

METHOD AND SYSTEM FOR CALIBRATING LASER

Field

[01] This disclosure relates to optical readers having laser light sources, in particular to methods and systems for calibrating a tunable laser such as but not limited to a micro-electromechanical system (MEMS) based vertical-cavity surface-emitting laser (VCSEL).

Background

[02] Structural health monitoring involves implementing a damage detection strategy for civil and mechanical engineering infrastructure which is key to developing a smart city.

[03] Many building structures, e.g. apartments, commercial buildings, are capable of having built-in optical sensors. However, due to costly readers, real-time monitoring is expensive to implement. Instead, manual reading has been conducted periodically or infrequently, e.g., twice a year. To better predict potential building structural failure, real-time monitoring is needed. Thus, a low-cost and low-power consumption optical reader is highly desirable for such applications.

[04] The key components in an optical reader are optical light source and detector, which are the main costly components and which consume majority of total power consumption. To reduce the cost and power consumption, the low-cost and power efficient vertical-cavity surface-emitting laser (VCSEL) is a good candidate component. However, wavelength tunability is a key challenge of such low-end light source. The output wavelength of VCSEL is tuned by micro-electromechanical systems (MEMS). The wavelength-voltage curve is typically non-linear, as shown in Figure 1A. However, for most of the applications, the sampling steps are to increase linearly in the wavelength or frequency domain. Thus, it is highly desirable to set the sampling points such that the laser output wavelength has a linear relationship with tuning steps.

[05] An existing method involves measuring the wavelength-voltage curve with a high-resolution spectrum analyser and then fitting the curve and performing a reverse function to ascertain voltage value for each sampling point. This method requires extra measurement equipment, e.g., high resolution spectrum analyser. This introduces extra manpower and time consumption, and also increases fabrication cost.

Furthermore, as the wavelength-curve varies with many parameters, recalibration is to be performed from time to time. This periodical recalibration process further increases maintenance costs.

[06] Another existing method involves an assumption that the peak wavelength of VCSEL shows a linear dependence on the squared membrane current of the MEMS. For linear tuning over the whole wavelength range, the membrane requires a modulation with the inverse function (square root) of the tuning characteristics. While this method is not dependent on extra equipment and may effectively reduce costs, it works well only when the requirement of wavelength reliability is not very high. To illustrate the performance of this square root fitting method, wavelength error within the whole wavelength range of one VCSEL was tested. The reference wavelength was read by a high resolution optical coherence microscopy (OCM). Figure 1B shows a test result which shows that wavelength error varies from -58 picometre (pm) to 133 pm within the tuning window of 0 Volts (V) to 18 V. For applications with wavelength resolution requirement of above 0.1 nanometre (nm), the square root fitting works well. However, for many applications with high wavelength resolution requirement, for example a FBG interrogator, where the wavelength reliability is normally as high as 10 pm. The square root fitting may not be able to meet such high wavelength reliability applications.

Summary

[07] According to a first aspect of the invention, a method for calibrating laser is provided which comprises:

- performing a wavelength-voltage tuning function initialisation which comprises:
 - performing a first voltage sweep at a laser at a first operating temperature to produce a first laser output;
 - detecting, by a photodetector, a first output spectrum produced by an etalon in response to the first laser output;
 - computing a plurality of first voltage values of a plurality of first signal peaks within the first output spectrum;
 - upon ascertaining a free spectral range (FSR) value of the etalon is smaller than or equal to a predetermined FSR value, identifying a plurality of first sections of the first output spectrum which are respectively defined by successive peaks of the first signal peaks;

based on the first voltage values within the first sections, ascertaining a plurality of first substantially linear wavelength-voltage parameters respectively corresponding to the first sections; and
ascertaining a first wavelength-voltage tuning table based on the first substantially linear wavelength-voltage parameters.

[08] In an embodiment, the step of performing the wavelength-voltage tuning function initialisation further comprises:

upon ascertaining the FSR value is greater than the predetermined FSR value, performing a second voltage sweep at the laser at a second operating temperature to produce a second laser output;
detecting a second output spectrum produced by the etalon in response to the second laser output;
computing a plurality of second voltage values of a plurality of second signal peaks within the second output spectrum;
deriving a third output spectrum based on the first output spectrum and the second output spectrum wherein the third output spectrum includes a plurality of third signal peaks based on the first signal peaks and the second signal peaks, wherein a plurality of third voltage values of the third signal peaks correspond to the first voltage values and the second voltage values;
upon ascertaining a third section length between two successive peaks of the third signal peaks is smaller than or equal to the predetermined FSR value, identifying a plurality of third sections of the third signal output spectrum which are respectively defined by successive peaks of the third signal peaks;
based on the third voltage values within the third sections, ascertaining a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections; and
ascertaining a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters.

