Effect of Optical Feedback on the Wavelength Tuning in DBR Lasers

Magnus Happach, David de Felipe, Victor Nicolai Friedhoff, Gelani Irmscher, Martin Kresse, Moritz Kleinert, Crispin Zawadzki, Walter Brinker, Martin Möhrle, Norbert Keil, Werner Hofmann, *Member, IEEE*, and Martin Schell

***Abstract*—Optical feedback has an impact on the tunability of lasers. We created a model of a tunable distributed Bragg reflector (DBR) laser describing the effect of optical feedback from a constant reflector distance on the wavelength tuning. Theoretical and experimental results are in good agreement. A further discussion of the model sheds light on design rules to reduce the effect of optical feedback on the tuning behavior. We introduced a new parameter called mode loss difference (MLD) as a metric for the feedback tolerance of the tuning behavior. A large MLD indicates higher tolerance of the laser to cavity length variations.**

***Index Terms*—Continuous Tuning, DBR Laser, external Cavity, Optical Feedback Interferometry, Optical Feedback, Tunable Laser.**

I. Introduction

THE reintroduction of a laser beam back into its laser cavity is called optical feedback [1]. The back reflected beam interferes with the laser cavity beam and induces changes in laser characteristics such as the output power, the gain voltage, the linewidth, the side mode suppression ratio (SMSR) [2], [3], the frequency chirp [4], and the bandwidth [5]. Depending on the feedback power ratio and the distance of the external reflector in respective to the output facet, the laser can show different characteristics. Five regimes can be distinguished [6], regime I: low feedback, which causes narrowing or broadening of the laser linewidth; regime II: feedback which causes splitting of the emission line and mode hopping; regime III: distance independent laser operation with narrowed linewidth; regime IV: distance independent laser operation with satellite modes separated from the main mode; regime V: an extended cavity operation. A further revised discussion of the optical feedback regimes with short and long external cavities [7] identified regions for self-mixing interferometry [8]. A further discussion of the transition from short to long cavity regime can be found in [9].

However, this does not tell us about the impact of optical feedback on the lasing mode stability during laser tuning. In order to describe the effect, we set up a laser model which allows the discussion of the wavelength tuning under optical feedback from a reflection at a constant short distance, which can be interpreted as an external cavity next to the laser cavity, from now on referred as feedback section. Based on the model we extend the perspective on the feedback parameters, which are the power ratio and the distance to the external reflection, and include certain laser design parameters like the laser cavity length, the full width half maximum (FWHM), and the maximum reflectivity of the Bragg grating. It turns out that not only the feedback power ratio determines the stability of a laser. The length ratio of the feedback section to laser cavity, from now on referred to as cavity ratio, impacts the mode stability as well as the FWHM [10], and the amplitude of the reflectivity of the Bragg grating [11]. Optical feedback as an uncontrolled effect can appear already within the laser module e.g. at the coupling point between the laser chip and the single mode fiber. The reflection can, but do not have to appear and might reduce the yield of good devices during production. Certain design rules are suggested which reduce the negative effects on the tunability in the case of optical feedback from a reflection at a constant distance external to the laser cavity.

Continuous tuning means shifting the longitudinal mode in wavelength while not inducing mode hops. A mode hop is the wavelength hop which takes place when another mode starts lasing because it suffers fewer losses. The range in which a mode can be tuned continuously is limited by these mode hops which. We call these ranges mode hop zones from now on. For a DBR laser without optical feedback the mode hops zones are straight and continuous tuning is possible by applying the tuning parameters with linear dependency. The optical feedback changes the shape of the mode hop zones and three tuning regimes of tunability were found:

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Magnus Happach was with the Fraunhofer Heinrich Hertz Institute, 10587 Berlin, Germany. He is now with Sonova AG, 8712 Stäfa, Switzerland.

David de Felipe, Gelani Irmscher, Martin Kresse, Moritz Kleinert, Crispin Zawadzki, Walter Brinker, Martin Möhrle, and Norbert Keil are with Fraunhofer Heinrich Hertz Institute, 10587 Berlin, Germany (e-mail: david.felipe@hhi.fraunhofer.de; gelani.irmscher@hhi.fraunhofer.de; martin.kresse@hhi.fraunhofer.de; moritz.kleinert@hhi.fraunhofer.de; crispin.zawadzki@hhi.fraunhofer.de; walter.brinker@hhi.fraunhofer.de; martin.moehrle@hhi.fraunhofer.de; norbert.keil@hhi.fraunhofer.de).

Victor Nicolai Friedhoff is with Humboldt University of Berlin, 10117 Berlin, Germany (e-mail: nicolai.friedhoff@mdc-berlin.de).

Werner Hofmann is with the Institute for Solid State Physics, Technical University of Berlin, 10623 Berlin, Germany (e-mail: werner.hofmann@tu-berlin.de).

Martin Schell is with Fraunhofer Heinrich Hertz Institute, 10587 Berlin, Germany, and also with the Institute for Solid State Physics, Technical University of Berlin, 10623 Berlin, Germany (e-mail: martin.schell@hhi.fraunhofer.de).

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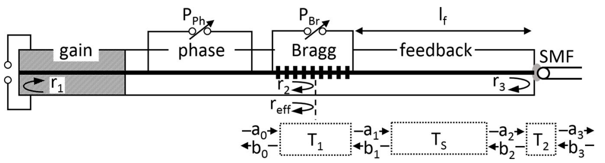

Fig. 1. Tunable Laser with an indium phosphide (InP) active gain section that is supplied by a constant current source. The wavelength of the laser can be tuned by the phase heating power P_{Ph} and the Bragg heating power P_{Br}. The passive and the feedback section are in the same polymer chip. The feedback section has the length l_f. The chips output is butt-coupled to a single mode fiber (SMF) with phase matching glue and has a small reflectivity. The T-Matrix sections show the division of the feedback section into its matrix elements T_1 for the Bragg grating, T_S the propagation through the waveguide and T_2 the small reflection. The parameter a_0, a_1, a_3, b_0, b_1, b_3 are vector elements.

Tuning Regime I: The mode hop zones have no or a weak sinusoidal perturbation. The laser is continuously tunable by applying the tuning parameters linearly. The laser is tolerant to laser cavity and feedback section length variations.

Tuning Regime II: The mode hop zones have a strong sinusoidal perturbation but do not intersect each other. The laser is continuously tunable but the tuning parameters need to be adjusted non-linearly. The laser is still tolerant to cavity ratio variations.

Tuning Regime III: The mode hop zones overlap periodically and create closed mode zones. Continuous tuning without forcing a mode hop is not possible. Small variations of the cavity ratio can cause a mode hop.

The laser we use in the experiments is a hybrid indium phosphide (InP)/Polymer laser with a design wavelength of 1570 nm [12]. The active InP section has a length of 400 μm; refractive index $n_a = 3.4$, and is supplied with a constant current. The passive section with a length of 1500 μm consists of a phase heating section which can be tuned by controlling the heating power P_{Ph} and a Bragg grating which can be tuned by controlling the Bragg heating power P_{Br} [13]. The Bragg grating has a penetration depth of 500 μm. The laser cavity is created by the left facet of the active section r_1 and the Bragg grating r_2, Fig. 1. The coupling point of the butt-coupled single mode fiber (SMF) with refractive index $n_{SMF} = 1.47$ and the Polymer chip with $n_p = 1.4634$ have a small difference in refractive index and create a reflection which is theoretically -52 dB. However, due to microcracks and humidity absorption of the glue we expect a reflection of approximately -45 dB. The section between the Bragg grating and the coupling point is the feedback section. The reflection coefficient is considered small enough such that no extended cavity operation would be created what is the case for a reflectivity greater than -9 dB [6]. Furthermore, we consider only one roundtrip of the back reflected beam which is from now on referred to as feedback beam.

