Longitudinal Cavity Mode Referenced Spline Tuning for Widely Tunable MG-Y Branch Semiconductor Laser

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Abstract. *This paper presents a novel method for wavelength-continuous tuning of a MG-Y-Branch Laser that possesses an intrinsic self-calibration capability. The method utilizes the measured characteristic output power pattern caused by the internal longitudinal cavity modes of the laser device to calibrate a set of cubical spline curves. The spline curves are then used to generate the tuning currents for the two reflector sections and the phase section of the laser from an intermediate tuning control parameter. A calibration function maps the desired laser wavelength to the intermediate tuning parameter, thus enabling continuous tuning with high accuracy.*

Keywords

MG-Y-branch laser, wavelength-continuous tuning, longitudinal cavity mode, spline curve tuning, intermediate tuning parameter.

1. Introduction

Achieving tuning ranges that spread over the entire optical communications C-Band through entirely solid state tuning means, the MG-Y-Branch tuned laser is one of the most interesting semiconductor lasers conceived in the last years. It is constructed by substituting the reflecting section of a Distributed Feedback Laser (DFB) by an arrangement of two electrically tunable reflection sections (modulated gratings) and a multimode coupler. Figure 1 shows a schematic view of the semiconductor structure. The device is fabricated from a single semiconductor chip.

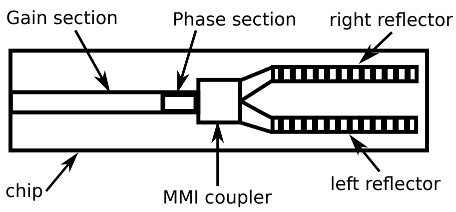

Fig. 1. Simplified semiconductor structure of a Y-Branch laser.

The two reflector sections are coupled to the gain section of the laser by a multimode coupler such that a Y shaped structure is formed. The device is named after this structure and can be found in publications under the name Modulated Grating Y-Branch Laser (MG-Y) [1, 2, 3, 6, 7, 8].

1.1 Tuning Via Reflector Currents

Each of the reflectors has a repetitive reflection pattern with properties determined by the period of the refractive index modulations. The spectral distance between the reflective peaks is chosen slightly different for the two reflectors, such that if both are superimposed, only one reflection peak of each reflector can overlap with a reflection peak of the other reflector. At the multimode coupler, the responses of both reflectors collectively form one half of the resonator reflector for the adjoined laser gain section (Fig. 2). This makes it possible to operate the laser at any wavelength of the spectrum where the responses of the two reflectors can be aligned.

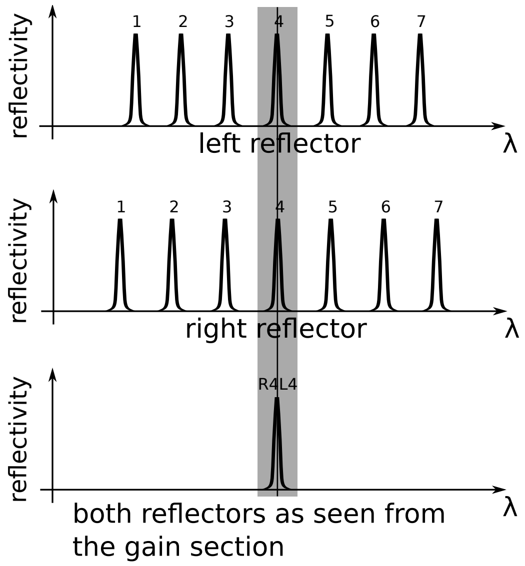

Fig. 2. Individual and combined reflection of the two reflectors.

If the reflective peaks of the reflectors are numbered consecutively according to their spectral position as shown in Fig. 2, the following Fig. 3 shows how the laser wavelength changes depending on the tuning currents of the left and right reflector. The lines labeled R1L1 to R7L7 represent areas where the corresponding reflector peaks R_n and L_n are spectrally aligned.