[09] In an embodiment, the step of performing the wavelength-voltage tuning function initialisation further comprises:

upon ascertaining the FSR value is greater than the predetermined FSR value, performing at least one iteration of a temperature-assisted initialisation until a third section length between two successive peaks of a plurality of third signal

peaks is smaller than or equal to the predetermined FSR value, wherein each temperature-assisted initialisation comprises:

- performing a second voltage sweep at the laser at a second operating temperature to produce a second laser output;
- detecting a second output spectrum produced by the etalon in response to the second laser output;
- computing a plurality of second voltage values of a plurality of second signal peaks within the second output spectrum;
- deriving a third output spectrum based on combining the first output spectrum and each second output spectrum of the at least one iteration wherein the third output spectrum includes the third signal peaks based on the first signal peaks and the second signal peaks of the at least one iteration, wherein a plurality of third voltage values of the third signal peaks are based on the first voltage values and the second voltage values of the at least one iteration;

upon ascertaining the third section length between two successive peaks of the third signal peaks is smaller than or equal to the predetermined FSR value, identifying the third sections of the third signal output spectrum which are respectively defined by successive peaks of the third signal peaks; and based on the third voltage values within the third sections, ascertaining a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections; and ascertaining a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters.

[010] In an embodiment, the step of performing the wavelength-voltage tuning function initialisation further comprises:

- recalibrating an existing wavelength-voltage tuning table of the laser with the third wavelength-voltage tuning table.

[011] In an embodiment, the two successive peaks correspond to two successive peaks having two highest voltage values among the third voltage values.

[012] In an embodiment, the step of performing the wavelength-voltage tuning function initialisation further comprises:

- recalibrating an existing wavelength-voltage tuning table of the laser with the first wavelength-voltage tuning table.

[013] In an embodiment, the step of performing the wavelength-voltage tuning function initialisation includes periodically performing the wavelength-voltage tuning function initialisation during operation of the laser.

[014] In an embodiment, the step of ascertaining the plurality of first substantially linear wavelength-voltage parameters respectively is by linear fitting or square root fitting.

[015] According to a second aspect of the invention, a system for calibrating laser is provided which comprises:

- a laser configured to emit laser beams and a micro-electromechanical system operably coupled thereto and configured to tune an output wavelength of the laser;

- an etalon configured to receive an output signal of the laser;

- a photodetector operably coupled to the etalon and configured to receive an output signal from the etalon; and

- a computing unit operably coupled to the laser, the micro-electromechanical system and the photodetector and configured to execute computer-executable instructions to perform a wavelength-voltage tuning function initialisation which comprises:

- performing a first voltage sweep at the laser at a first operating temperature to produce a first laser output;

- detecting, by the photodetector, a first output spectrum produced by the etalon in response to the first laser output;

- computing a plurality of first voltage values of a plurality of first signal peaks within the first output spectrum;

- upon ascertaining a free spectral range (FSR) value of the etalon is smaller than or equal to a predetermined FSR value, identifying a plurality of first sections of the first output spectrum which are respectively defined by successive peaks of the first signal peaks;

- based on the first voltage values within the first sections, ascertaining a plurality of first substantially linear wavelength-voltage parameters respectively corresponding to the first sections; and

- ascertaining a first wavelength-voltage tuning table based on the first substantially linear wavelength-voltage parameters.

[016] In an embodiment, the wavelength-voltage tuning function initialisation further comprises:

- upon ascertaining the FSR value is greater than the predetermined FSR value, performing a second voltage sweep at the laser at a second operating temperature to produce a second laser output;
- detecting a second output spectrum produced by the etalon in response to the second laser output;
- computing a plurality of second voltage values of a plurality of second signal peaks within the second output spectrum;
- deriving a third output spectrum based on combining the first output spectrum and the second output spectrum wherein the third output spectrum includes a plurality of third signal peaks based on the first signal peaks and the second signal peaks, wherein a plurality of third voltage values of the third signal peaks correspond to the first voltage values and the second voltage values;
- upon ascertaining a third section length between two successive peaks of the third signal peaks is smaller than or equal to the predetermined FSR value, identifying a plurality of third sections of the third signal output spectrum which are respectively defined by successive peaks of the third signal peaks;
- based on the third voltage values within the third sections, ascertaining a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections; and
- ascertaining a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters.

[017] In an embodiment, the wavelength-voltage tuning function initialisation further comprises:

- upon ascertaining the FSR value is greater than the predetermined FSR value, performing at least one iteration of a temperature-assisted initialisation until a third section length between two successive peaks of a plurality of third signal peaks is smaller than or equal to the predetermined FSR value, wherein each temperature-assisted initialisation comprises:
 - performing a second voltage sweep at the laser at a second operating temperature to produce a second laser output;
 - detecting a second output spectrum produced by the etalon in response to the second laser output;

computing a plurality of second voltage values of a plurality of second signal peaks within the second output spectrum;
deriving a third output spectrum based on combining the first output spectrum and each second output spectrum of the at least one iteration wherein the third output spectrum includes the third signal peaks which correspond to the first signal peaks and the second signal peaks of the at least one iteration, wherein a plurality of third voltage values of the third signal peaks correspond to the first voltage values and the second voltage values of the at least one iteration;
upon ascertaining the third section length between two successive peaks of the third signal peaks is smaller than or equal to the predetermined FSR value, identifying the third sections of the third signal output spectrum which are respectively defined by successive peaks of the third signal peaks;
based on the third voltage values within the third sections, ascertaining a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections; and
ascertaining a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters.