II. Model of the DBR Laser Under Optical Feedback

Optical feedback from a reflection at a constant distance can be treated as an external cavity. A laser with such an additional feedback section is a two-cavity problem and can be simplified by the effective mirror model whereby the laser will be reduced to a single cavity with a wavelength dependent effective reflectivity. This model is valid for steady state analysis [11]. However, for fast continuous tuning and a long distance to the external reflection the wavelength of the back reflected beam may differ to the beam of the laser cavity. Therefore, we assume in our model that the wavelength tuning is slow and the external reflection near such that the steady state assumption is justified. The effective reflectivity can be derived from the transmission matrix formalism. The reflectivity spectrum of Bragg gratings can be approximated by the shape of a normal distribution.

Furthermore, we determine the lasing wavelength by the mode which suffers the fewest mirror loss. The good agreement of the model with experimental results shows that this approach is adequate even if, strictly speaking, for some the mode selection by the narrowest linewidth has to be considered as well [6], [14]. The distribution of the material gain is considered as broad enough such that it can be assumed as constant for the discussed wavelength.

A. Effective Bragg Grating Reflectivity Under Optical Feedback

A Bragg grating is a waveguide with alternating narrowed and broadened width to introduce a contrast of the effective refractive index in order to reflect a small part of the laser cavity beam back with each period of the grating. An analytical description of such a section can be performed using the transfer matrix or T-matrix formalism [15].

1) Transfer Matrix: The T-Matrix formalism enables straight forward calculation of the reflectivity of a chain of different optical sections, e.g. the propagation of a beam through a Bragg grating and subsequent transmission through a waveguide until it eventually reaches a small index disturbance which reflects part of the beam back. Fig. 1 shows the Bragg grating T_1, the propagation section T_s with length l_f, and the small index contrast T_2 which accounts for the reflection coefficient r_3. A detailed description of the matrices can be found in [10], [11], [15]. The reflectivity $R_M = r_M^2$ can be calculated using the reflection coefficient, $r_M = |\frac{a_0}{b_0}|$. The vector elements a_0 and b_0 can be calculated by $\binom{a_0}{b_0} = T_1 T_S T_2 \binom{a_3}{b_3}$. The T-matrix formalism needs multiple calculation iterations and a collection of various parameters. Therefore, we use the normal distribution as an approximation to reduce the efforts of calculating the Bragg grating's properties as follows.

2) Normal Distribution: The T-matrix formalism describes the Bragg spectra with an additional reflection outside the grating itself. However, it might be too elaborate to implement the whole calculation as well as finding the correct set of parameters. Therefore, we use an approximation which concentrates on the main peak and neglects the satellite peaks. The main peak, which has the highest reflectivity of the Bragg spectrum, will be described in a first step with the normal distribution. The reflection $r_B(\lambda)$ and transmission $t_B(\lambda)$ coefficients can be expressed as

$$r_B(\lambda) = r_2 \cdot \mathrm{Exp}\left[- \frac{(\lambda - \lambda_B)^2}{\left(\sqrt{Log[2]} \cdot \Delta\lambda_{FWHM}\right)^2} \right]$$

$$t_B(\lambda) = \sqrt{1 - r_B^2(\lambda)} \tag{1}$$

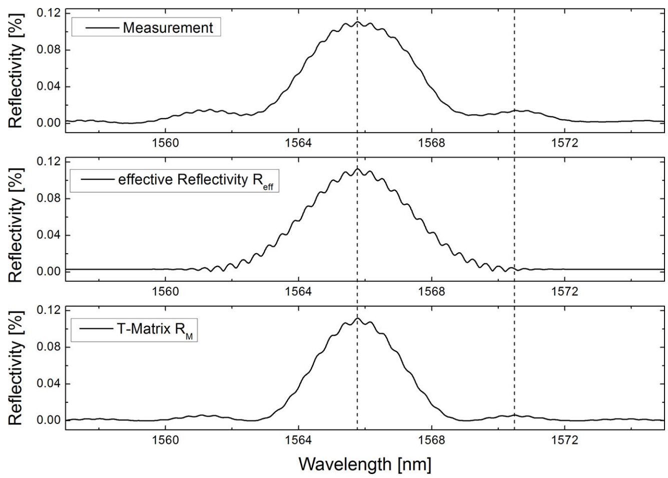

Fig. 2. Comparison of the calculated and the measured reflectivity from a Bragg grating with a slight reflectivity at the coupling point at the butt coupling point.

where $\Delta\lambda_{\mathrm{FWHM}}$ is the FWHM of the spectra, λ_{B} the Bragg wavelength where the reflection and transmission coefficients have their maximum and minimum at r_2, respectively. The normal distribution can now be considered in the effective mirror model as described in [11], [16]. The effective mirror model reduces the two-cavity problem to one cavity and considers the influence of the optical feedback in a wavelength dependent reflectivity. The shape of the Bragg grating in the effective mirror model can be considered by $r_{\mathrm{B}}(\lambda)$. Due to a small reflection r_3, multiple reflections between the Bragg grating and the reflection will be ignored and only one round-trip will be considered. Furthermore, with the optical length $L_{\mathrm{f}} = n_{\mathrm{f}} \cdot l_{\mathrm{f}}$ and with the approximation of $r_3 \approx 0$ the effective reflection coefficient is

$$r_{eff}(\lambda) = r_B(\lambda) + \frac{t_B^2(\lambda) r_3 Exp\left[-2i\frac{2\pi}{\lambda}L_f\right]}{1 + r_B(\lambda) r_3 Exp\left[-2i\frac{2\pi}{\lambda}L_f\right]}$$
$$\approx r_B(\lambda) + t_B^2(\lambda) r_3 Exp\left[-2i\frac{2\pi}{\lambda}L_f\right]. \qquad (2)$$

The reflectivity can be calculated by $R_{\mathrm{eff}}(\lambda) = |r_{\mathrm{eff}}(\lambda)|^2$. Fig. 2 shows the measured reflectivity, the calculated reflectivity R_{eff} using the normal distribution, and the calculated reflectivity R_{M} by applying the T-Matrix formalism. The reflectivity spectrum has been measured by connecting the SMF, Fig. 1, to a reflection spectrometer. The reflection r_3 and the grating together create a Fabry-Pérot cavity which results into the small perturbation on top of the Bragg grating spectra. For the calculations the reflection has been considered as $r_3 = -45$ dB which lies in the range of the refractive index difference between the polymer and the single mode fiber; the optical length of the feedback section has been assumed as $L_{\mathrm{f}} = 3184$. All the spectra show a sinusoidal perturbation on top of the Bragg grating caused by the optical feedback. The T-Matrix formalism also shows the satellite peaks in contrast to the normal distribution which expresses the main peak only. Since in our model we select the lasing mode with the maximal reflectivity, we can neglect the satellite peaks with less reflectivity.

