator for generating the second drive current on the basis of the envelope of the data signal.
- 25 2. The laser assembly according to claim 1, wherein the heating region is configured to have characteristics of heat generation that are matched to those of the first semiconductor region.

3. The laser assembly according to claim 1 or 2, wherein the heating region has substantially the same shape and material composition as the first semiconductor region.

5 4. The laser assembly according to any one of claims 1 or 2, wherein the heating region comprises a second semiconductor region, a parallel waveguide or a metallic heater made of resistive material.

5. The laser assembly according to any one of claims 1 to 4, wherein the
10 heating region is arranged so that heat generated by the heating region may diffuse to the first semiconductor region and heat up the first semiconductor region.

6. The laser assembly according to claim 5, wherein the characteristics of heat generation of the heating region are chosen in such a manner that a heat
15 transfer from the heating region to the first semiconductor region during the intervals between successive transmission periods is dimensioned so that a temperature of the first semiconductor region during the intervals between successive periods of transmission is kept at the same level as during the transmission periods.

20

7. The laser assembly according to any one of claims 1 to 6, wherein the heating region is optically inactive and/or is optically insulated from the first semiconductor region.

25 8. The laser assembly according to any one of claims 1 to 7, wherein the semiconductor laser further comprises another heating region that is electrically insulated from the first semiconductor region and arranged in proximity to the first semiconductor region such that the first semiconductor region is sandwiched between the heating region and the another heating region; and

wherein the drive unit is further configured to apply a third drive current to the another heating region in the intervals between successive transmission periods.

5 9. The laser assembly according to claim 8, wherein the another heating region is arranged so that heat generated by the another heating region may diffuse to the first semiconductor region and heat up the first semiconductor region.

10 10. The laser assembly according to claim 9, wherein the characteristics of heat generation of the heating region and the another heating region are chosen in such a manner that a heat transfer from the heating region and the another heating region to the first semiconductor region during the intervals between successive transmission periods is dimensioned to keep a temperature of the first
15 semiconductor region during the intervals between successive periods of transmission at the same level as during the transmission periods.

 11. The laser assembly according to any one of claims 1 to 10, wherein the drive unit is configured to generate the second drive current such that the second
20 drive current is different from zero during at least a portion of each of the intervals between successive transmission periods.

 12. A method of driving a semiconductor laser having a first semiconductor region for generating or modulating an optical signal in response to a first drive
25 current that is applied to the first semiconductor region, and a heating region that is arranged in proximity to the first semiconductor region and electrically insulated from the first semiconductor region, wherein the heating region is configured to have characteristics of heat generation that are matched to those of the first semiconductor region, the method comprising:

generating the first drive current on the basis of a data signal indicative of data to be transmitted by means of the optical signal;
generating an envelope of the data signal;
generating the second drive current on the basis of the envelope of the data
5 signal;
applying the first drive current to the first semiconductor region during respective transmission periods of the semiconductor laser; and
applying a second drive current to the heating region in the intervals between successive transmission periods.

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13. The method according to claim 12, wherein the heating region comprises a second semiconductor region, a parallel waveguide or a metallic heater made of resistive material.

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14. The method according to any one of claims 12 or 13,
wherein the semiconductor laser further comprises another heating region that is electrically insulated from the first semiconductor region and arranged in proximity to the first semiconductor region such that the first semiconductor region is sandwiched between the heating region and the another heating region;
20 and

wherein the method further comprises applying a third drive current to the another heating region in the intervals between successive transmission periods.

100

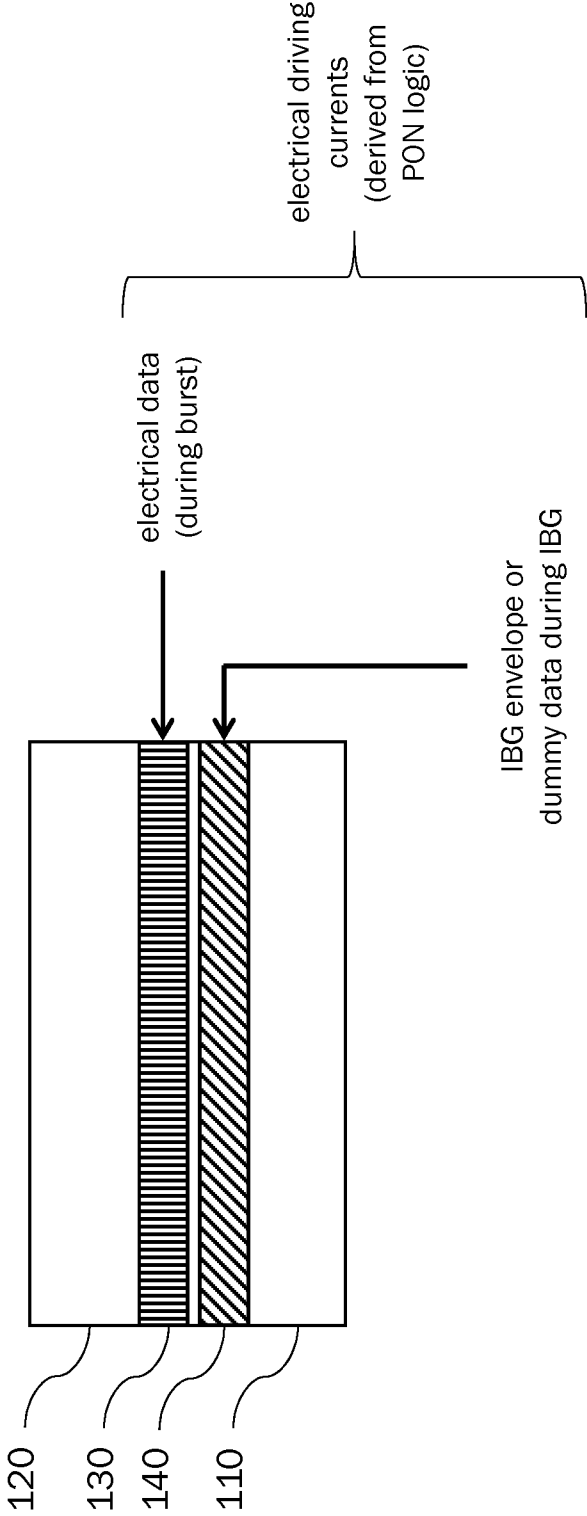
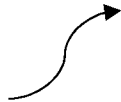