[018] In an embodiment, the wavelength-voltage tuning function initialisation of further comprises:

recalibrating an existing wavelength-voltage tuning table of the laser with the third wavelength-voltage tuning table.

[019] In an embodiment, the two successive peaks correspond to two successive peaks having two highest voltage values among the third voltage values.

[020] In an embodiment, the wavelength-voltage tuning function initialisation further comprises:

recalibrating an existing wavelength-voltage tuning table of the laser with the first wavelength-voltage tuning table.

[021] In an embodiment, the step of performing the wavelength-voltage tuning function initialisation includes periodically performing the wavelength-voltage function initialisation during operation of the laser.

[022] In an embodiment, the step of ascertaining the plurality of first substantially linear wavelength-voltage parameters respectively is by linear fitting or square root fitting.

[023] In an embodiment, the laser is a vertical-cavity surface-emitting laser or an external cavity tunable laser.

[024] According to a third aspect of the invention, an optical interrogator comprising the system for calibrating laser according to any one of the embodiments as described above or in the present disclosure.

Brief Description of Drawings

[025] Figure 1A shows a typical non-linear wavelength-voltage curve of an output of a MEMS based VCSEL.

[026] Figure 1B shows a wavelength error of a MEMS based VCSEL using square root fitting.

[027] Figure 2 shows a functional diagram of a laser apparatus having calibrating functions.

[028] Figure 3 shows a flow chart for methods for calibrating a laser apparatus.

[029] Figure 4A shows a detected optical signal (first output spectrum) using the photodetector.

[030] Figure 4B shows a wavelength to voltage reference curve having a non-linear relationship.

[031] Figure 4C shows wavelength error of the tested wavelength curve as compared with the reference curve measured by high resolution optical spectrum analyser.

[032] Figure 5A shows a wavelength of a VCSEL linearly increasing with operating temperature.

[033] Figure 5B shows two tested wavelength-voltage curves corresponding to a first operating temperature (T1) and a second operating temperature (T2), and also shows the differences between the two tested wavelength-voltage curves in the inset .

[034] Figure 5C shows two detected output spectrums (first and second output spectrums).

[035] Figure 5D shows wavelength errors for different section lengths or FSRs.

[036] Figure 5E shows linear fitting at sections S₁ and S₂ which positions are annotated in Figure 5C.

[037] Figure 5F shows linear fitting at sections S_{n-1} and S_n which positions are annotated in Figure 5C.

[038] Figure 5G shows a non-limiting example of a part of a wavelength-voltage tuning table.

[039] Figure 5H shows an output spectrum of etalon after the initialisation.

Detailed Description

[040] In the following description, numerous specific details are set forth in order to provide a thorough understanding of various illustrative embodiments of the invention. It will be understood, however, to one skilled in the art, that embodiments of the invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure pertinent aspects of embodiments being described. In the drawings, like reference numerals refer to same or similar functionalities or features throughout the several views.

[041] Embodiments described in the context of one of the methods or devices are analogously valid for the other methods or devices. Similarly, embodiments described in the context of a method are analogously valid for a device, and vice versa.

[042] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[043] In the context of various embodiments, including examples and claims, the articles “a”, “an” and “the” as used with regard to a feature or element include a reference to one or more of the features or elements. The terms “comprising”, “including”, “having”, and their related terms are intended to be open-ended and mean that there may be additional features or elements other than the listed ones. Identifiers such as “first”, “second” and “third” are used merely as labels, and are not intended to impose numerical requirements on their objects, nor construed in a manner imposing any relative position or time sequence between limitations. The term “and/or” includes any and all combinations of one or more of the associated listed items. The term

“coupled” and related terms are used in an operational sense and are not necessarily limited to a direct physical connection or coupling. Thus, for example, two devices may be coupled directly, or via one or more intermediary devices. In certain examples, devices may be suitably coupled such that information or signal can be passed there between, while not sharing any physical connection with each other. For example, two devices may be communicably coupled via a wired or wireless connection. Based on the present disclosure, a person of ordinary skill in the art will appreciate a variety of ways in which coupling exists in accordance with the aforementioned definition. The term “substantially” or “approximately” is understood to include minor deviation or fluctuation. However, in the context of the embodiments, including examples and claims, the term “substantially linear” may include references to “linear”, and vice versa. For example, a substantially linear tuning relationship may be fully linear or may be mostly linear with minor deviation or fluctuation.

[044] The present disclosure provides methods and systems for calibrating a tunable laser, and more particularly, for calibrating a MEMS based laser by wavelength-voltage tuning function initialisation. Non-limiting examples of MEMS based laser include VCSEL laser and external cavity tunable laser. With the present disclosure, a tunable laser is capable of self-recalibrating its wavelength-voltage tuning table without any additional measurement equipment, e.g., high resolution optical spectrum analyser, aside from the laser. In particular, this self-calibration is enabled by a combination of an etalon, a photodetector of the laser, including any other usual components of the laser. The laser is further capable of performing self-recalibration upon user instruction or automatically, e.g., during self-initialisation which may take place during initiating operation of the laser and/or periodically during operation of the laser. The wavelength-voltage tuning table of the laser may therefore be calibrated or updated in real-time, on demand, and/or periodically, whether upon user instruction or automatically.