B. Model for the Calculation of the Lasing Wavelength Under Optical Feedback

To calculate the emitted wavelength of a tunable laser we have to consider the condition for the round-trip phase by $\lambda_{\mathrm{k}} = 2L_{\mathrm{cav}}/(\mathrm{k} + \Phi_{\mathrm{eff}}/2\pi)$ which allows the calculation of the possible lasing modes k and their related wavelength λ_{k} with the optical length L_{cav} of the laser cavity [11]. The phase shift Φ_{eff} from the feedback section is defined as $\Phi_{\mathrm{eff}} = -t_2^2\, r_3 \sin(4\pi L_{\mathrm{f}}/\lambda)/r_2$. The lasing mode is determined by the smallest loss or, for certain feedback levels, by the smallest linewidth [6], [14]. However, this work neglects the mode selection by the laser linewidth. Also, due to $r_3 \approx 0$ the phase shift will approximately vanish, $\Phi_{\mathrm{eff}} \approx 0$. The dependency of the effective mirror loss of each mode can be described as $\alpha_{\mathrm{m}}(\lambda_{\mathrm{k}}) \approx \mathrm{Log}[1/r_1 r_{\mathrm{eff}}(\lambda_{\mathrm{k}})]$ [2]. To determine the wavelength $\lambda_{\mathrm{Lasing}}$ of the lasing mode, we identify the mode that suffers the fewest losses,

$$\lambda_{Lasing} = \mathrm{Min}\left[\alpha + \alpha_m(\lambda_k)\right] \qquad (3)$$

Due to the reciprocal dependency of the mirror loss to the effective reflectivity, we can determine the lasing wavelength using the maximum reflectivity. The internal loss α is strictly speaking also wavelength dependent. However, for the calculation of the lasing mode selection it is acceptable to consider this parameter as constant and to determine the wavelength by the mode which suffers the fewest mirror losses and has the highest effective reflectivity.

Due to the thermal dependency of the refractive index described by the thermo-optic coefficient (TOC) and the thermal expansion (TE) of the cavity length l_{cav}, the optical length L_{cav} changes with temperature variations ΔT through applying power at the phase heating section with $dL/dT = \Delta L = (TO + n \cdot TE) \cdot l \cdot \Delta T$. The same occurs for the Bragg grating which can be tuned by applying electrical heating power to the heating section of the Bragg section [17] and thereby changing the Bragg wavelength. The lasing wavelength for a set of heating powers $\{P_{\mathrm{Br}}, P_{\mathrm{Ph}}\}$ can be calculated by determining the length of the laser cavity, solving the condition for the round-trip phase for a set of modes k and equation (3).

Fig. 3 shows three calculated wavelength mappings with the same laser cavity length of $L_{\mathrm{cav}} = 3550\ \mu$m, cavity ratio $L_{\mathrm{f}}/L_{\mathrm{cav}} = 0.5$, and different feedback power ratios. The mapping with no optical feedback, Fig. 3(a), has straight mode hop zones, shown by the black lines, and continuous tuning is possible, shown by the black arrow. For the laser with a feedback power ratio of -45 dB, Fig. 3(b), the mode hop zones have a sinusoidal perturbation. Continuous tuning is still possible, even when the perturbation narrows the mode hop free area. The mapping with feedback of -30 dB has mode hop zones which intersect periodically. Continuous tuning over the full tuning range is not possible anymore, shown by the discontinuous arrows.

In order to compare the model with experiments, we have measured a wavelength mapping of a laser with optical feedback of about -45 dB, Fig. 4. The mode hop zones where the lasing mode hops from one mode k to another mode k $\pm$ 1 [18] are marked by a black line. Compared to a laser without feedback [19] the mode hop zones are not straight but have a sinusoidal

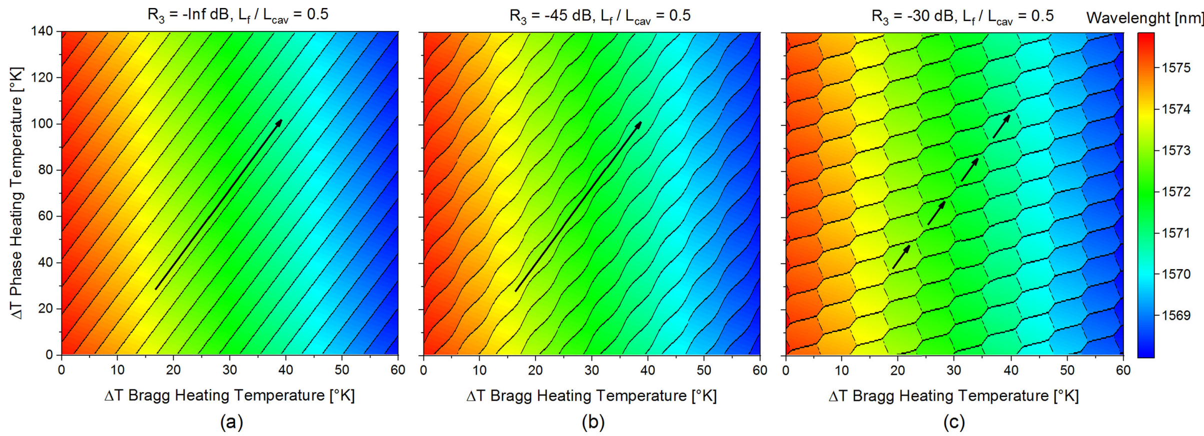

Fig. 3. Calculated wavelength mappings of a laser with a laser cavity length of $L_{cav} = 3550$ μm and a cavity ratio of 0.5 under different feedback power ratios. The black lines show the mode hop zones. The black arrow shows possible continuous tuning lines. (a) with no optical feedback and straight mode hop zones, (b) weak optical feedback and sinusoidal perturbation of the mode hop zones, and (c) strong feedback with periodical contact of the mode hop zones.

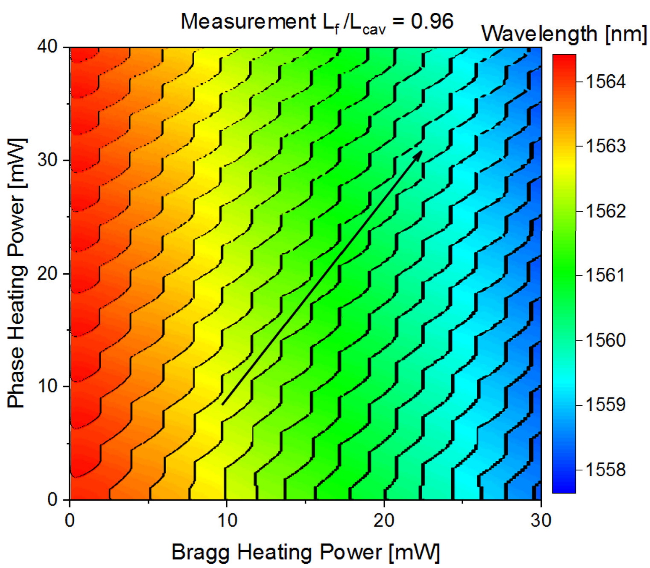

Fig. 4. Measured wavelength mapping with different Bragg and phase heating powers. The solid black lines mark the mode hop sections. The ratio of the laser cavity $L_{cav} = 3535$ μm and the feedback cavity $L_f = 3388$ μm is ratio = 0.96.

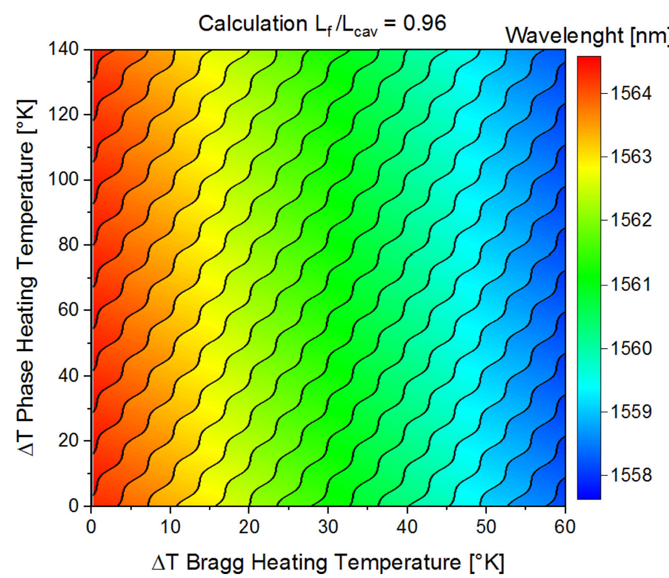

Fig. 5. Calculated wavelength mapping with different Bragg and phase heating temperatures. The solid black lines mark the mode hop sections.

perturbation. The root cause of the perturbation is the optical feedback which changes the shape of the reflectivity spectra of the Bragg grating, Fig. 2. Thereby, the mirror loss of the modes is shifted by the additional sinusoidal reflectivity on top of the Bragg reflectivity. The comparison of the measurement with the calculated mapping in Fig. 4 shows similar sinusoidal dependency of the mode hop zones and a similar wavelength range.