Fig. 1

200

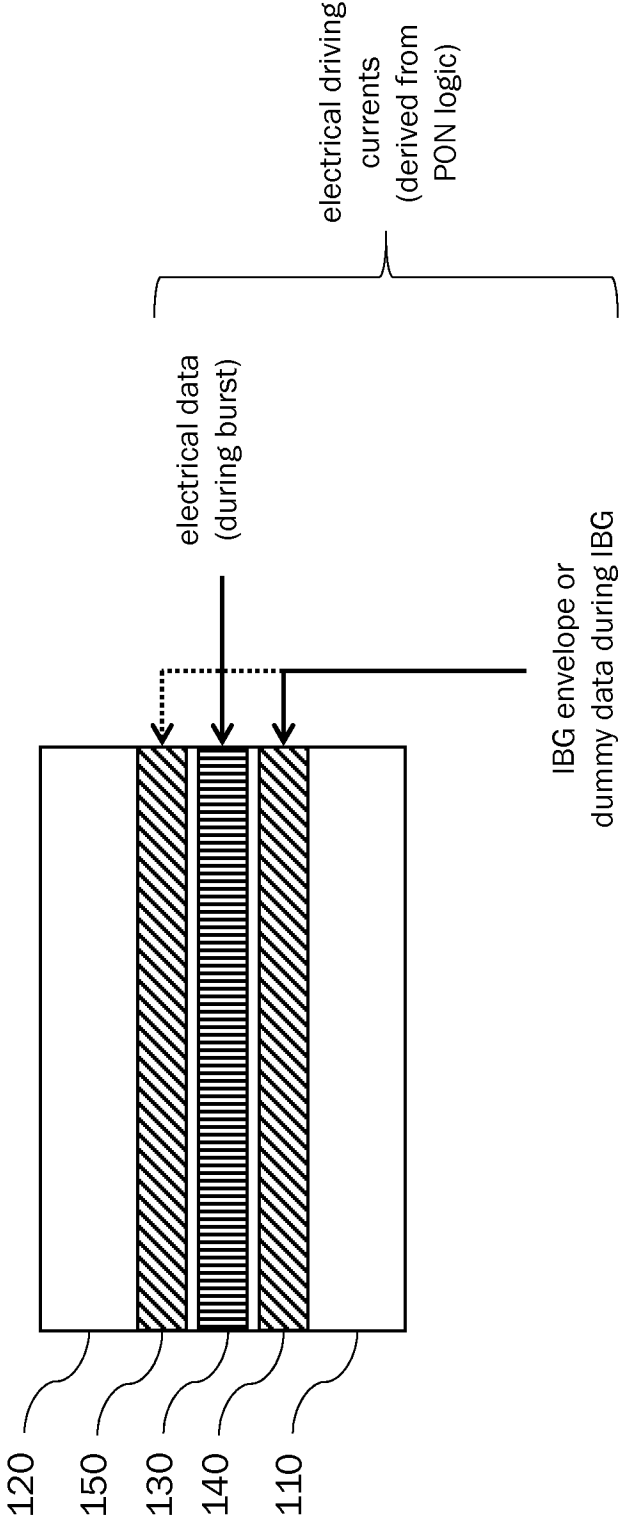
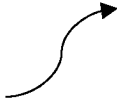