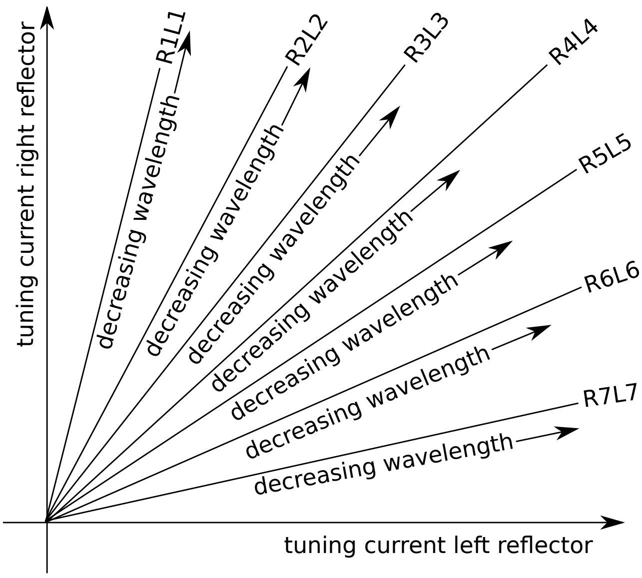

Fig. 3. Lines of alignment (tracks) of the reflector reflectivity peaks $R_n L_n$.

Now the position and spacing of the reflector reflectivity peaks can be chosen such that the tuning ranges covered by the lines of alignment adjoin in a gapless manner, providing full coverage of the desired wavelength range.

1.2 Longitudinal Cavity Mode Adjustment

For the sake of simplicity, so far we have examined the laser tuning mechanism without taking into account that in the laser resonator, as with practically every laser, longitudinal cavity modes exist. It is thus in reality not possible to achieve continuous tuning along the reflector alignment tracks without the laser jumping from one cavity mode to the next adjacent cavity mode.

This has several consequences:

- Discrete operating areas form along the alignment tracks wherever a cavity mode is centered.
- Laser output power varies within the discrete operating areas, with a power maximum indicating a centered longitudinal cavity mode
- At the boundary regions between two adjacent operating areas, laser operation is unstable (i.e. several modes may be present at the same time). For this reason and due to their visual appearance in diagrams showing the emitted laser power, the operating areas are also called islands.

Measuring the emitted laser output power of the device depending on the currents of the two reflector sections thus typically yields diagrams such as shown in the following Fig. 4. This diagram visualizes the current of the internal reference photodiode and therefore the emitted laser output power of a Syntune/Ignis/Finisar S7500 MG-Y-Branch Laser Device over 150 by 150 steps of the two reflector currents between zero and 16 mA. The phase section current was held at zero during the measurement.

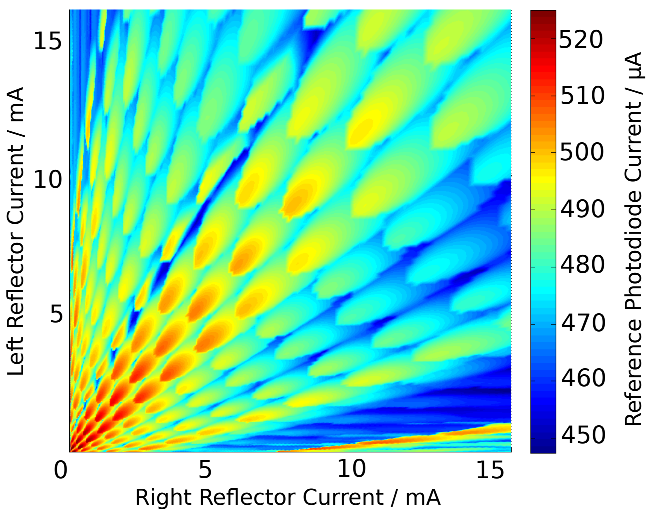

Fig. 4. Emitted laser power measured as the reference photodiode current depending on the two reflector currents.

The fact that the tuning tracks are divided into islands with boundary regions of unstable non-singlemode laser operation between adjacent islands would make continuous tuning impossible if no additional means of manipulating the resonator cavity were provided. The easiest way to achieve this is to introduce an adjustable section into the resonator that allows to alter the delay a lightwave experiences passing through it (Fig. 1). The section is called the phase section because it provides a means of adjusting phase delay in the resonator. Passing current through the phase section decreases the phase shift the lightwave encounters on its way through the section, thus decreasing the wavelength of the generated lightwave. This causes the islands to shift outward in the diagram toward shorter wavelengths and over the former boundary region where singlemode operation used to cease. Given proper design of the laser, this makes it possible to stitch together islands, achieving seamless coverage of the entire operating range while maintaining high sidemode suppression ratio (SMSR). However, even though the phase section may permit tuning over several cavity modes, it is still necessary to keep the two reflector peaks aligned, else the detuning achieved with the phase section may drive the laser outside the reflector spectral range. This can be understood as the combination of two effects:

- The wavelength selective reflection obtained from the combined reflection spectra of the two tunable reflectors.
- The longitudinal cavity modes present in the resonator which are an intrinsic property of any laser that relies on the Fabry-Perot resonator principle or modifications of it.