III. Design Rules for Reliable Wavelength Tuning Under Optical Feedback

A. Cavity Ratio

The wavelength mapping of a laser with optical feedback in Fig. 4 has a cavity ratio of the feedback and laser cavity of $L_f/L_{cav} = 0.96$. The mode hop zones are not straight and have a sinusoidal perturbation. It is still possible to tune the laser continuously in its wavelength by adjusting the phase and the Bragg heating power linearly, shown by the black arrow. On the other hand, a laser with cavity ratio of 0.92, shown in Fig. 6, has more strongly shifted mode boundaries and it would be difficult to tune the laser continuously by applying the heating linearly without hitting some mode hop zones along the way. However, tuning the powers non-linearly can be used to tune the laser continuously without hitting any mode hop zones, shown by the dashed arrow. To show which cavity ratio enables better tunability we can use the approximation of the effective reflection coefficient, equation (2). This equation describes the shape of the Bragg grating and the sinusoidal perturbation on top of the reflectivity considering the exponential function. By inserting the condition for the round-trip phase $\lambda_k = 2L_{cav}/(k+\Phi_{eff}/2\pi)$ with $\Phi_{eff} \approx 0$ due to $r_3 \approx 0$ and using Euler's formula it follows

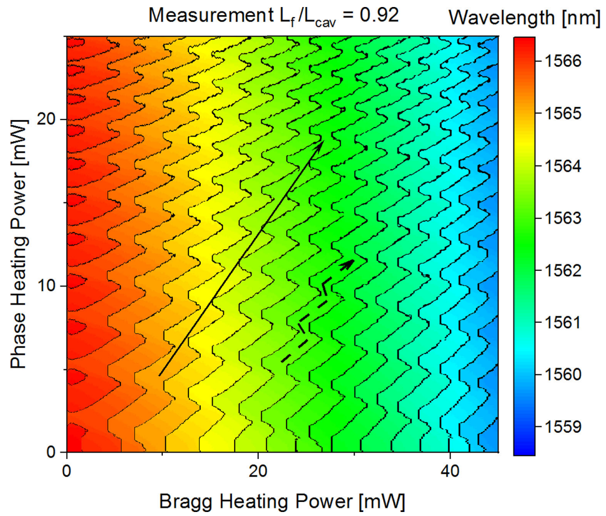

Fig. 6. Measured wavelength mapping with different Bragg and phase heating powers. The solid black lines mark the mode hop sections. The ratio of the laser cavity $L_{cav} = 3535\ \mu m$ and the feedback cavity $L_f = 3250\ \mu m$ is ratio = 0.92. The black arrow shows a continuous tuning line which strikes through the mode hop zones. The dashed arrow shows a possible tuning line without linear adjustment of the tuning parameters.

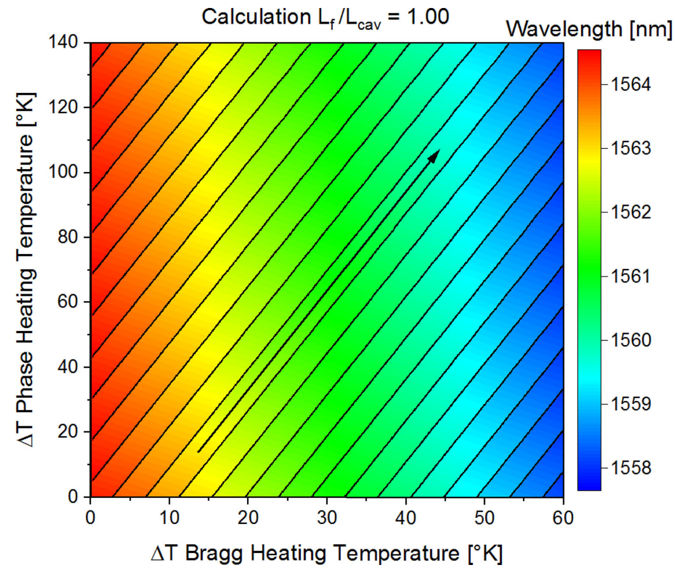

Fig. 8. Calculated wavelength mapping with different Bragg and phase heating temperatures with $L_{cav} = L_f$. The solid black lines mark the mode hop sections. The arrow shows a continuous tuning trajectory.

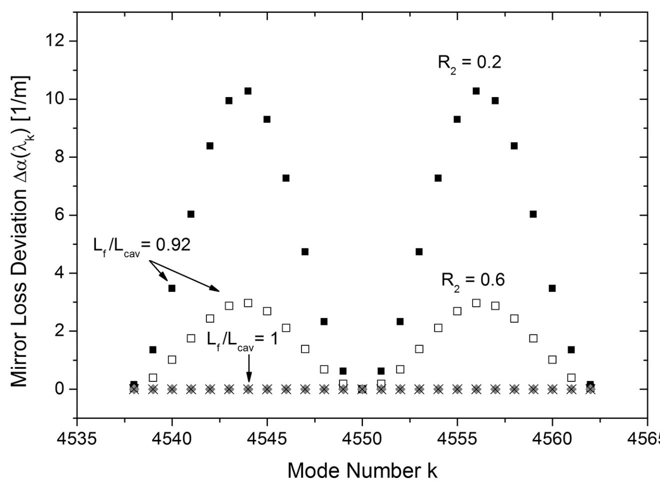

Fig. 7. Calculated mirror loss deviation $\Delta\alpha_m$ as the difference of the mode loss with and without optical feedback. The laser cavity modes k remains constant for an even ratio between the feedback cavity length for different reflectivities $R_2 = 0.2$ or 0.6 at $R_3 = -40$ dB. For a non-integer ratio $L_f/L_{cav} = 0.92$ the modes show a sinusoidal variation of the mirror loss. The deviation increases with decreasing reflectivity of the Bragg grating.

for the effective reflection coefficient

$$r_{eff}(k) \approx r_B + t_B^2 r_3 \times \left(\cos\left[-4\pi \frac{L_f}{L_{cav}} k\right] + i \cdot \sin\left[-4\pi \frac{L_f}{L_{cav}} k\right]\right). \quad (4)$$

Considering the case $L_f \neq N \cdot L_{cav}$ with N as an integer we see different shares of the sinus and cosines term for every mode k. Fig. 7 shows the calculated mirror losses deviation for a laser with $L_f/L_{cav} = 0.92$. The mode loss deviation is the difference of the mode loss without optical feedback compared to its mode loss under optical feedback. Each mode suffers different mirror losses and the perturbation of the losses are sinusoidal. This results into a preference of certain modes that have lower losses. The mode hop zones will be shifted and will have a sinusoidal perturbation.