[045] An etalon’s free spectral ranges (FSR) refers to a spacing in optical frequency or wavelength between two successive reflected or transmitted optical intensity or power maxima or minima of the etalon. Wavelength error may increase with the FSR. In case that the FSR value is too large to maintain a high wavelength reliability, the operation temperature of the laser may be tuned to further assist the wavelength-voltage tuning function initialisation. This would reduce wavelength error when wavelength reliability requirement increases, such as to picometre scale.

[046] Accordingly, the methods and systems of the present disclosure would obviate problems associated with conventional built-in wavelength-voltage tuning table which cannot be re-calibrated or updated. Such problems include significant wavelength error due to high FSR value which does not meet wavelength reliability requirement. In contrast, methods and systems of the present disclosure perform re-calibration or update of the wavelength-voltage tuning table of the laser.

[047] Figure 2 shows a functional diagram of a laser apparatus (alternatively referred to as “laser”) having calibrating functions. The laser may be incorporated in an optical interrogator, e.g. fiber Michelson interferometer configured to interrogate fiber Bragg grating (FBG) sensor(s).

[048] The laser may include a vertical-cavity surface-emitting laser (VCSEL) or another type of laser emitter which is configured to emit laser beams and a micro-electromechanical system (MEMS) operably coupled thereto and configured to tune an output wavelength of the laser.

[049] The laser further includes an etalon (alternatively referred to as Fabry–Pérot etalon). Etalon is a popular optical component configured to calibrate wavelength in many tunable lasers. In this disclosure, etalon is further configured to assist the wavelength tuning function initialisation.

[050] The laser further includes a photodetector which is configured to detect and measure intensity of incident optical power or signals from the etalon by converting the incident optical power or signals from the etalon into electrical signals.

[051] The laser further includes an optical coupler which is configured to split optical power or signals into multiple paths and/or combine multiple optical power or signals into one path. In this disclosure, the optical coupler is configured to tap or split the output of VCSEL to the etalon and to an output port of the laser.

[052] The laser further includes a computing unit which is configured to execute computer-executable instructions to perform various functions and procedures described in relation to Figure 3, e.g., laser driver and temperature control, wavelength sweep control, tuning voltage initialisation, wavelength calibration or recalibration. Accordingly, the computing unit is operably coupled to the VCSEL and/or MEMS, and the photodetector. The computing unit may include one or more computer processors.

[053] The laser may further include a memory storage (not shown) which is configured to store computer-executable instructions to perform various functions. Accordingly, the memory storage is operably coupled to the computing unit.

[054] The laser may further include other components, e.g., power supply, which are conventional to laser and not described here.

[055] Figure 3 shows a flow chart for methods for calibrating a laser. In particular, the flow chart describes procedures of a wavelength-voltage tuning function self-initialisation of a tunable laser.

[056] In block 31, a first voltage sweep is performed at the tunable laser to produce a first laser output at the tunable laser. The first voltage sweep is performed at linear scale and at a first operating temperature of the laser. Block 31 then proceeds to block 32.

[057] In block 32, a first output spectrum or optical power produced by an etalon is detected by a photodetector. The first output spectrum is produced by the etalon in response to its receipt of the first laser output. The first output spectrum includes a range of optical signal amplitudes against a range of tuning voltages and includes a plurality of first signal peaks across the range of tuning voltages. In this block, a plurality of first voltage values (or first positions) of the first signal peaks are also computed or calculated. Block 32 then proceeds to block 33.

[058] In block 33, a FSR value of the etalon is compared against a predetermined FSR value (FSR_s). The predetermined FSR value may be suitably selected based on wavelength reliability requirement. If the FSR value of the etalon is ascertained as smaller than or equal to the predetermined FSR, block 33 proceeds to block 34.

[059] In block 34, a plurality of first sections of the first output spectrum are identified. The first sections are respectively defined by successive peaks of the first signal peaks of the first output spectrum. In other words, the first output spectrum is divided into a plurality of first sections wherein each section length (alternatively referred to as first section length) is taken as between a signal peak to an adjacent signal peak (alternatively referred to as two successive signal peaks) of the first output spectrum, and includes at most one FSR. In other words, each first section length corresponds to a difference in voltage values of two successive signal peaks of the first output spectrum. It is to be appreciated that the first section length varies as voltage varies, e.g., first section length decreases as voltage increases. Block 34 then proceeds to block 35.

[060] In block 35, based on the ascertained first voltage values within the first sections, a plurality of first substantially linear wavelength-voltage parameters respectively corresponding to the first sections are independently ascertained.

Accordingly, within each first section, pairs of the wavelengths and tuning voltages provide a plurality of substantially linear tuning relationships in view of the non-linear wavelength voltage relationship. For example, linear fitting may be performed to calculate a tuning voltage for each wavelength step or value within each first section. To simplify processing, linear fitting may be performed for a laser with low-end or low-power computing unit. Alternatively, square root fitting based on a square root relationship between wavelength and voltage may be performed. This may improve wavelength accuracy for larger FSR but may not provide significant improvement for smaller FSR. Block 35 then proceeds to block 36.