The following Fig. 5 illustrates this mechanism by showing the individual spectral characteristics of the involved parts of the laser and their resultant combination that ultimately governs the laser tuning behaviour.

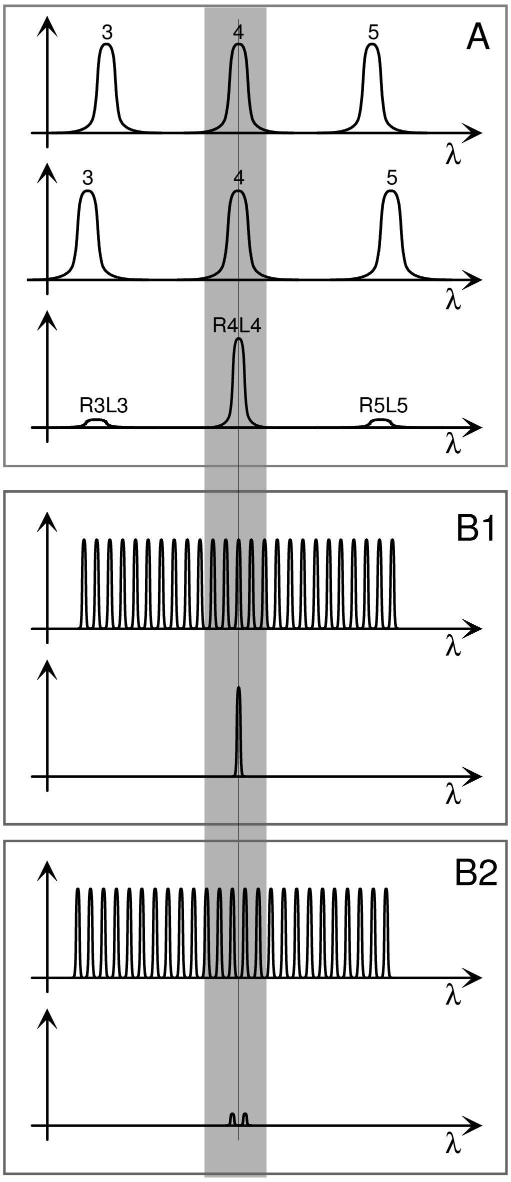

Fig. 5. Illustration of the combination of the tuning reflector spectral response and the laser cavity mode characteristics, not to scale. See text for detailed description.

The upper three curves (A) show the reflective response of the two reflectors and their combined reflection. This is the tuning mechanism described in Section 1.1 and Fig. 2.

The effect of the longitudinal cavity modes is illustrated in B1 and B2. B1 shows the spectral response of the longitudinal cavity modes (upper curve) and the resultant emitted spectrum (lower curve) for the case that the cavity mode is correctly aligned. This represents the situation in the center of an operating island. B2 illustrates the case of a non-aligned longitudinal cavity mode and the resultant emission spectrum. This represents the situation between two operating islands.

2. Self Calibrated Tuning

Additionally to presenting its working principle, the previous section showed how the already rather complex and unique tuning mechanism of the MG-Y-Branch Laser is further complicated by the occurrence of longitudinal cavity modes. However, the very same longitudinal cavity modes can also form the foundation of a novel approach to achieving continuous tuning as well as self-calibration capability which will be presented in the following text.

2.1 Longitudinal Cavity Mode Referencing

From the basic operating principle of the MG-Y-Branch Laser, it can be seen that the islands, each indicating a properly aligned longitudinal cavity mode, are spaced equidistant in wavelength. This is due to the periodic spectral nature of the longitudinal cavity modes that can be observed in every laser resonator, especially those of the fabry perot type. The locations of the island centers thus provide a means of relative calibration of the wavelength, comparable to the spectral response of a Fabry-Perot Interferometer.

Since the island centers can be easily detected by measuring the laser ouput power as a function of the two reflector tuning currents (Fig. 4) and detecting the local maxima, all combinations of the two reflector currents yielding optimally centered longitudinal cavity modes can be recorded. Note that this has to be done at a constant current setting for the phase tuning section to keep the spectral spacing of the longitudinal cavity modes constant.

In order to use the equidistant spacing of the islands to calibrate the laser wavelength, a parameter T_{Track} is introduced to describe the position of the islands along a track. With $T_{Track} = 0$ at the beginning of the track and δT_{Track} denoting the spacing between the islands, T_{Track} becomes an intermediate tuning parameter that is calibrated by the spectral spacing of the longitudinal cavity modes. The laser tuning via T_{Track} is thus normalized to the spectral spacing of the devices' own longitudinal cavity modes.