On the other hand, using a design with $L_f = N \cdot L_{cav}$ would reduce the impact of the optical feedback on the tuning characteristic. In this case, the modes of the feedback section fit exactly to the modes of the laser cavity and no additional loss takes place. The sine term in equation (4) would remain zero and the cosine term always equal to one. All modes would suffer the same amount of mirror loss and no preference would emerge. Fig. 7 shows the calculated mirror losses of certain laser modes. For $L_f \neq L_{cav}$ all modes have different losses whereby the loss characteristic is sinusoidal. For $L_f = L_{cav}$, the variation of the losses is zero. Assuming all modes suffer the same interference loss at all times the lasing mode is determined by the mirror loss of the Bragg grating only and is not dependent on the influence of the optical feedback, ensuring continuous wavelength tuning. Taking this into account we can state a design rule for a laser under optical feedback in order to reduce impact on the mode hop zones to a minimum,

$$L_f = N \cdot L_{cav}\ ; N := 1,\ 2,\ 3, \ldots \quad (5)$$

We calculated the mapping of a laser with −45 dB optical feedback using this design rule, Fig. 8. The mode hop zones are straight and continuous tuning of a laser under optical feedback is possible by adjusting the heating powers linearly.

B. Absolute Reflectivity and FWHM of the Bragg Grating

The length of the feedback section and the strength of the feedback are common parameters to evaluate if the laser is stable. Based on the described model we can additionally consider

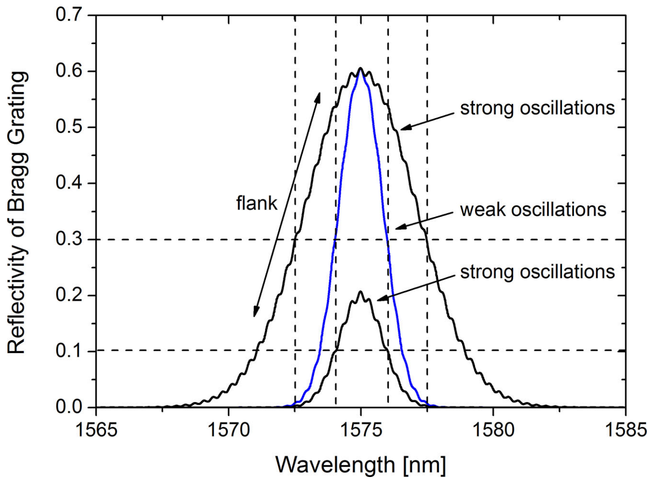

Fig. 9. Calculated effective reflectivity shape of the Bragg grating approximated by a normal distribution with a FWHM of 2 nm and 5 nm and different maximum reflectivities of 0.2 and 0.6 at −40 dB feedback. The length of the feedback section is 3550 μm. The grating with lower reflectivity shows stronger oscillations from the optical feedback compared to the grating with higher reflectivity. The grating with higher FWHM shows stronger oscillations from the optical feedback compared to the grating with lower FWHM.

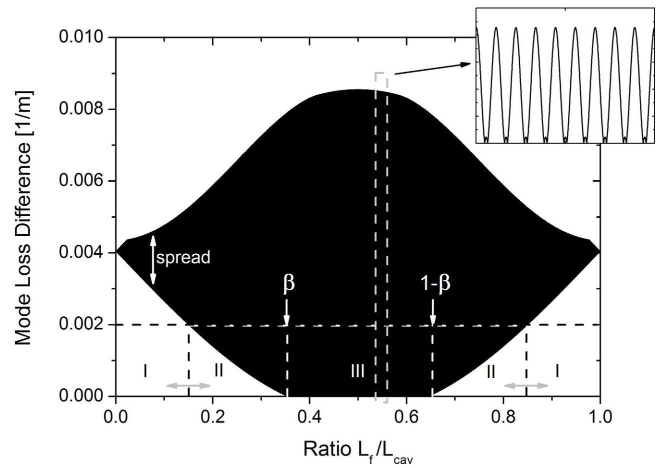

Fig. 10. Mode loss difference of a laser with cavity length of 3550 μm, a grating with 4 nm FWHM, R = 0.2, and a feedback of −50 dB. The gray arrows show that there is a smooth transition zone between tuning regimes I and II and a strict separation is not possible.

further parameters like the FWHM of the Bragg grating and the maximum of the reflectivity. The grating determines which mode suffers the fewest losses and selects the lasing mode. Therefore, the parameters of the grating must be considered in the design of a laser with integrated optical feedback.

The maximum reflectivity of the Bragg grating $r_2{}^2 = R_2$ has an influence on the maximum value of the mirror loss deviation because it defines the strength of the output power and with it the total number of the back reflected photons, which eventually influences the amplitude of the losses. The smaller the reflectivity the higher the deviation of the mode's losses, Fig. 7. Fig. 9 shows calculated Bragg gratings approximated by a normal distribution, with a FWHM = 2 nm and optical feedback of −40 dB. The length of the feedback section is equal to the laser cavity, equation (5). The maximal reflectivities are 0.2 and 0.6. The grating with higher reflectivity shows weaker oscillations compared to the one with lower reflectivity. For the following discussion, we define a flank as the section with a strong slope to the peak of the reflectivity, Fig. 9. The grating with higher reflectivity has steeper flanks and the oscillations from the feedback do not impact the shape of the grating. The grating with lower reflectivity and lower slope of the flanks shows stronger oscillations.

Additionally, the FWHM impacts the slope of the flanks as well. Fig. 9 shows additionally the calculated grating approximated by a normal distribution with a FWHM of 5 nm. The strength of the optical feedback is −40 dB and the length of the feedback section is 3550 μm. The grating with lower FWHM has weak oscillations compared to the one with higher FWHM. As seen for the grating with higher reflectivity the bigger slope of the flanks leads to a reduced impact of the optical feedback. Furthermore, the plateau of the maxima is broader for a higher FWHM. Therefore, multiple oscillations on the maxima peak can be seen. To reduce the impact of the optical feedback on the Bragg grating, a high reflectivity of the grating and a low FWHM are advantageous.

C. Mode Loss Difference

It has been shown in the previous sections that a cavity ratio of $L_f/L_{cav} = 1$, a high reflectivity, and a low FWHM of the Bragg grating improves the laser stability. However, considering only one of these parameters does not grant stable laser operation. In order to give a broader overview of the set of values for the parameters, we define the mode loss difference (MLD) as the difference in losses between the mode with the minimal loss k and the mode with the second minimal loss k^*

$$MLD = \alpha_m(\lambda_k) - \alpha_m(\lambda_{k^*}). \quad (6)$$

The mode k^* can but does not have to be a mode next to the lasing mode k. For example, given a broad grating with low reflectivity, high FWHM, and strong feedback, it may happen that $k^* = k + 2$. Fig. 10 shows the MLD for a set of values, FWHM = 4 nm, $R_2 = 0.2$, $R_3 = -50$ dB, as a function of the cavity ratio. As stated in the previous section the ratios of 0 and 1 are stable, equation (5). For this cavity ratio the MLD is far above zero and the MLD spreads minimally. The MLD spread indicates the variation of the MLD with small changes of the cavity ratio and can be used as an indicator for the laser stability. For example, a certain temperature change of the laser module results in a change of the optical length of the laser and the feedback cavity. This changes the cavity ratio and thereby also the MLD. If the parameter set causes the MLD spread to be small such that the MLD remains stable, the laser would remain stable because the lasing mode still suffers the lowest losses. On the other hand, if the MLD spread is large such that the MLD could even drop to zero, minimal changes in the cavity ratio would result in chaotic behavior of the laser. A MLD = 0 means that two modes have equal losses at the same time and single mode operation cannot be granted. At this point laser