[061] In block 36, a first wavelength-voltage tuning table based on the first substantially linear wavelength-voltage parameters is ascertained. The table includes tuning voltage values and corresponding wavelengths. An existing wavelength-voltage tuning table which is configured for use by the laser may be updated to or replaced by the ascertained first wavelength-voltage tuning table. In other words, the existing wavelength-voltage tuning table of the laser may be recalibrated with the first wavelength-voltage tuning table.

[062] The sequence of blocks 31 to 36 takes place if the FSR value is smaller than or equal to the predetermined FSR value. However, if the FSR value is greater than the predetermined FSR value, block 33 proceeds to blocks 331 to 333 which performs a temperature-assisted initialisation. This temperature-assisted initialisation may be performed once, multiple predetermined times, or iterated until a stop condition is satisfied.

[063] In block 331, the operating temperature of the laser is adjusted or set to a second operating temperature which is distinct from the first operating temperature, e.g., higher or lower than the first operating temperature.

[064] In block 332, a second voltage sweep is performed at the laser to produce a second laser output at the laser. The second voltage sweep is performed at linear scale and at the second operating temperature of the laser.

[065] In block 333, a second output spectrum or optical power produced by the etalon is detected by the photodetector. The second output spectrum is produced by the etalon in response to its receipt of the second laser output. The second output spectrum provides a range of optical signal amplitudes against a range of tuning voltages and includes a plurality of second signal peaks across the range of tuning voltages. In this block, a plurality of second voltage values (or second positions) of the

second signal peaks are also computed or calculated. The second output spectrum substantially follows the first output spectrum except for a wavelength shift ($\Delta\lambda$). In other words, the second output spectrum differs from the first output spectrum in relation to wavelength only.

[066] A third output spectrum is derived based on, e.g., combining, the first output spectrum and the second output spectrum wherein the third output spectrum includes a plurality of third signal peaks based on, e.g., combining, the first signal peaks and the second signal peaks. This combining may include superimposing the first and the second output spectrums across the voltage range. As described above, peak magnitudes of the first signal peaks and the second signal peaks remain the same in the third output spectrum, however, the second signal peaks are wavelength-shifted or displaced from the first signal peaks. Hence, in the third output spectrum, a third section length between two successive third signal peaks (i.e. any adjacent signal peaks) is shorter than a first section length between successive first signal peaks as well as a second section length between successive second signal peaks. It is to be appreciated that the third section length varies as voltage varies, e.g., third section length decreases as voltage increases. In an example, the third section length may be identified at two successive peaks having the two highest voltage values among the third voltage values. In another example, the third section length may be identified at two successive peaks having non-highest voltage values among the third voltage values.

[067] The third section length is compared against the predetermined FSR value. If the third section length is ascertained as smaller than or equal to the predetermined FSR value, block 333 proceeds to block 34.

[068] In block 34, a plurality of third sections of the third signal output spectrum, which are respectively defined by successive peaks of the third signal peaks, are identified. In other words, the third output spectrum is divided into third sections wherein each third section includes at most one FSR which is taken between two successive signal peaks. It is to be noted that it may not be necessary to identify or ascertain a plurality of sections for the second output spectrum. Block 34 then proceeds to block 35.

[069] In block 35, a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections are independently ascertained based on the ascertained third voltage values within the third sections. Accordingly, within each third section, pairs of the wavelengths and tuning voltages

provide a plurality of substantially linear tuning relationships in view of the non-linear wavelength voltage relationship. For example, linear fitting may be performed to calculate a tuning voltage for each wavelength step within each third section. Alternatively, square root fitting may be performed. Block 35 then proceeds to block 36.

[070] In block 36, a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters is ascertained. An existing wavelength-voltage tuning table which is configured for use by the laser may be updated to or replaced by the ascertained third wavelength-voltage tuning table. In other words, the existing wavelength-voltage tuning table of the laser may be recalibrated with the third wavelength-voltage tuning table.

[071] It is to be appreciated that in block 333, if the third section length is ascertained as greater than the predetermined FSR value, the temperature-assisted initialisation procedures of blocks 331 to 333 may be iterated until a stop condition is satisfied, e.g., a third section length obtained during the final or most recent iteration is ascertained as smaller than or equal to the predetermined FSR value. With the iteration(s), the third output spectrum is derived based on the first output spectrum and the second output spectrums of the iteration(s). The third voltage values of the third output spectrum are based on the first voltage values and the second voltage values of the iteration(s). Upon satisfaction of the stop condition, block 333 proceeds to block 34 in which a plurality of third sections of the third output spectrum, which are respectively defined by successive peaks of the third signal peaks, are identified. Block 34 then proceeds to block 35 in which a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections are independently ascertained based on the ascertained third voltage values. Block 35 then proceeds to block 36 in which a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters is ascertained. An existing wavelength-voltage tuning table which is configured for use by the laser may be updated to or replaced by the ascertained third wavelength-voltage tuning table.