To use T_{Track} for simplified tuning of the laser, a relationship has to be established between the reflector tuning currents and T_{Track}. Since the available information about this relationship consists of the locations of the islands along the track - effectively a set of measured points $(I_{Tune}/T_{Track})^1$ that lie on the curve - any method describing this curve will give a formulation of the relationship. A convenient approach to formulating a function that passes through a set of fulcrum points are cubical splines. Utilizing polynomials of only third degree, the cubical splines were experimentally proven to be less susceptible to numerical errors caused by

[1] In this text, I_{Tune} is used for the sake of brevity to express that the context is identical for both reflector tuning currents I_{Left} and I_{Right}

particularly small or large coefficients such as encountered when using higher order polynomials in place of the splines.

Thus, if a cubical spline is fitted through the centers of the islands (OA) defined by points (I_{Tune}/T_{Track}) and T_{Track} is chosen such that the difference δT_{Track} in its value between two adjacent islands OA_{m-1}, OA_m is constant for all islands and tracks, this has the following consequences:

- T_{Track} becomes proportional to the emitted laser wavelength λ_L.
- The spline curve represents the sought-for relationship between tuning current and wavelength.

The following Fig. 6 illustrates this tuning current curve as generated by fitting a cubical spline trough the measured fitting points (I_{Tune}/T_{Track}).

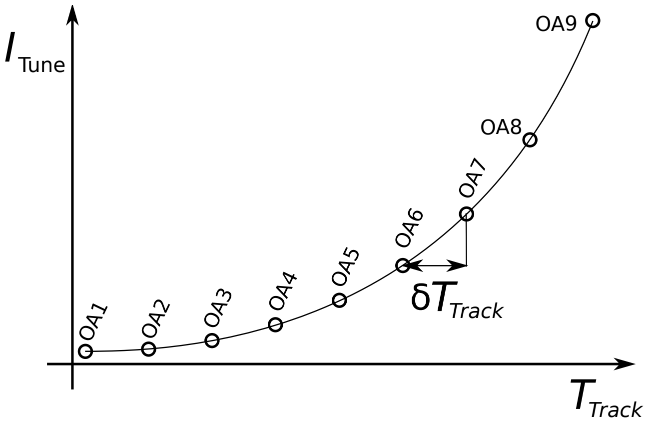

Fig. 6. Spline running through the centers of the islands (OA) of the tuning current curve of one track with intermediate tuning parameter T_{Track} as input of the spline.

Since δT_{Track} corresponds to a shift in laser wavelength λ_{OA} defined by the spectral spacing of the longitudinal cavity modes λ_{LCM}, tuning via T_{Track} is directly mapped to the grid defined by λ_{LCM}, which in turn is identical to the spectral spacing of the operating areas λ_{OA}. This can be used as a method of calibration if λ_{LCM} is considered an acceptable wavelength reference. In combination with an additional etalon such as the one integrated in the S7500 laser module, the accuracy can be further improved by calibrating T_{Track} using the etalon response. This possibility will be elaborated in Section 2.6.

2.2 Longitudinal Cavity Mode Control

So far we have examined the generation of the tuning currents for the two reflectors I_{Left}, I_{Right}. However, for continuous tuning along the tracks the phase section needs to be supplied with a suitable tuning current I_{Phase} as well. From the basic operating principle and especially the section about longitudinal cavity modes the function of the phase section can be readily understood. Since the phase section is part of the laser resonator, current injected into the phase section changes the delay the lightwave experiences during transit through it. This can be seen as a change in resonator length, thus altering the wavelength of the cavity mode. To characterize the response function of the phase section, its influence on the locations of the islands was measured. The following Fig. 7 shows the laser output power as measured by the reference photodiode of the device along one of the operating tracks for I_{Phase} between 0 and 3.5 mA.

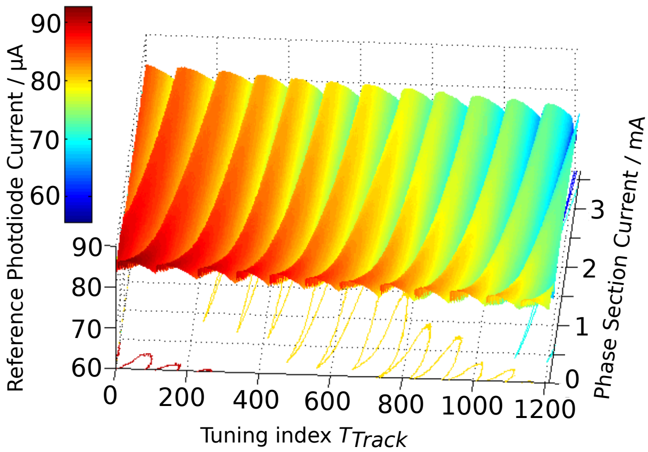

Fig. 7. I_{RefPD} as measured along operating track 7 for I_{Phase} between 0 and 3.5 mA.