Fig. 2

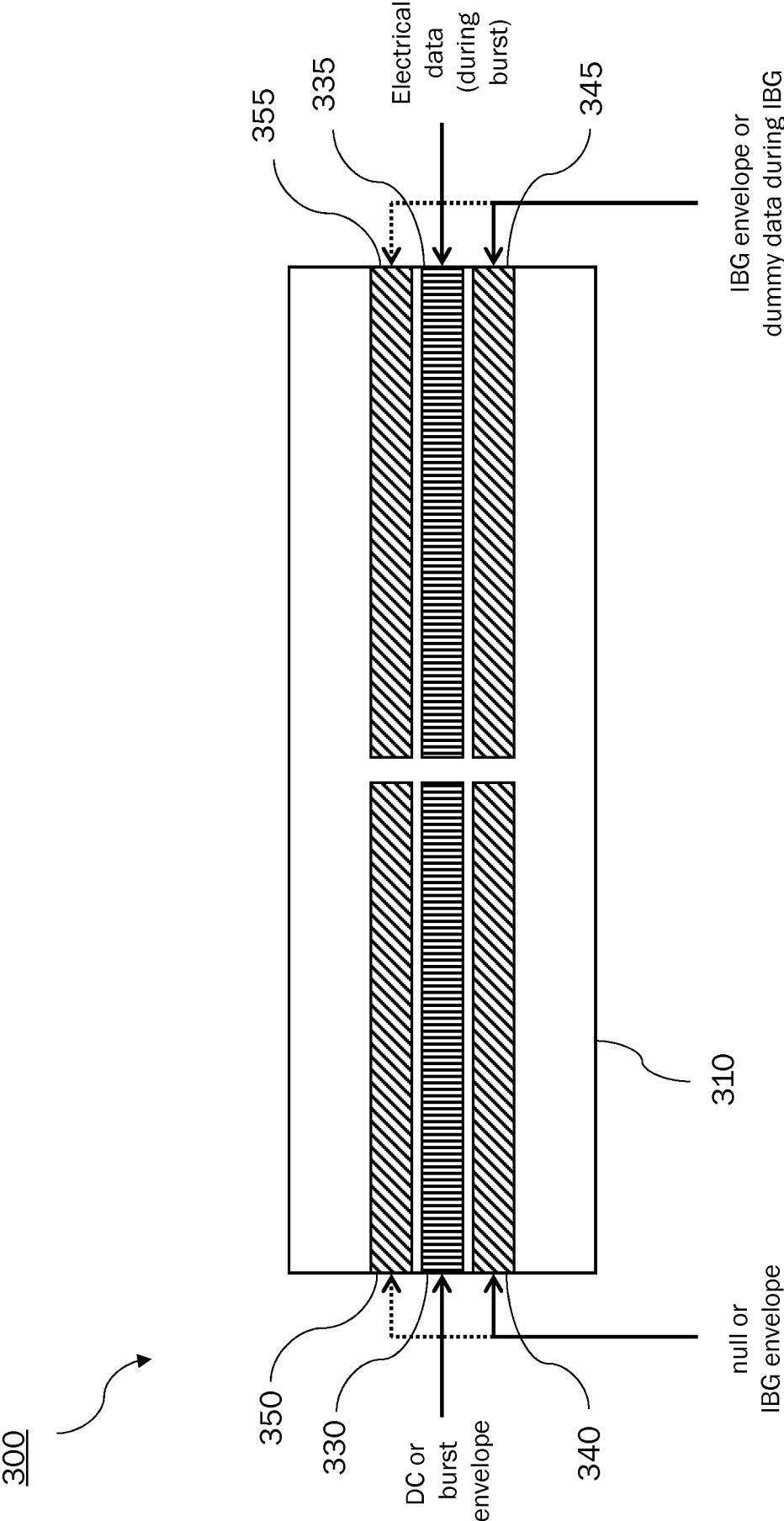


Fig. 3

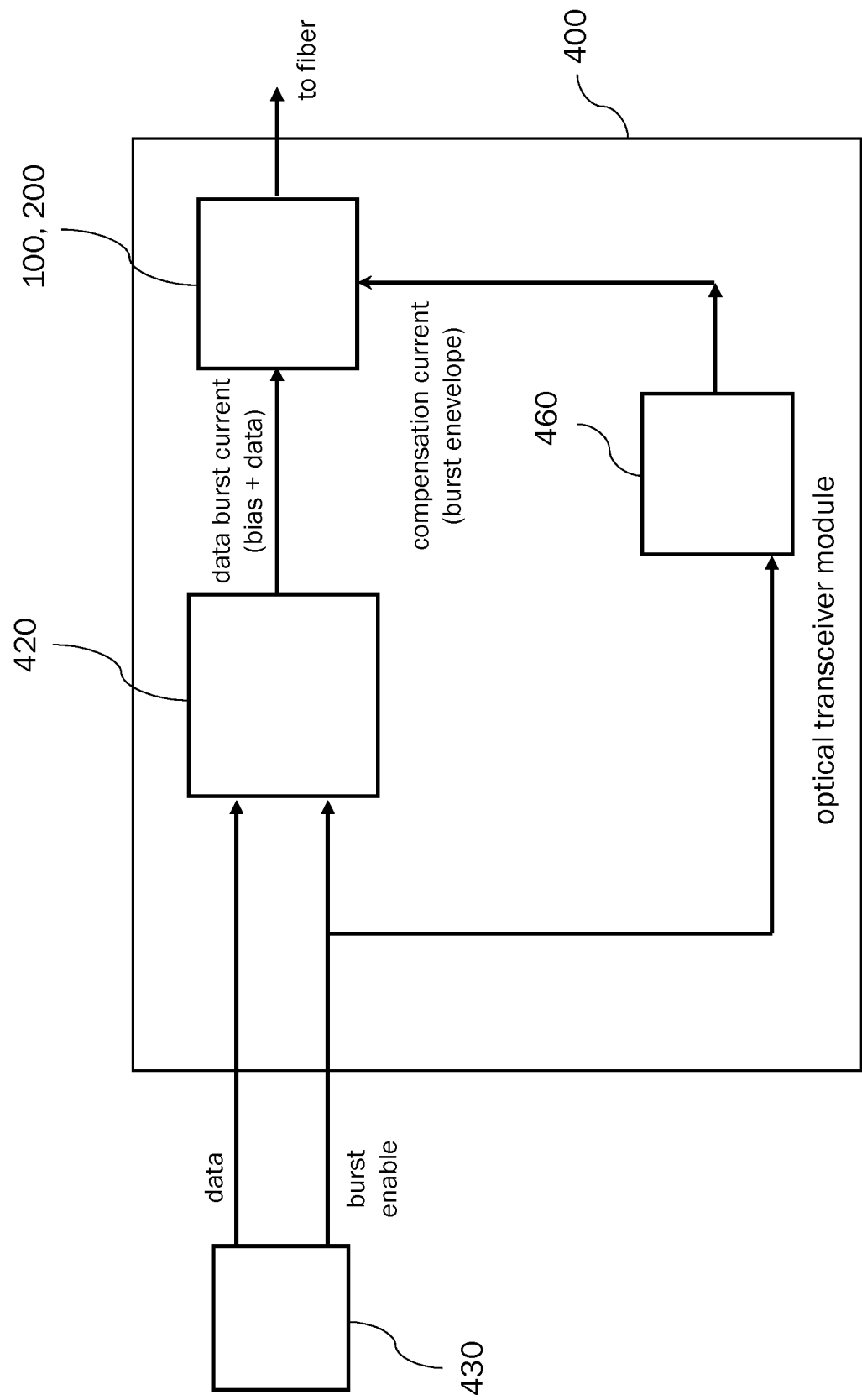


Fig. 4

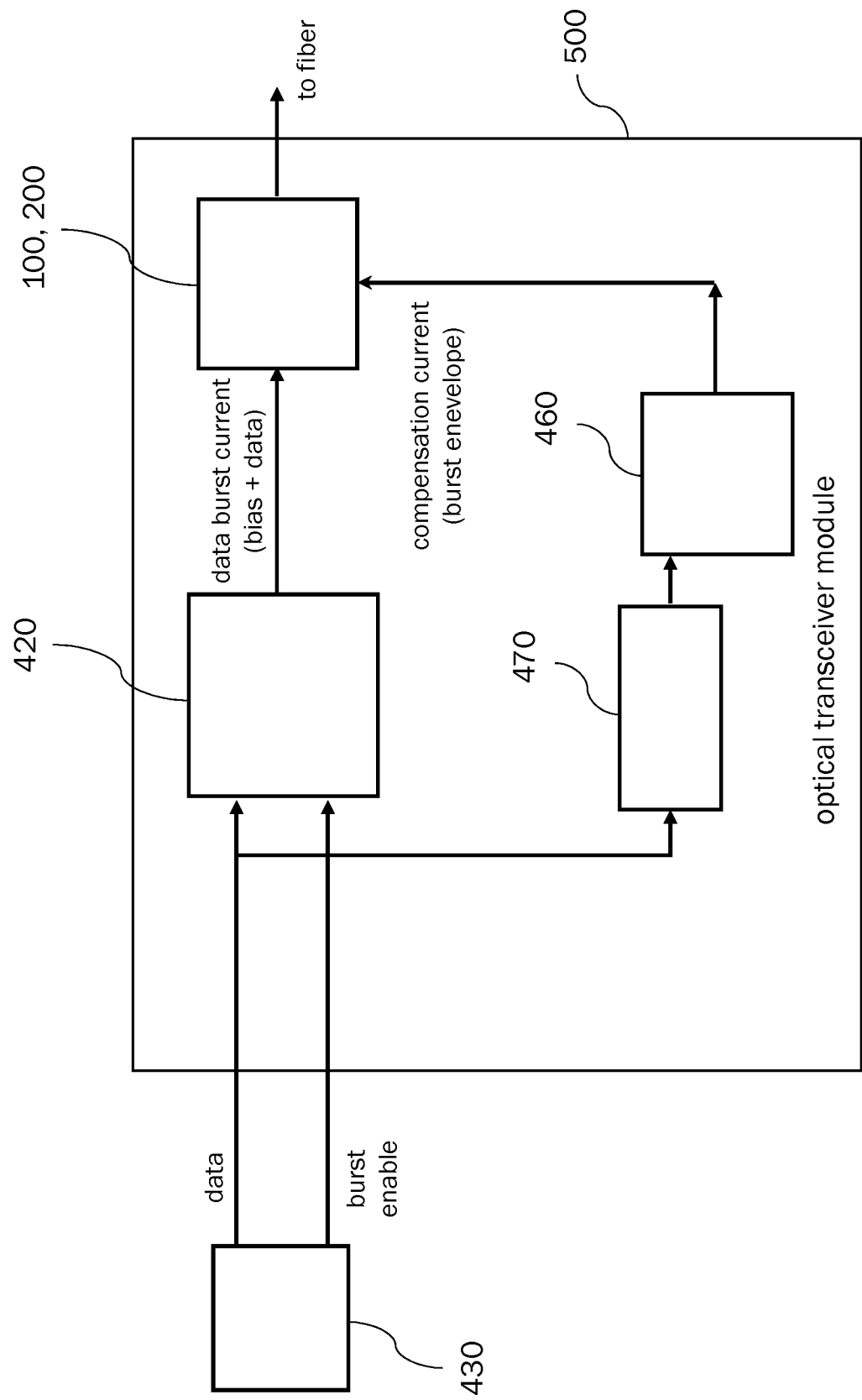


Fig. 5

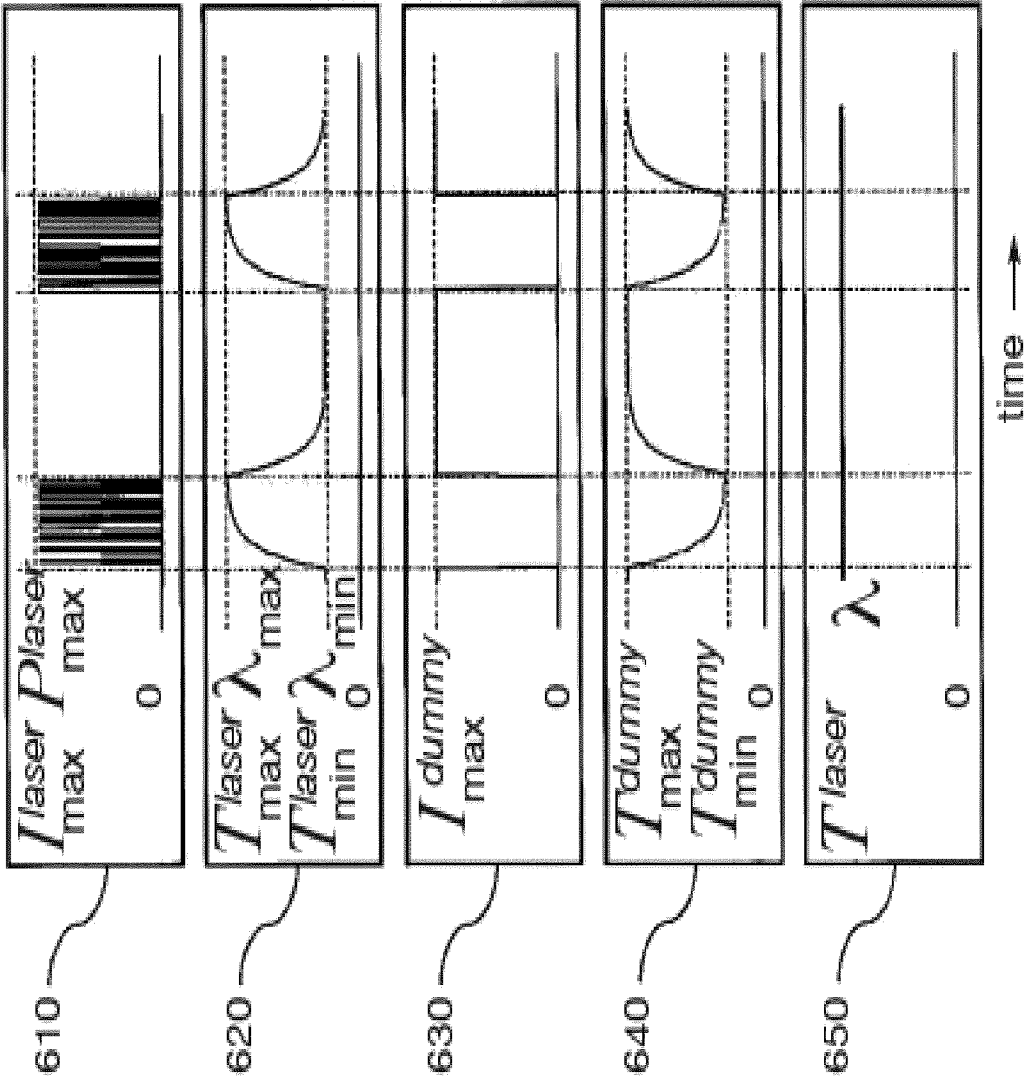


Fig. 6

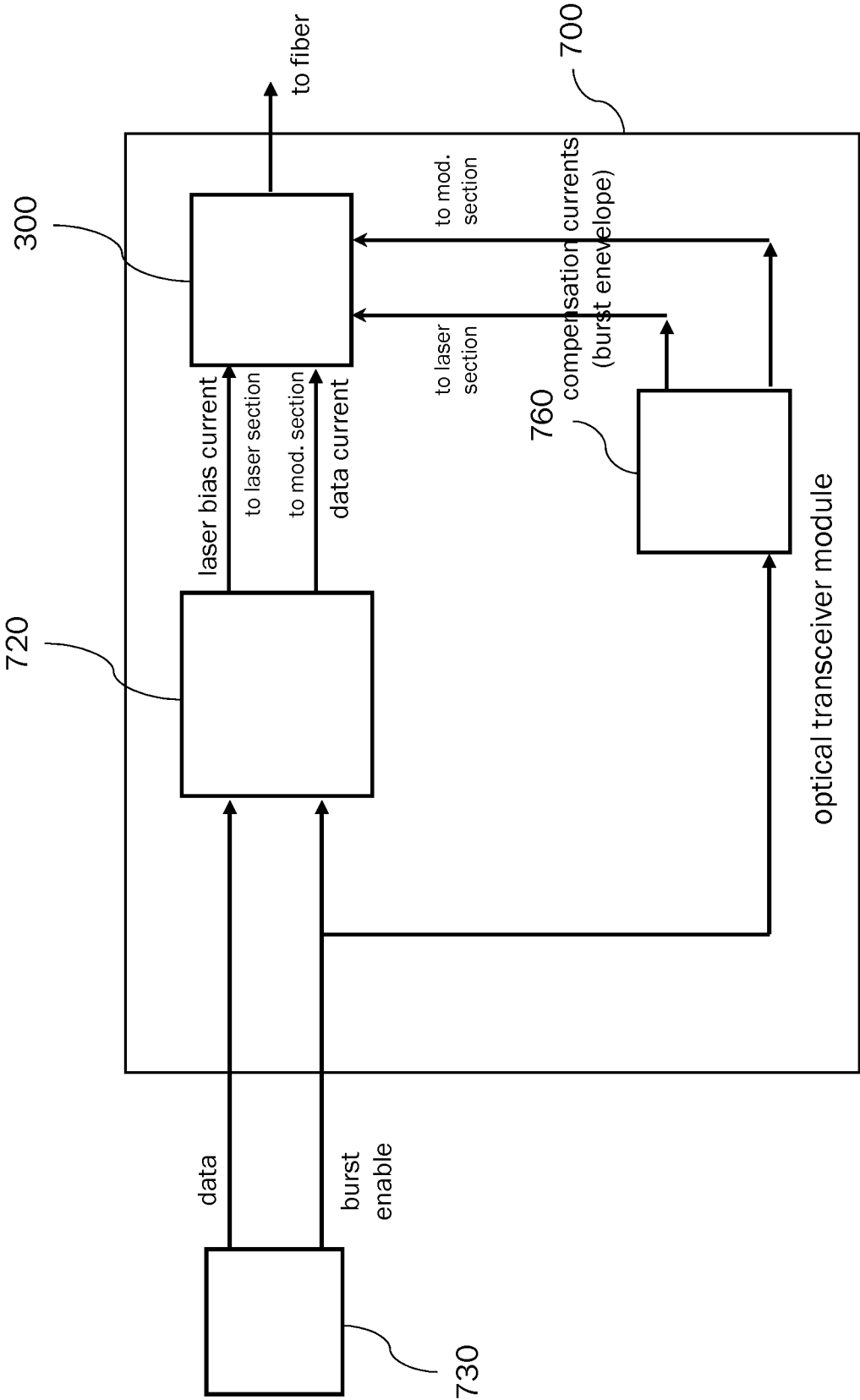


Fig. 7