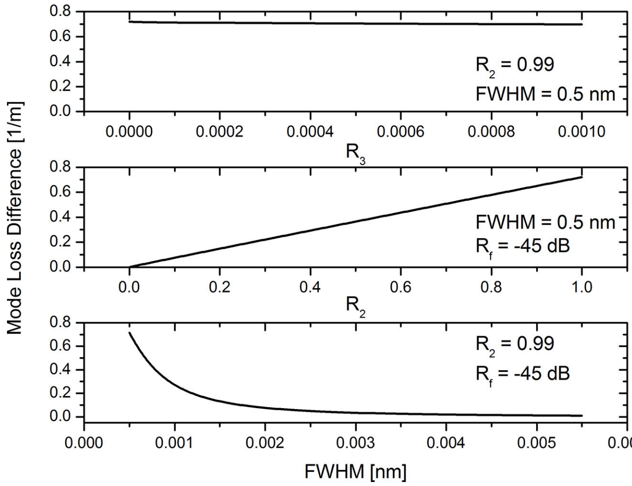

Fig. 11. Mode loss difference at a cavity ratio of $L_f/L_{cav} = 0$ for different sets of the feedback reflectivity R_3, maximum reflectivity of the grating R_2, and the FWHM of the grating.

cavity tuning should be considered as well. Tuning the laser is achieved by a change of the laser cavity length, resulting in a change of the cavity ratio. A huge MLD-spread would cause a big change of the MLD during the tuning. The cavity ratios can be split into three regimes resulting in different behavior of the MLD, see Fig. 10.

The parameters R_3, R_2 and FWHM impact the MLD to different degrees. Fig. 11 shows the MLD for a cavity ratio of $L_f/L_{cav} = 0$ and different sets of parameters. For different feedback reflectivities at $R_2 = 0.99$ and FWHM $= 0.5$ nm the change of the MLD is small compared to the R_2 and FWHM sweep. Due to the small variations of the feedback strength the MLD also varies only slightly. However, increasing the feedback strength reintroduces more photons back into the laser cavity and increases the losses and decreases the MDL.

For a FWHM of 0.5 nm and a feedback strength of -45 dB the MLD reaches values between 0 and 0.7 when varying R_2. With a low R_2 more photons will exit the laser cavity, the output power gets increased and more photons get reflected back into the laser cavity which results into a higher mirror loss deviation, Fig. 7. However, we do have to take into account that the MLD strongly depends on the shape of the grating. With a lower reflectivity R_2 the flank of the grating becomes flatter and more modes will suffer a higher reflectivity. Therefore, we have a high mirror loss deviation and a low MLD for low reflectivity R_2 and a low mirror loss deviation and a high MLD for a high reflectivity R_2.

The MLD does not vary a lot for big FWHM between 3 and 5 nm because for such widths multiple modes do suffer a high reflectivity, Fig. 9. However, decreasing the FWHM to e.g. lower than the free spectral range of the laser will significantly increase the MLD because only one mode is on the top of the grating's spectra and suffers the highest reflectivity.

D. Tuning Regime Parameter β

In order to divide the cavity ratios into tuning regimes of the same linear/non-linear/no tunability behavior, we define the tuning regime parameter β as the first cavity ratio with MLD equal to zero.

$$\beta = Cavity\ Ratio\,(MLD = 0) \tag{7}$$

At this cavity ratio the mode hop zones will periodically touch each other and continuous tuning is not possible anymore. Between β and 1- β the MLD will oscillate and reach zero periodically. This impacts the laser tuning because it is established inter alia by changing the laser cavity length L_{cav}. This changes the cavity ratio L_f/L_{cav} and with it periodically the MLD. Fig. 10 shows the oscillation of the MLD for different cavity ratios. The tuning parameter β is about 0.35 for a laser with a cavity length of 3550 μm, a grating FWHM of 4 nm, a maximum reflectivity of 0.2, and a feedback power ratio of -50 dB. For a cavity length of 1-β the MLD is again above zero, the mode zones do not contact each other anymore.

E. Tuning Regimes

Based on the tuning regime parameter β we can divide the cavity ratios into three different tuning regimes.

Tuning Regime I: starts from the cavity ratio of zero and ends at tuning regime II. A clear separation of these two regimes is not possible because there is a smooth transition between the linear and non-linear tunability. However, it can be stated that within tuning regime I, it is always possible to tune the laser continuously by adjusting the heating powers linearly. Fig. 10 shows with grey arrows that the end cannot be determined strictly. The lasing mode suffers the lowest loss, respectively the highest reflectivity, compared to the mode with the second lowest loss. The mode hop zones are a little shifted, but linear adjustment of the heating powers is sufficient, Fig. 12(a). Tuning Regime I appears twice, at the cavity ratio of 0 and 1, and for all further cavity ratios equal to the integer N.

Tuning Regime II: lies between tuning regime I and the tuning regime parameter β. The β parameter indicates the cavity ratio where the MLD reaches zero. In this tuning regime continuous tuning is still possible. However, a linear adjustment of the heating powers might no longer be sufficient, Fig. 12(b). This tuning regime is a transition zone between linear tunability and non-tunability.

Tuning Regime III: is located between the parameters β and 1- β. In this tuning regime the MLD reaches zero for any cavity ratio and the MLD spread is maximal. Continuous tuning is not possible and the mode hop zones contact each other periodically, Fig. 12(c). This tuning regime appears once in the center, surrounded by tuning regime II from both sides. For certain design parameters, for example a low FWHM, it might happen that this tuning regime does not appear and the MLD does not reach zero.

F. Laser Cavity Length

In the previous discussion we always assumed a constant length of the laser cavity. Going back to the discussion of the effective reflectivity with an additional sinusoidal perturbation on top of the normal distribution, the length of the laser cavity can have an impact as well when the cavity design rule is applied, equation (5). Upon decreasing the cavity length and

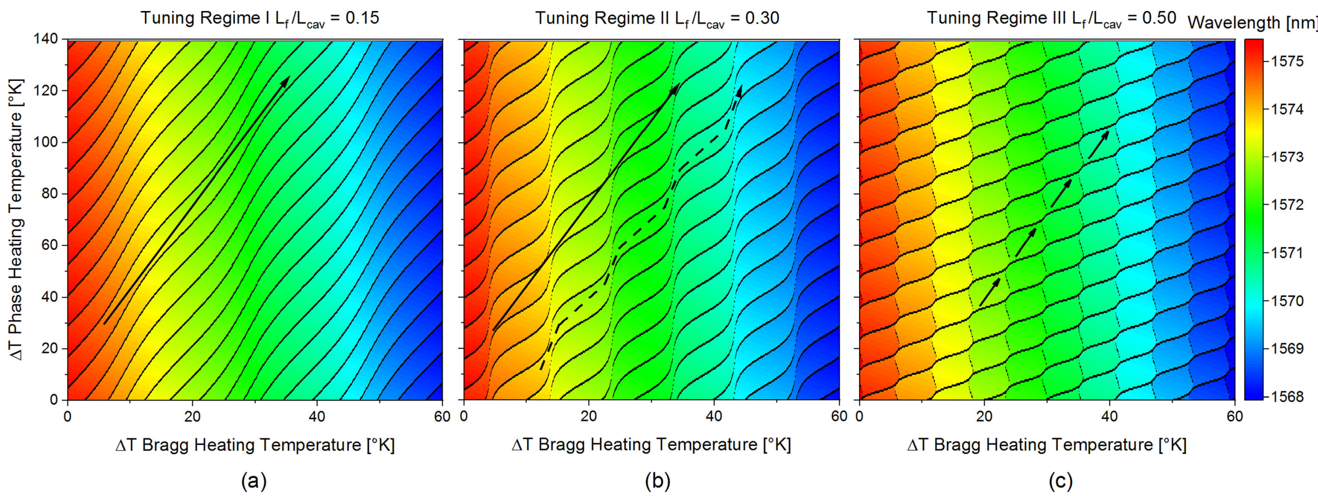

Fig. 12. Calculated wavelength mappings of a laser with cavity length of 3550 μm and (a) regime I. and cavity ratio of 0.15 where continuous tuning is possible by linear adjustment of the heating powers; (b) regime II and cavity ratio of 0.30 where continuous tuning is still possible even if a linear adjustment of the heating powers is no longer sufficient. The dashed arrow shows a possible non-linear tuning trajectory; (c) regime III and cavity ratio of 0.50 where continuous tuning is not possible. The mode hop zones get in touch.