The position on the operating track is indicated by T_{Track}. The difference δT_{Track} in the value of T_{Track} between two adjacent operating areas was chosen to be 100. Underneath the diagram plane coloured curves indicate lines of equal I_{RefPD} to highlight the slight decrease of I_{RefPD} for higher values of T_{Track}. Figure 7 thus shows the shift of the islands due to the phase section current I_{Phase}. Apart from a high degree of parallelism, the curves exhibit a very linear shape above currents of ca. 0.5 mA. The only available literature covering this aspect originates from the manufacturer and precursing research projects conducted at the University Gent [1, 2, 3]. The shape of the curve is therein described as a "sub-linear" without giving information about the mechanism causing this behaviour. Own investigations exceeding the scope of literature research were not pursued as neither the necessary technical resources were available nor a significant benefit regarding the realisation of the tuning method was anticipated from improved knowledge about the precise physical background of the function shape.

The high degree of parallelism of the individual curves as well as their linear shape for $I_{Phase} > 0.5$ mA are optimal for efficient modeling due to their high degree of redundancy and simple shape. Figure 7 further shows that the phase section allows to introduce enough wavelength shift to traverse from one operating area to the next adjacent one. If only slightly higher currents are used than visible in Fig. 7, this even becomes possible within the linear range of the phase section tuning curves.

Repeating the same measurement for only a small number of phase section current increments provides enough information to lay linear approximation lines through the operating area centers. Figure 8 shows the resultant diagram.

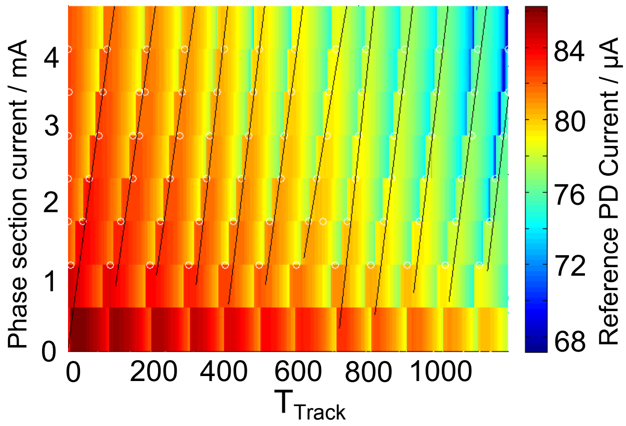

Fig. 8. I_{RefPD} as measured along operating track 7 for 8 increments of I_{Phase} between 0 and 5 mA, centers of operating areas are marked with white circles, linear approximation lines (black) intersect the maxima.

For this measurement, the phase section current was incremented in 8 steps from 0 to 5 mA. Using a peak finding algorithm, the local maxima of I_{RefPD} were determined for $I_{Phase} > 0.5$ mA to omitt the nonlinear portion of the curve. Linear functions (black lines) were fit to pass through the maxima (white circles) of each phase curve. This procedure effectively reduces the number of measurements required and the amount of data that has to be analyzed in order to locate the operating areas.

Somewhat contradicting to what could be expected from the operating principle of the MG-Y-Brach Laser is the observation that the slope of the phase response curves is subject to some light variations for the individual operating areas. Investigation of these variations showed that they are distributed in a random fashion, i.e. a distinctive pattern etc. could not be found.

The phase section current curves can therefore be modeled quite comfortably using simple linear equations if the nonlinear portion of the curves is omitted. This is possible since the phase section provides enough tuning shift in the linear portion to traverse from one operating area to the next adjacent one.

2.3 Aspects of Practical Implementation

For the application of the tuning model in an experiment or prototype, it is worthwhile to examine the shape of the phase current curves regarding the location of the maxima. Figure 7 exhibits a distinctive asymmetry in this aspect resulting in unique structures shaped like turbine blades. The maxima along these blades are located close to the blade edge, where the transition to the next aligned cavity mode occurs. Regarding the implementation of a model in an experiment, this situation is not optimal as it requires high accuracy to prevent missing the edge of the blade and falling on the adjacent one. Fortunately a simple remedy can be implemented in the form of an arbitrarily chosen offset that shifts the linear tuning equation more toward the middle of the blade. While this obviously changes the operating wavelength of the laser, it significantly decreases the risk of missing a blade. The resulting change in wavelength can later be removed by a calibration function (Section 2.6) with minimal effort. This calibration function provides a relationship between the desired wavelength and T_{Track} and therefore compensates both offsets as well as other wavelength errors.