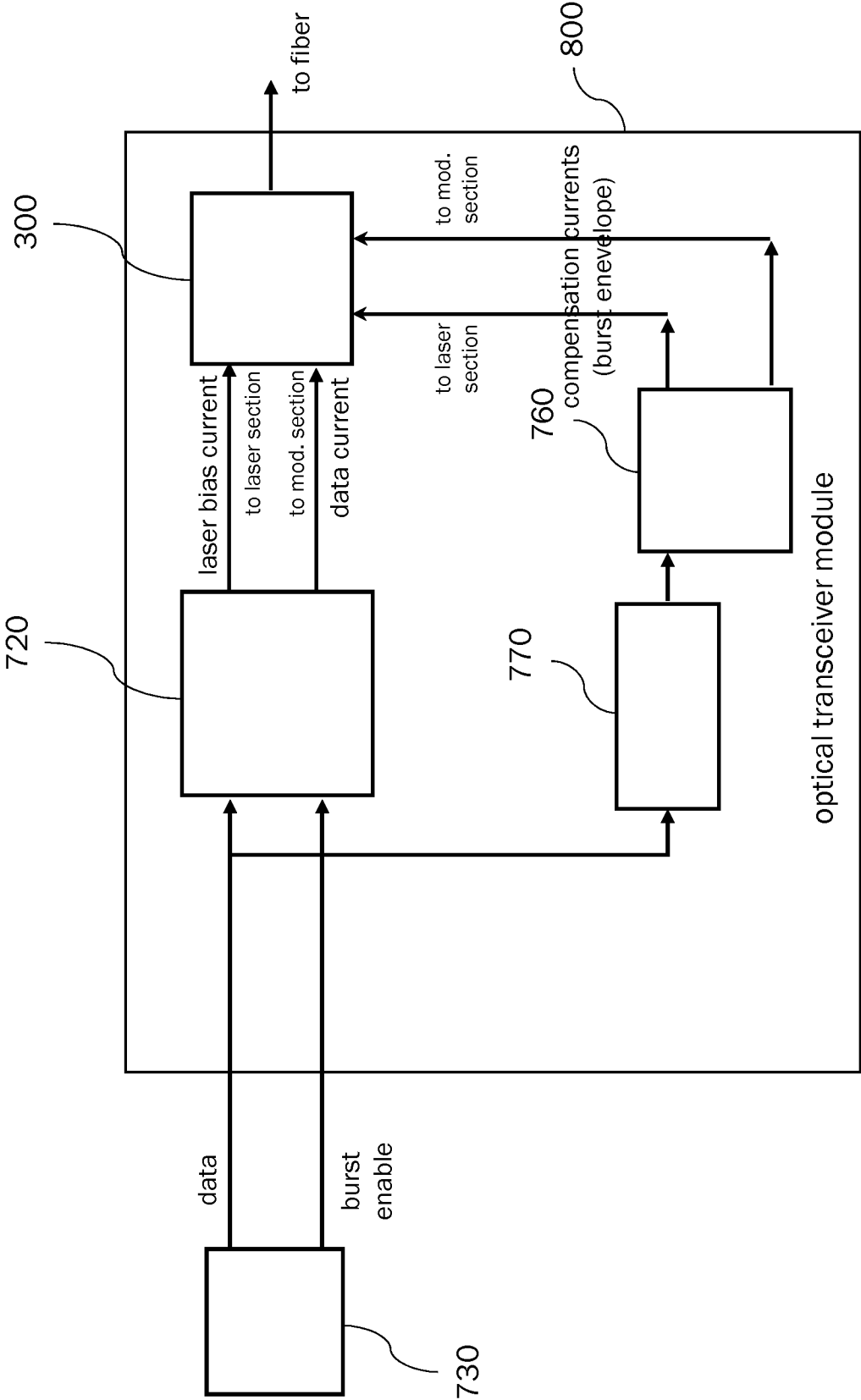


Fig. 8

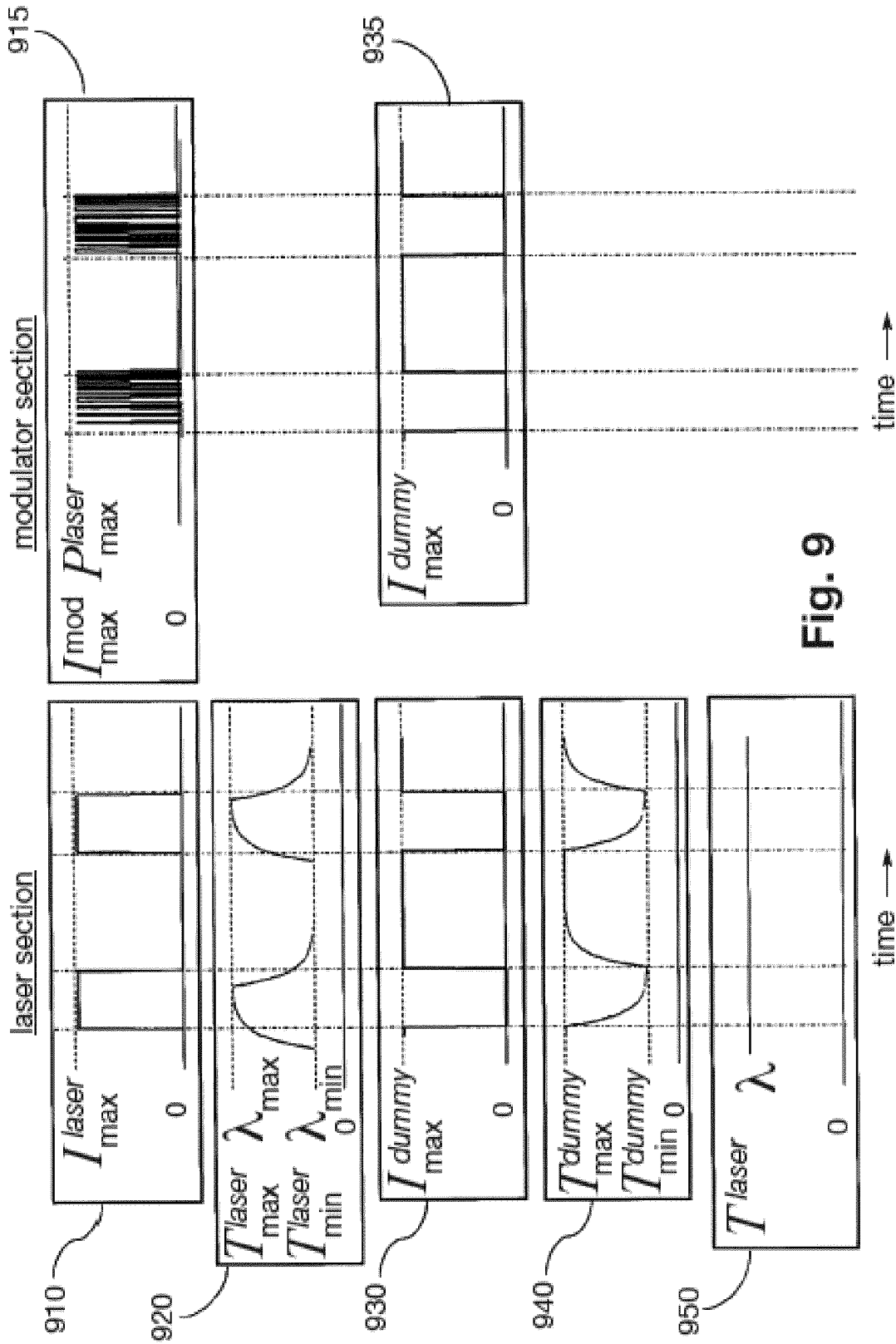


Fig. 9

1000

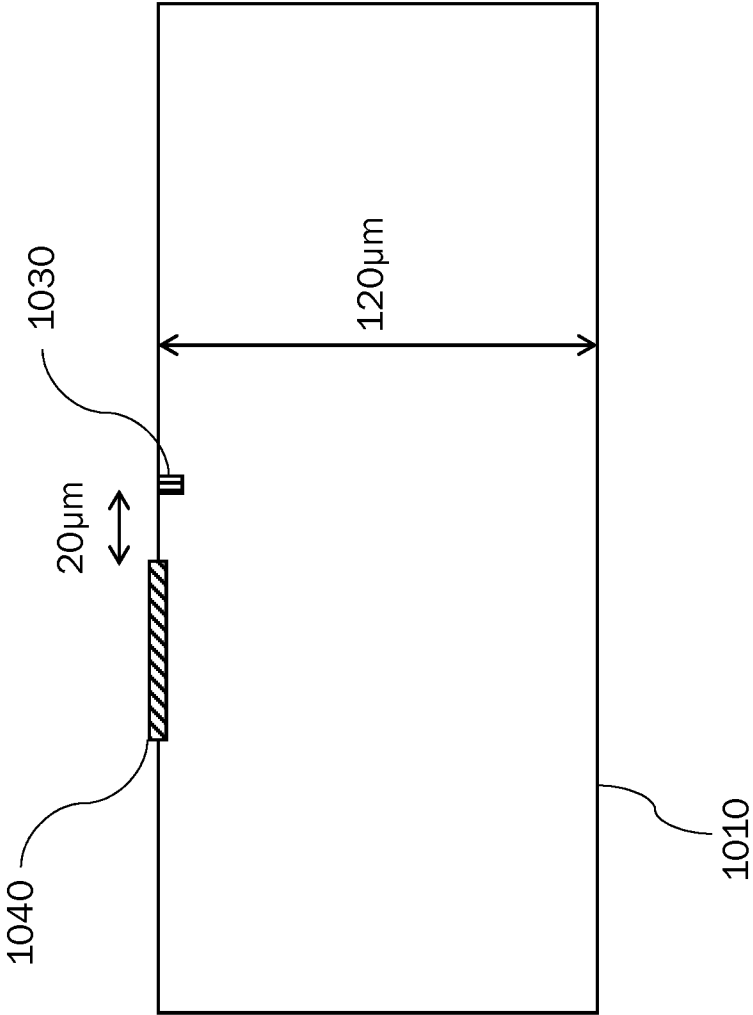


Fig. 10

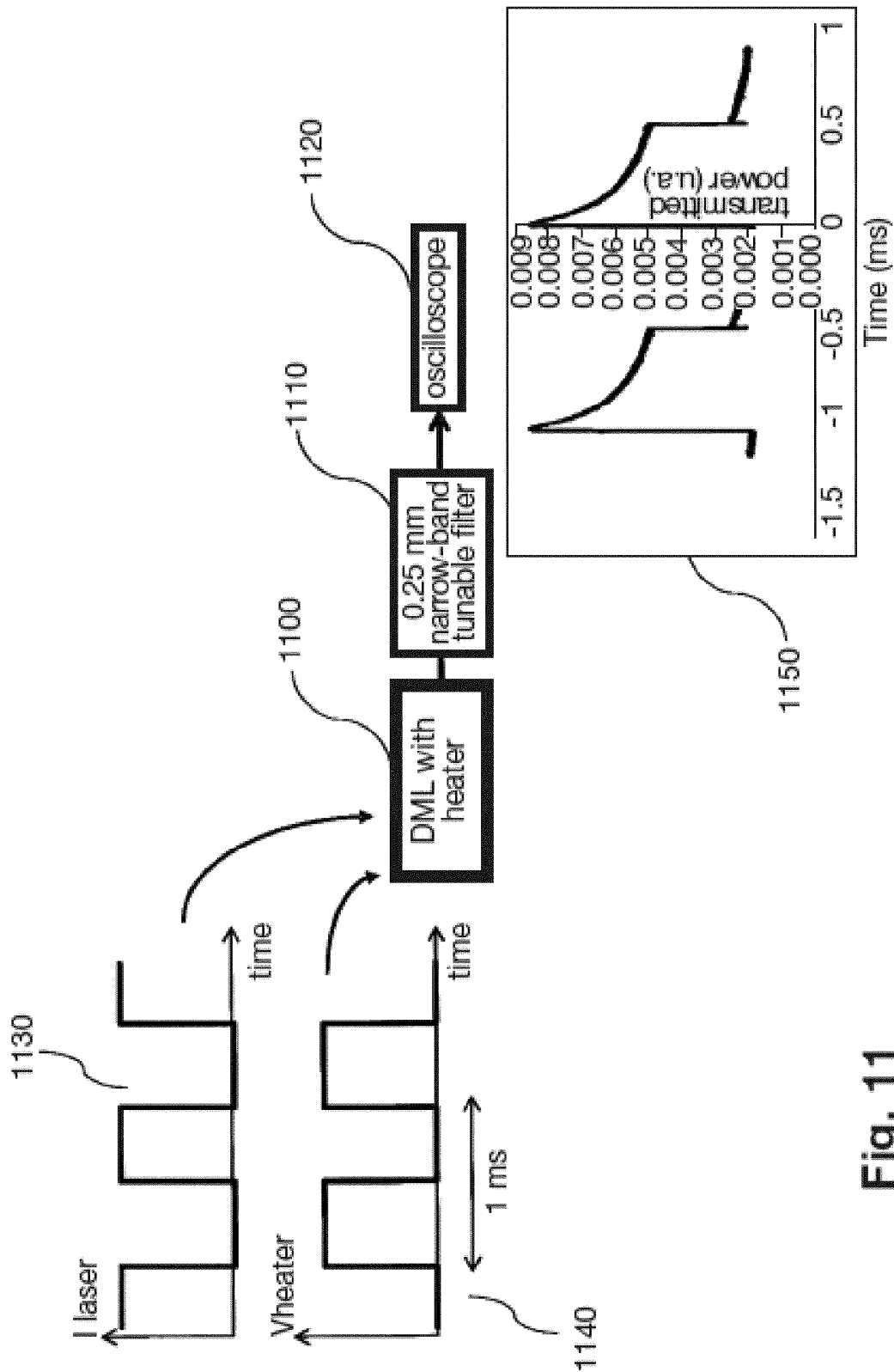


Fig. 11

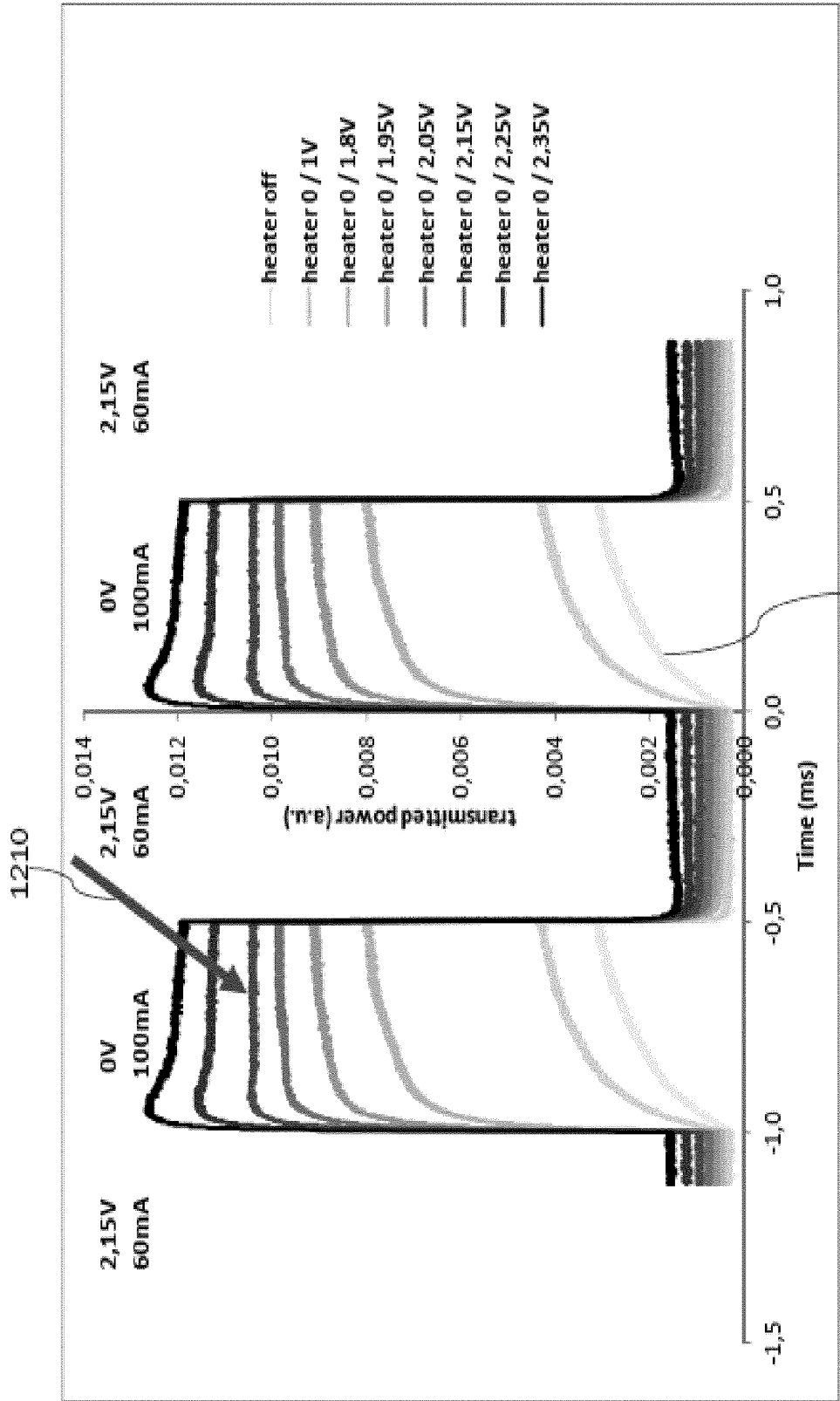


Fig. 12a

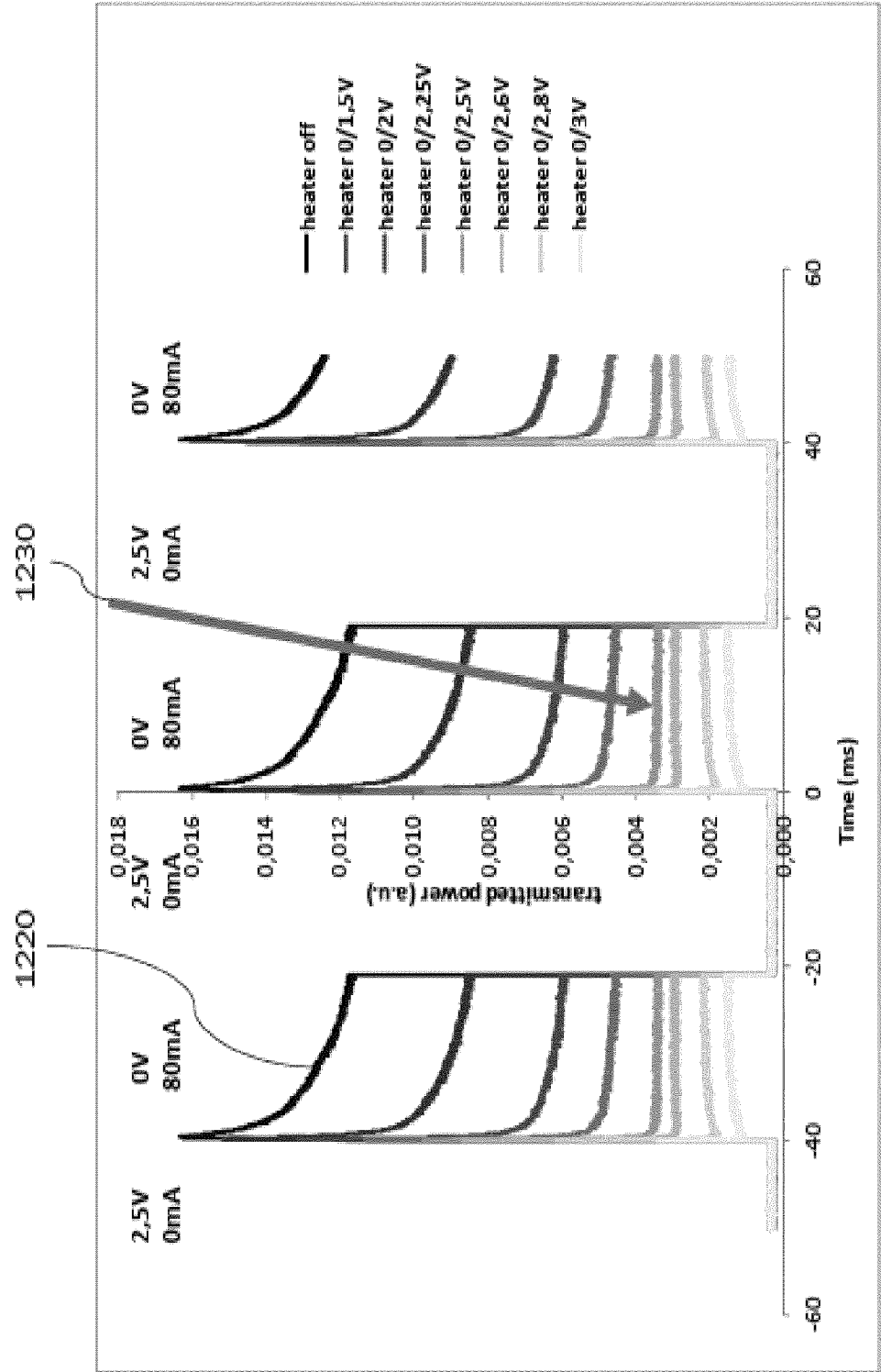


Fig. 12b

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2016/051244

A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S5/068

ADD. H01S5/026 H01S5/042

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/264525 A1 (SENGA HISASHI [JP] ET AL) 30 December 2004 (2004-12-30) paragraphs [0076] - [0104]; figures 10-13 -----	1-7, 11-13
A	US 5 345 459 A (RICHARDSON BRUCE A [CA] ET AL) 6 September 1994 (1994-09-06) column 2, line 53 - column 4, line 26; figures 1-3, 5A, 5C -----	1-14
A	US 2008/063016 A1 (BHATIA VIKRAM [US] ET AL) 13 March 2008 (2008-03-13) paragraphs [0027] - [0038]; figures 4, 5 -----	1, 2, 4-14
A	DE 42 31 177 A1 (SIEMENS AG [DE]) 24 March 1994 (1994-03-24) column 3, line 51 - column 5, line 23; figures 4a, 4b -----	1, 12



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

16 March 2016

Date of mailing of the international search report

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Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Riechel, Stefan

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2016/051244

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