[072] It is to be appreciated that the various procedures in the flow chart of Figure 3 are directly and/or indirectly controlled and/or executed by the computing unit in cooperation with the laser, MEMS, etalon and/or photodetector.

[073] In accordance with the above description and associated figures, an example method and system for calibrating a MEM-based VCSEL was performed and verified.

In this example, wavelength of the VCSEL was tuned by changing the voltage of MEMS from 0 V to 18 V with a step of 1 mV. The detected optical signal (first output spectrum) using the photodetector was recorded by the computing unit and shown in Figure 4A. Here, the FSR of the etalon wavelength reference filter used was 0.8 nm.

[074] Using a Finisar high resolution optical channel monitor as reference, Figure 4B shows that the wavelength to voltage reference curve 41 (illustrated as solid line) has a non-linear relationship. Applying the procedures described with reference to the flowchart of Figure 3, e.g., blocks 31 to 36 are performed without requiring performance of blocks 331 to 333, and using linear fitting between two signal peaks produced by the etalon, which is according to one FSR, a tested wavelength curve 42 (illustrated as dash line), comprising linear fitted parameters (multiple wavelength voltage relationships), was ascertained. The tested wavelength curve 42 substantially overlaps with the reference curve 41 at higher voltage values but produces some wavelength error at lower voltage values. Figure 4B is annotated with a dashed box to highlight the wavelength error.

[075] Figure 4C shows wavelength error of the tested wavelength curve 42 as compared with the reference curve 41 measured by high resolution optical spectrum analyser. Linear fitting was adopted in ascertaining the tested wavelength curve 42. As observed, wavelength error decreases with decrease of the FSR. For FSR below 0.4 nm, the wavelength error is compatible with the wavelength noise of the VCSEL.

[076] As the FSR of the calibration etalon was large, the wavelength error might exceed threshold requirement. In this case, temperature-assisted initialisation as described in blocks 331 to 333 was applied. The wavelength of the VCSEL increases with the operation temperature linearly as shown in Figure 5A. From the example implementation, a wavelength shift of 111.6 pm per degree Celsius (°C) is observed from Figure 5A. The coefficient of determination (R^2) was about 0.9997 when temperature increased from 10 °C to 30 °C.

[077] With the application of temperature-assisted initialisation, two wavelength-voltage reference curves were obtained corresponding to a first operation temperature (T1) and a second operation temperature (T2). Figure 5B shows these two wavelength-voltage reference curves measured with high resolution optical spectrum analyser. To verify whether the two curves are identical other than wavelength-shifting, one of the curves is shifted to match the other and the differences between two curves after shift are shown in the inset of Figure 5B. As shown, the maximum wavelength

mismatch is observed at lower voltages as wavelength is less sensitive to tuning voltage at low voltages. Thus, in many applications, the tuning voltage will start from a suitable predetermined value to avoid this low voltage range. In the present example, once the tuning voltage is higher than 3 V, the wavelength mismatch is lower than $\pm 0.5 \times 10^{-5}$.

[078] Applying the procedures according to blocks 331 to 333 of Figure 3, two output spectrums (first and second output spectrums) were obtained across same tuning voltages (third voltage values) as shown in Figure 5C. The output spectrum labelled T1 (or first output spectrum corresponding to the first operating temperature) corresponds to Figure 4A while the output spectrum labelled T2 (or second output spectrum corresponding to the second operating temperature) is wavelength-shifted from T1. Since linear fitting worked well at higher tuning voltages, e.g., near 18 V, the wavelength shift may be estimated via the last signal peak positions of the respective output spectrums (two successive signal peak positions having highest voltage values among the third voltage values) considering the wavelength shift is linear for smaller FSR. For example, the wavelength shift (D) of the T2 curve is half of the duration (D_0), i.e., $D = D_0/2$. Each wavelength at each signal peak position in the T2 curve may be the corresponding wavelength in T1 curve minus half of the FSR. Thus, the two sets of signal peaks will form a new set of peaks similar to the free space range of $FSR/2$, as shown in Figure 5C. Hence, in accordance with block 333, a third output spectrum is derived based on a combination of the first and the second output spectrum (T1 and T2 curves) such that the third output spectrum provides a smaller FSR value or finer FSR than the first and the second output spectrum.

[079] If necessary, the temperature-assisted initialisation procedures according to blocks 331 to 333 of Figure 3 are iterated so that multiple finer temperature shifts may be performed to provide more reference peak wavelengths. The total wavelength window is then divided into more sections (third sections), each section (third section) is the wavelength range in between two adjacent peaks in the combined wavelength peaks. Figure 5D shows wavelength errors for different section lengths (0.8 nm, 0.4 nm, 0.2 nm, 0.1 nm, 1.6 nm) or FSRs. It is shown that wavelength error is reduced with smaller section length.