2.4 Fitting of the I_{Phase} Equations

As a minimum, two points are required to fit a linear equation to each phase current curve, however, a greater number allows to increase precision and reduce errors. Doing so comes at the reasonable cost of measuring I_{RefPD} along the track several times (see Fig. 8) for the different levels of I_{Phase}, which is a very fast process compared to the initial measurement of $I_{RefPD}/I_{Right}, I_{Left}$. The island locations determined by the initial spline curve measurement thus form the starting points of the phase section tuning curves while their steepness is determined from the aforementioned measurements at various higher levels of I_{Phase}. Since T_{Track} of all islands is known by measurement, the current level $I_{PhaseSwitchOA_n}$ at which the switch from one island OA_n to the next adjacent one OA_{n+1} may be performed is given by

$$I_{PhaseSwitchOA_n} = I_{PhaseCurveOA_n}(OA_{n+1}), \quad (1)$$

i.e. the point when T_{Track} is has reached the level of the next adjacent island OA_{n+1}. For the sake of clarity, we have so far only considered the case of traversing operating areas by incrementing T_{Track}. It is however obvious that the process is analogous for decrementing T_{Track}. Figure 9 illustrates how the phase section current has to be changed in accordance to T_{Track} in order to traverse from one island to its neighbor islands.

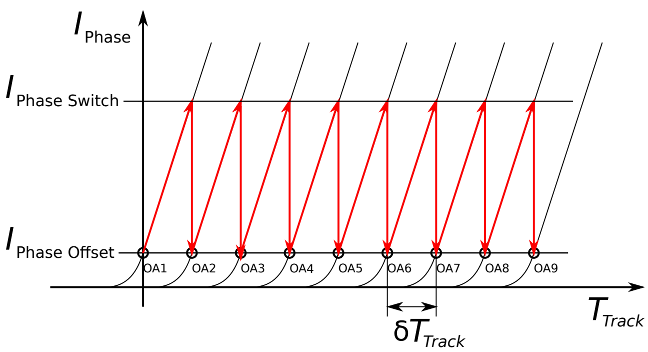

Fig. 9. Phase section tuning current during switchover procedure for traversing from one operating area to its neighboring areas.

Accordingly, the operating areas at the ends of a track form the transition points between adjacent tracks.

2.5 Operating Track Stitching

By joining together the tuning ranges of the individual tracks at their respective endpoint islands, seamless tuning over the complete device tuning range is achieved. Regarding the practical realisation, this raises the question as to how redundant islands can be automatically excluded from the scheme to prevent discontinuities in a tuning parameter T_{Device} covering the entire device tuning range. Two approaches to solve this aspect were investigated:

- Boundary values for I_{Tune} define ranges in which the tuning currents for the individual tracks are allowed to lie. If islands happen to lie outside these ranges, they are classified as redundant and disregarded. Experiments showed that this approach is feasible considering the drift experienced with the measured device characterization data. In fact, state-of-the-art channel based tuning systems rely on such data entirely, so it can be considered more than adequate for the mere purpose of limiting the current ranges of the operating tracks. However, it relies on externally provided data that the tuning system can not autonomously generate through own measurements. Also, some means of external optical wavelength measurement (optical spectrum analyzer or wavemeter) is required to perform such production calibration.
- The shape of the response curve of a relative wavelength reference such as the integrated etalon is measured along each individual track. The individual curves can then be aligned such that a seamless transition occurs. That way, redundant islands can be identified quite easily. However, the free spectral range of the etalon has to be amenable for such a procedure, i.e. it must not be too small or too large. In the case of a too small free spectral range, ambiguity problems of the etalon curve peaks arise during the alignment of the etalon ration curves. For too large free spectral ranges, the ambiguity problems occur at the islands themselves. Experiments (graphical alignment) conducted with the integrated etalon showed that this approach is feasible, however requires considerable software development effort to be usable in a production system.