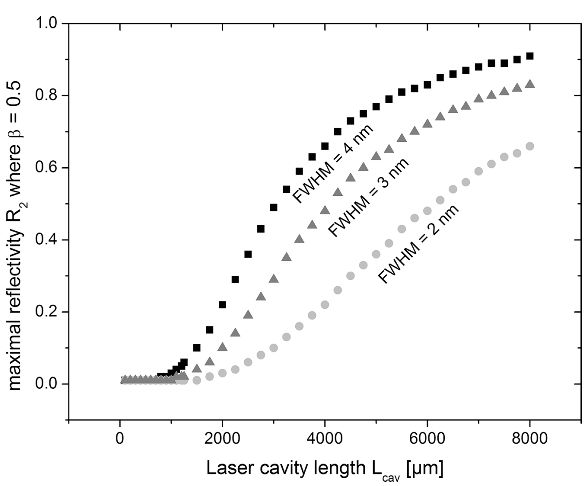

Fig. 13. Reflectivity R_2 from where the β-parameter starts to be 0.5 and the MLD does not get zero anymore for different cavity lengths and $R_3 = -40$ dB.

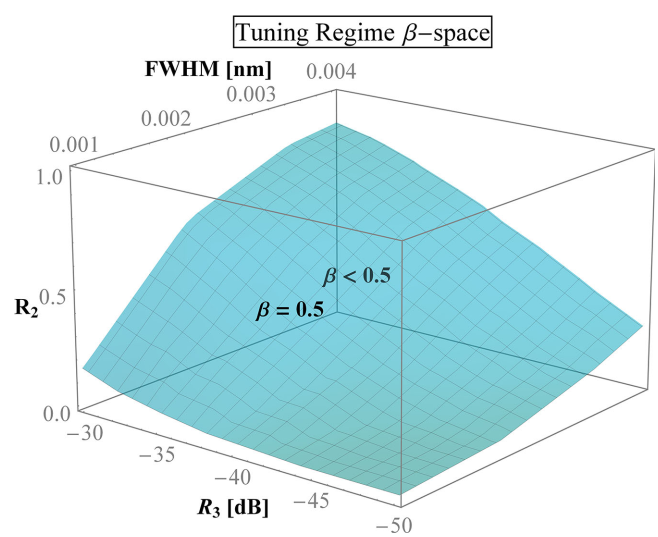

Fig. 14. Calculated tuning parameter β for different values of the FWHM, the maximal reflectivity of the Bragg Grating R_2, and the reflectivity of the optical feedback reflection point R_3. The used laser cavity length is 3550 μm.

with it the feedback section length, the period of the sinusoidal perturbation gets larger. With a larger period, lesser oscillations will take place on top of the grating. Or the other way around, a shorter laser cavity increases the free spectral range. In this case, a broader FWHM can be tolerated because fewer modes suffer the reflectivity on top of the grating. Fig. 13 shows the reflectivity R_2, which would be necessary to have a laser with tuning parameter $\beta = 0.5$. For such a case tuning regime III would not occur and the laser would be feedback resistant for all cavity ratios and continuous tunable without touching any mode hop zones. The larger the laser cavity length, the higher must be the reflectivity to reach $\beta = 0.5$. The lower the FWHM, the lower must be R_2.

G. Tuning Regime β-Space

The discussion of the parameters R_2, R_3, FWHM, cavity ratio, and the laser cavity length show that their correct adjustment is mandatory to design a laser which is reliable tunable in case of reflection points at fixed distances due to unavoidable coupling points. In order to give a more readable picture of the parameters, we calculated the β-parameter for different value sets: $0 \leq R_2 \leq 1$, $0 \leq R_2 \leq 0.001$ (-50 dB $\leq R_3 \leq -30$ dB), and 1 nm $\leq$ FWHM $\leq$ 4 nm. This parameter space is from now on referred to as β-space. The β-space has been calculated for two different cavity lengths, 3550 μm and 2500 μm.

Fig. 14. shows a 3D plot of the tunability parameter β (R_2, R_3, and FWHM). The surface cuts the space into parameter sets with $\beta = 0.5$ which means tuning regime III does not occur such that the laser is tunable for all cavity ratios; and $\beta < 0.5$ which means that the MLD will be zero for some cavity ratios and tuning regime III appears.

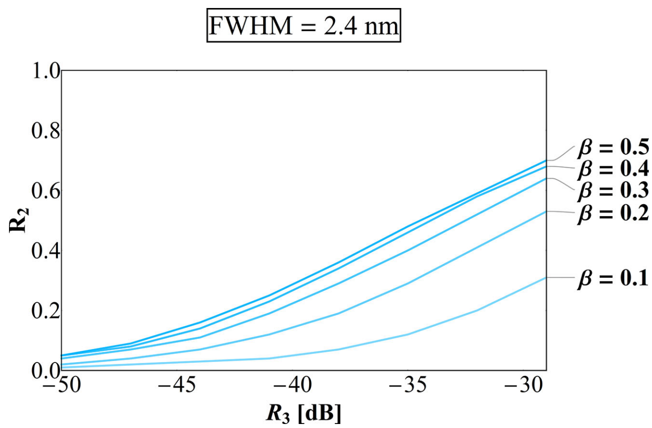

Fig. 15. Calculated tuning parameter β for a FWHM $= 2.4$ nm for different maximal reflectivities of the Bragg Grating R_2, and the reflectivity of the optical feedback reflection point R_3. The used laser cavity length is 3550 μm.

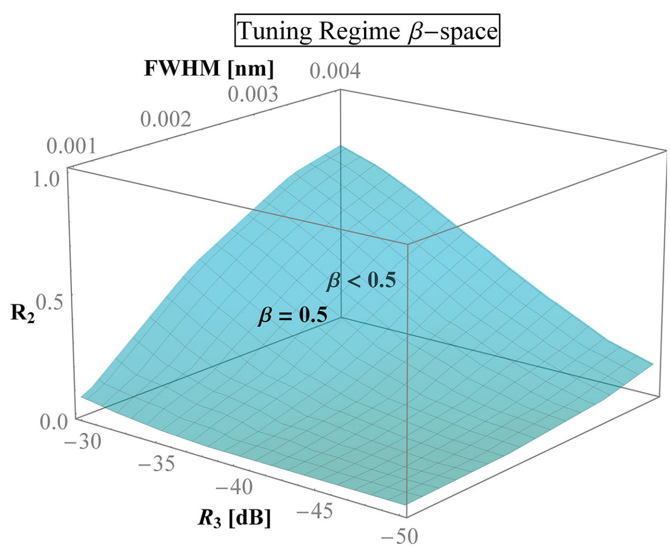

Fig. 16. Calculated tuning parameter β for different values of the FWHM, the maximal reflectivity of the Bragg Grating R_2, and the reflectivity of the optical feedback reflection point R_3. The used laser cavity length is 2500 μm.