[080] The voltage for the sampling points inside each section is calculated linearly. In this way, the tuning voltage values for the whole spectrum range can be ascertained

and tabled for wavelength sweeping. Figure 5E shows linear fitting at sections S_1 and S_2 which positions are annotated in Figure 5C while Figure 5F shows linear fitting at sections S_{n-1} and S_n which positions are annotated in Figure 5C. At lower voltages (Figure 5E), there are wavelength errors as the linear fitted line diverges slightly from the reference line. At higher voltages (Figure 5F), there is no or insignificant wavelength error as the linear fitted line overlaps with the reference line. Based on aggregating the linear fittings of the various sections, a wavelength-voltage table is ascertained. Once the tuning wavelength-voltage table is ascertained, the wavelength-voltage tuning function initialisation is completed.

[081] Figure 5G shows a non-limiting example of a part of a wavelength-voltage tuning table for wavelength range 1543.086 nm to 1541.926 nm with 0.008 nm intervals. The table is derived from the linear fittings of the relevant section having voltage range approximately 17.0 V to approximately 18.0 V.

[082] Figure 5H shows an output spectrum of etalon after the initialisation. It is shown that the output wavelength decreases linearly with the increase of scanning points. Here, the wavelength step for each sampling is 10 pm. The output spectrum, having substantially equal section lengths, shows a good linear wavelength tuning feature of the VCSEL.

[083] The disclosure provides a non-transitory computer-readable medium having computer-readable code executable by at least one computer processor to perform the methods/steps as described in the foregoing, e.g., Figure 3.

[084] Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the disclosure. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the disclosed embodiments. The embodiments and features described above should be considered exemplary.

Claims

1. A method for calibrating laser, the method comprising:

performing a wavelength-voltage tuning function initialisation which comprises:

performing a first voltage sweep at a laser at a first operating temperature to produce a first laser output;

detecting, by a photodetector, a first output spectrum produced by an etalon in response to the first laser output;

computing a plurality of first voltage values of a plurality of first signal peaks within the first output spectrum;

upon ascertaining a free spectral range (FSR) value of the etalon is smaller than or equal to a predetermined FSR value, identifying a plurality of first sections of the first output spectrum which are respectively defined by successive peaks of the first signal peaks;

based on the first voltage values within the first sections, ascertaining a plurality of first substantially linear wavelength-voltage parameters respectively corresponding to the first sections; and

ascertaining a first wavelength-voltage tuning table based on the first substantially linear wavelength-voltage parameters.

2. The method of claim 1, wherein performing the wavelength-voltage tuning function initialisation further comprises:

upon ascertaining the FSR value is greater than the predetermined FSR value, performing a second voltage sweep at the laser at a second operating temperature to produce a second laser output;

detecting a second output spectrum produced by the etalon in response to the second laser output;

computing a plurality of second voltage values of a plurality of second signal peaks within the second output spectrum;

deriving a third output spectrum based on the first output spectrum and the second output spectrum wherein the third output spectrum includes a plurality of third signal peaks based on the first signal peaks and the second signal peaks, wherein a plurality of third voltage values of the third signal peaks correspond to the first voltage values and the second voltage values;

upon ascertaining a third section length between two successive peaks of the third signal peaks is smaller than or equal to the predetermined FSR value, identifying a plurality of third sections of the third signal output spectrum which are respectively defined by successive peaks of the third signal peaks;

based on the third voltage values within the third sections, ascertaining a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections; and

ascertaining a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters.

3. The method of claim 1, wherein performing the wavelength-voltage tuning function initialisation further comprises:

upon ascertaining the FSR value is greater than the predetermined FSR value, performing at least one iteration of a temperature-assisted initialisation until a third section length between two successive peaks of a plurality of third signal peaks is smaller than or equal to the predetermined FSR value, wherein each temperature-assisted initialisation comprises:

performing a second voltage sweep at the laser at a second operating temperature to produce a second laser output;

detecting a second output spectrum produced by the etalon in response to the second laser output;

computing a plurality of second voltage values of a plurality of second signal peaks within the second output spectrum;

deriving a third output spectrum based on combining the first output spectrum and each second output spectrum of the at least one iteration

wherein the third output spectrum includes the third signal peaks based on the first signal peaks and the second signal peaks of the at least one iteration, wherein a plurality of third voltage values of the third signal peaks are based on the first voltage values and the second voltage values of the at least one iteration;

upon ascertaining the third section length between two successive peaks of the third signal peaks is smaller than or equal to the predetermined FSR value, identifying the third sections of the third signal output spectrum which are respectively defined by successive peaks of the third signal peaks;

based on the third voltage values within the third sections, ascertaining a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections; and

ascertaining a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters.

4. The method of claim 2 or claim 3, wherein performing the wavelength-voltage tuning function initialisation further comprises:

recalibrating an existing wavelength-voltage tuning table of the laser with the third wavelength-voltage tuning table.

5. The method of any one of claim 2 to claim 4, wherein the two successive peaks correspond to two successive peaks having two highest voltage values among the third voltage values.

6. The method of claim 1, wherein performing the wavelength-voltage tuning function initialisation further comprises:

recalibrating an existing wavelength-voltage tuning table of the laser with the first wavelength-voltage tuning table.

7. The method of any one of claim 1 to claim 5, wherein performing the wavelength-voltage tuning function initialisation includes periodically performing the wavelength-voltage tuning function initialisation during operation of the laser.