2.6 Wavelength Calibration

The final step required in order to obtain a tuning method that uses the desired wavelength λ_{Target} as an input to steer the tuning currents is to calibrate T_{Device} or T_{Track} to a wavelength standard. Two possible approaches are discussed in this paragraph:

- Calibration using an absolute wavelength reference such as an external instrument like an optical spectrum analyzer or a wavemeter.
- Calibration using a relative wavelength reference such as the integrated etalon or an external one.

While the first solution is a simple and straightforward one that provides high accuracy, it has numerous disadavantages such as beeing rather slow due to the large number of measurements required for high resolution or the fact that external optical instruments are necessary to perform it. This renders the preceeding efforts regarding self-calibrating more or less worthless as the final step can not be performed without external instrumentation.

The latter solution only relies on a structurally simpler kind of reference, an etalon, and thus is more amenable for integration into the system. It also can be performed in much less time since only the currents of the internal two photodiodes of the S7500 laser module, namely I_{RefPD} and I_{Etalon}, have to be sampled and processed. However, this comes at the expense of beeing an only relative reference, i.e. it is possible to calibrate a change in wavelength and not the absolute value of the wavelength. Effectively this can be seen as a ruler that has no numerical markings on it but only a graticule. This aspect has to be adressed by additional means of referencing, which may be for example the reflection spectrum of a known FBG integrated into the system that is used as a wavelength marker to calibrate the absolute wavelength. Other possibilities include some form of Look Up Table provided during manufacture that associates a set of spectral landmarks such as operating areas or peaks of the etalon reflection ratio curve to a table of absolute wavelengths.

3. Experimental Verification

To assess the performance of the longitudinal cavity mode referenced tuning method experimentally, it was integrated into the LabView based laser control program to generate the tuning currents for the laser from a desired T_{Track}. The actual laser wavelength generated by the laser was measured simultaneously with a BaySpec optical spectrum analyzer module.

The tuning model was implemented in LabView using cubical spline elements to calculate the tuning currents for the desired wavelength. Neither a mechanism to stitch together several tracks nor a calibration function were implemented since their functionality is very straightforward and no further gain of knowledge was anticipated by simply joining together the tuning ranges of the individual tracks or removing wavelength deviations that in fact are the most interesting aspect of this experiment.

During the experiment, T_{Track} was scanned over the operating range of one track of the device while the following parameters were recorded:

- Emitted Wavelength λ,
- Reference Photodiode Current I_{RefPD},
- Etalon Photodiode Current I_{Etalon}.

The obtained values were stored together with all other experiment data in a file.

3.1 Performance Evaluation

In order to evaluate the accuracy attained with the longitudinal cavity mode referenced tuning method, it was used to generate the tuning currents for the individual tracks for sweeps of T_{Track} along the full operating track. The following figures were generated from data collected during a sweep along Track 7 and stand exemplary for all other operating tracks as the results for the remaining tracks were very similar.

The following Fig. 10 shows the Integral Nonlinearity (INL) of the emitted wavelength depending on the tuning parameter T_{Track} for Track 7. The INL is normally known as a characteristic used to describe the quality of Digital to Analog Converters (DAC). In our case, it is applicable as a quality measure as well since the process of converting an integer number (T_{Track}) to an analog value such as the emitted wavelength can be seen as a digital to analog conversion, too. Thus the INL describes the wavelength deviation from an ideal linear relationship between T_{Track} and the emitted wavelength.

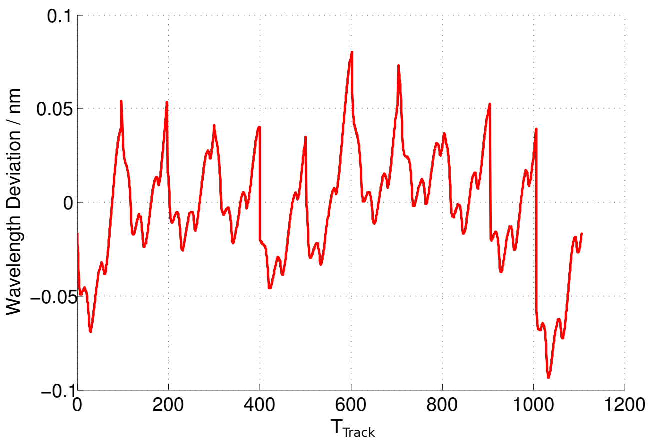

Fig. 10. Integral Nonlinearity (INL) of T_{Track} for Track 7.

The curve exhibits distincitive gradients at regular intervalls. This is due to the fact that the difference between two islands in T_{Track} was chosen to be $\delta T_{Track} = 100$. Thus at these locations, gradients can be expected since the laser shifts form one island to its neighbor island. To assess these gradients in greater detail, the derivative of the emitted wavelength was calculated. This curve is shown in Fig. 11.