The tolerance of the tunability decreases significantly with increasing R_3. Feedback levels of $R_3 = 10^{-4}$ (-40 dB) need a reflectivity of the Bragg grating of 0.5 to ensure tunability over all cavity ratios if the FWHM is 4 nm. On the other hand, a FWHM of 1 nm would make the laser more robust against the feedback strength and the reflectivity R_2 can be chosen in the lower range.

Fig. 15 shows a cross section of the β-space at a FWHM of 2.4 nm. Compared to a FWHM of 4 nm the β-parameter is already 0.5 for a reflectivity $R_2 \approx 0.6$ and a strong feedback of $R_3 = 10^{-3}$. As stated in the previous section, a lower FWHM makes the laser more tolerant to optical feedback.

Fig. 16 shows the same calculation but with a smaller cavity length of 2500 μm compared to Fig. 14 with 3550 μm. The β -space shows that a shorter laser cavity is more tolerant to feedback. It needs a lower reflectivity R_2 and the FWHM can be chosen in a broader range while maintaining continuous tunability. This is related to the lesser oscillations on top of the reflectivity due to the shorter feedback section. Therefore, a broader FWHM can be chosen. Also, the reflectivity of the Bragg grating R_2 can be lowered because the reflectivity oscillations broaden and the lower slope of the grating's flanks are still sufficient such that only one mode experiences the highest reflectivity.

IV. Conclusion

This paper describes a model of a tunable laser with optical feedback from a constant distance reflection which can be handled as an external cavity. It determines the lasing wavelength by finding the mode with the smallest mirror losses. Based on this model it is possible to calculate wavelength mappings which fit well with experiment. We discuss the laser design parameters which are indispensable for wavelength tuning in the presence of optical feedback. Assuming the cavity ratio of the optical length of the feedback and the laser cavity as an integer describes the case with straight mode hop zones and ensures continuous tunability with linear tuning parameter adjustment. Furthermore, a decrease of the FWHM and an increase of the reflectivity of the Bragg grating show higher tolerance of the tunability of the laser under optical feedback. With the introduced mode loss difference parameter, it is possible to easily predict in which tuning regime a certain laser design will operate. In tuning regime I, it is possible to tune the laser continuously by adjusting the heating power linearly; in tuning regime II tunability is possible by non-linear adjustment of the heating powers; in tuning regime III it is not possible to tune the laser continuously. Furthermore, the spread of the MLD is a good indicator of how much the MLD varies with cavity ratio variations. The tuning regime parameter β derived here from the MLD cavity ratio sweep permits to easily predict if a given set of laser design parameters results into a continuous tunable laser.

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Magnus Happach received the Master of Science degree in physics from the Technical University in Berlin in 2015. He worked as a Student Assistant at the Fraunhofer Heinrich Hertz Institute (HHI) for almost three years. He currently works at the Sonova AG, Switzerland.

David de Felipe received the Telecommunications Engineering degree from the Universitat Politècnica de València (UPV), Spain, in 2010. In 2011 he joined the Fraunhofer Heinrich Hertz Institute (HHI) to pursue his PhD in collaboration with the Technische Universität Berlin (TUB), Germany. His current interests are opto-electronic integrated devices based on a hybrid polymer-InP integration platform, and integrated tunable lasers for telecom, Datacom, and spectroscopy.

Victor Nicolai Friedhoff received the Master of Science degree in physics from Humboldt-University in Berlin in 2016. He worked as a Student Assistant at the Fraunhofer HHI for almost 3 years while being a student. He is currently a PhD student in theoretical statistical Biophysics at Humboldt-University.

Gelani Irmscher is a Ph.D. student in the field of distributed fiberoptic sensing with the Federal Institute for Materials Research and Testing BAM. He joined the HHI's Polymer OEIC group within the Photonics Components department as a Student Assistant, completed here his bachelor's and master's thesis, and graduated in Engineering Science from TU Berlin in 2019.

Martin Kresse joined Fraunhofer Heinrich Hertz Institute (HHI) as a Research Associate in 2018 after receiving his Master's degree in physics from TU Berlin. He is a part of HHI's Polymer OEIC group within the Photonics Components Department.

Moritz Kleinert joined Fraunhofer Heinrich Hertz Institute (HHI) in 2013 after receiving his master's degree from TU Berlin and obtained his Ph.D. for his work on the hybrid photonic integration of graphene-based optoelectronic devices in 2018. He is the Project Manager with the Hybrid PICs group and author/co-author of more than 40 papers in international journals and conference contributions.

Crispin Zawadzki received the diploma in electronic engineering from the Technical University of Berlin in 1995 and in the same year he joined Fraunhofer HHI. He is currently Project Leader and has been responsible for the process development and PLC/OEIC-fabrication in several research projects with national and international industrial partners. He holds several patents and is the author/co-author of more than 100 scientific publications and conference papers.

Walter Brinker received the diploma in physics from University Münster, Germany, in 1984. In 1985 he joined Heinrich Hertz Institute für Nachrichtentechnik (HHI) in Berlin. His research interest focus on optical characterization of III-V based photonic devices. He currently works on the hybrid integration of III-V components with polymeric waveguide structures.

Martin Möhrle joined Fraunhofer Heinrich Hertz Institute in 1988 and received the Ph.D. degree from the Technical University of Berlin in 1992. He has more than twenty five years' experience and expertise in InP based lasers, amplifiers and modulators. Currently he is Head of the Laser Development Group within the department Photonic Components. He holds several patents on laser devices and is author/co-author of more than 100 papers.

Norbert Keil joined Fraunhofer HHI in 1987 and has more than 30 years of experience in the development of polymer-based hybrid photonic integrated circuits. Currently, he is Head of the Hybrid PICs group and Deputy Head of the Photonic Components department. He holds several patents and is the author / co-author of more than 200 scientific publications and conference papers.

Werner Hofmann (Member, IEEE) is Professor for nanophotonic devices and CTO of the Center of Nanophotonics at the Technical University of Berlin, Germany. He received the Dipl-Ing degree in 2003 and the Dr.-Ing. degree in 2009 both from the Technical University of Munich, Germany. From 2003 to 2008, he was with the the group of Prof. Amann at the Walter Schottky Institute, where he was engaged in the research on long-wavelength vertical-cavity surface-emitting lasers (VCSELs). Subsequently, he joined Prof. Chang-Hasnain´s Group, University of California at Berkeley, where he worked on the incorporation of high-contrast gratings into VCSEL devices. In 2010, he joined the Technical University of Berlin as Principal Scientist in the group of Prof. Bimberg. Since 2013 Prof. Hofmann is leading his own group focusing on ultra-high-speed nanophotonic devices. Since 2014 he is also with the Xiamen University, P. R. China as Guest Professor. Prof. Hofmann has authored over 100 papers cited over 500 times and has presented over 10 invited talks and tutorials on international conferences. He is a member of the Association of the German Engineers (VDI), the German Association of University Professors (DHV), and the IEEE Photonics Society.

Martin Schell is Professor for optic and optoelectronic integration with Technical University Berlin, and the Director of Fraunhofer HHI. He is a Board Member of the European Photonics Industry Consortium (EPIC), of OptecBB (Competence Network Optical Technologies Berlin/Brandenburg), and member of the Photonics21 Board of Stakeholders. From 2000 to 2005, he served as a product Line Manager, then Head of Production and Procurement at Infineon Fiber Optics. From 1996 to 2000 he was Management Consultant at The Boston Consulting Group. Before that, he spent one year as a Visiting Researcher at The Tokyo University, Japan. He received the Dipl.-Phys. degree from the RWTH Aachen in 1989, and the Dr. rer. nat. degree from the Technical University Berlin in 1993.