8. The method of any one of claim 1 to claim 6, wherein ascertaining the plurality of first substantially linear wavelength-voltage parameters respectively is by linear fitting or square root fitting.
9. A system for calibrating laser, the system comprising:
 - a laser configured to emit laser beams and a micro-electromechanical system operably coupled thereto and configured to tune an output wavelength of the laser;
 - an etalon configured to receive an output signal of the laser;
 - a photodetector operably coupled to the etalon and configured to receive an output signal from the etalon; and
 - a computing unit operably coupled to the laser, the micro-electromechanical system and the photodetector and configured to execute computer-executable instructions to perform a wavelength-voltage tuning function initialisation which comprises:
 - performing a first voltage sweep at the laser at a first operating temperature to produce a first laser output;
 - detecting, by the photodetector, a first output spectrum produced by the etalon in response to the first laser output;
 - computing a plurality of first voltage values of a plurality of first signal peaks within the first output spectrum;
 - upon ascertaining a free spectral range (FSR) value of the etalon is smaller than or equal to a predetermined FSR value, identifying a plurality of first sections of the first output spectrum which are respectively defined by successive peaks of the first signal peaks;
 - based on the first voltage values within the first sections, ascertaining a plurality of first substantially linear wavelength-voltage parameters respectively corresponding to the first sections; and

ascertaining a first wavelength-voltage tuning table based on the first substantially linear wavelength-voltage parameters.

10. The system of claim 9, wherein the wavelength-voltage tuning function initialisation further comprises:

upon ascertaining the FSR value is greater than the predetermined FSR value, performing a second voltage sweep at the laser at a second operating temperature to produce a second laser output;

detecting a second output spectrum produced by the etalon in response to the second laser output;

computing a plurality of second voltage values of a plurality of second signal peaks within the second output spectrum;

deriving a third output spectrum based on combining the first output spectrum and the second output spectrum wherein the third output spectrum includes a plurality of third signal peaks based on the first signal peaks and the second signal peaks, wherein a plurality of third voltage values of the third signal peaks correspond to the first voltage values and the second voltage values;

upon ascertaining a third section length between two successive peaks of the third signal peaks is smaller than or equal to the predetermined FSR value, identifying a plurality of third sections of the third signal output spectrum which are respectively defined by successive peaks of the third signal peaks;

based on the third voltage values within the third sections, ascertaining a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections; and

ascertaining a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters.

11. The system of claim 9, wherein the wavelength-voltage tuning function initialisation further comprises:

upon ascertaining the FSR value is greater than the predetermined FSR value, performing at least one iteration of a temperature-assisted initialisation until a third section length between two successive peaks of a plurality of third signal peaks is smaller than or equal to the predetermined FSR value, wherein each temperature-assisted initialisation comprises:

performing a second voltage sweep at the laser at a second operating temperature to produce a second laser output;

detecting a second output spectrum produced by the etalon in response to the second laser output;

computing a plurality of second voltage values of a plurality of second signal peaks within the second output spectrum;

deriving a third output spectrum based on combining the first output spectrum and each second output spectrum of the at least one iteration wherein the third output spectrum includes the third signal peaks which correspond to the first signal peaks and the second signal peaks of the at least one iteration, wherein a plurality of third voltage values of the third signal peaks correspond to the first voltage values and the second voltage values of the at least one iteration;

upon ascertaining the third section length between two successive peaks of the third signal peaks is smaller than or equal to the predetermined FSR value, identifying the third sections of the third signal output spectrum which are respectively defined by successive peaks of the third signal peaks;

based on the third voltage values within the third sections, ascertaining a plurality of third substantially linear wavelength-voltage parameters respectively corresponding to the third sections; and

ascertaining a third wavelength-voltage tuning table based on the third substantially linear wavelength-voltage parameters.

12. The system of claim 10 or claim 11, wherein the wavelength-voltage tuning function initialisation of further comprises:

recalibrating an existing wavelength-voltage tuning table of the laser with the third wavelength-voltage tuning table.

13. The system of any one of claim 10 to claim 12, wherein the two successive peaks correspond to two successive peaks having two highest voltage values among the third voltage values.

14. The system of claim 9, wherein the wavelength-voltage tuning function initialization further comprises:

recalibrating an existing wavelength-voltage tuning table of the laser with the first wavelength-voltage tuning table.

15. The system of any one of claim 9 to claim 14, wherein performing the wavelength-voltage tuning function initialisation includes periodically performing the wavelength-voltage function initialisation during operation of the laser.

16. The system of any one of claim 9 to claim 15, wherein ascertaining the plurality of first substantially linear wavelength-voltage parameters respectively is by linear fitting or square root fitting.

17. The system of any one of claim 9 to claim 16, wherein the laser is a vertical-cavity surface-emitting laser or an external cavity tunable laser.

18. An optical interrogator comprising the system for calibrating laser according to any one of claim 9 to claim 17.

19. A non-transitory computer-readable medium having computer-readable code executable by at least one computer processor to perform the method according to any one of claim 1 to claim 8.