The gradients exhibit a tendency to negative deviations which can be explained by the direction of the sweep along the operating track. Further the diagram shows that the gradients remain within reasonable values (max. 0.1 nm).

An interesting feature of the diagram are the small periodic changes that appear to cover the complete track range and were found on all tracks. The exact origin of these changes could not be determined. It might be caused by a form of a parasitic reflection based Fabry Perot filter characteristic in the experiment setup.

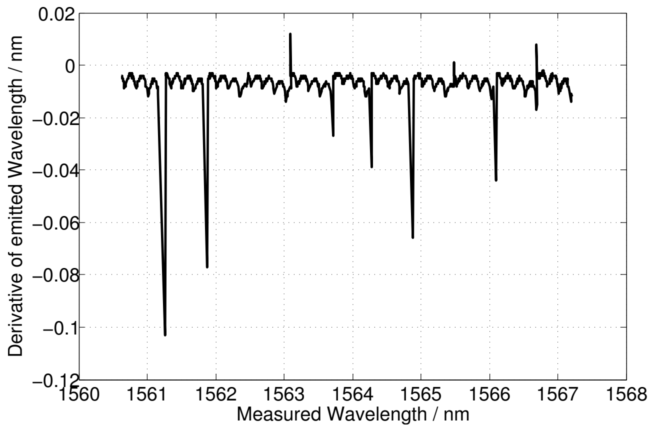

Fig. 11. Derivative of the emitted Wavelength for Track 7.

The following Fig. 12 shows the phase section current depending on the emitted wavelength as it was generated by the tuning model during the sweep along Track 7.

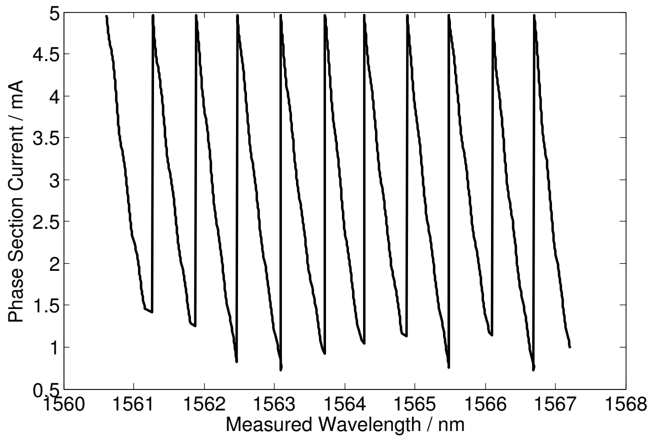

Fig. 12. I_{Phase} vs. emitted Wavelength for Track 7.

Finally, Fig. 13 shows the current of the integrated etalon photodiode depending on T_{Track}. The peaks occur at fixed intervals of 50 GHz and may therefore be utilized as a wavelength reference. The diagram exhibits slight irregularities in the wavelength distance between the individual peaks which in turn represent the wavelength deviations already shown in Fig. 10 and 11.

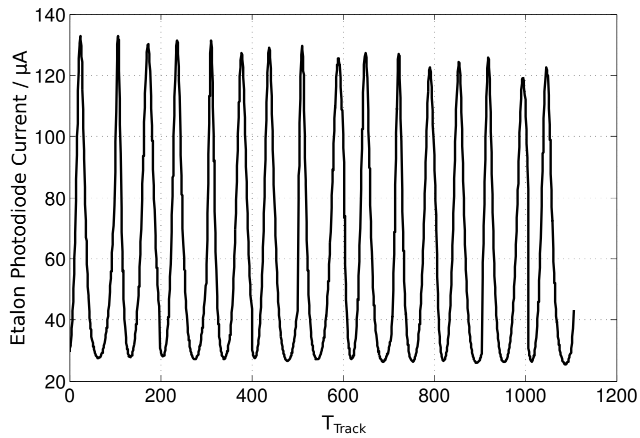

Fig. 13. I_{Etalon} depending on T_{Track} measured along Track 7.

4. Conclusions

The presented wavelength control method makes it possible to operate a MG-Y Branch Laser at arbitrary wavelengths within its operating spectral range. Continuous tuning can be performed while the laser is kept in single mode operation. Owing to the fundamental operating principle of the MG-Y Branch Laser, tuning linearity is best in situations where no switchover from one longitudinal cavity mode to another occurs. At switchover points wavelength derivatives of ca. 100 pm were observed.

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