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Semester's Thesis

Diode injection stability

Comparison between a Fabry-Perot diode and an anti-reflective coated diode

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Abstract

The stability of diode injection is studied in this thesis. The stability ranges of clean diode injection when varying injection power and slave current are measured for an anti-reflective coated diode (AR) and a non-coated Fabry-Perot diode (FP). The diodes were tested for three different injection powers (0.25 mW, 1 mW, 3 mW). In comparison the AR-diode is found to be much more stable for all tested injection regimes and is suggested for future use in order to improve upon stability. However, the AR-diode cannot produce as much output power as the FP-diode. In addition the power output characteristics and behavior of the diodes are studied.

Contents

1 Introduction **1**

2 Diode injection theory **2**

2.1 AR-diode and FP-diode 2

2.2 Free running diode laser 3

2.3 Diode injection 4

3 Diode test setup **7**

4 Measured injection characteristics **9**

4.1 Free-running diodes 9

4.2 Stability analysis 10

4.2.1 Stability at 3 mW injection power 12

4.2.2 Stability at 1 mW injection power 12

4.2.3 Stability at 0.25 mW injection power 12

4.2.4 Discussion 13

4.3 Power characteristics 13

4.3.1 Power characteristics of the FP-diode 14

4.3.2 Power characteristics of the AR-diode 14

4.3.3 Precise current scan 16

4.3.4 Discussion 17

5 Summary **19**

6 Conclusion **22**

7 Outlook **23**

A Appendix **25**

A.1 The TIQI 729 nm laser setup 25

List of Figures **25**

Bibliography **28**

1. Introduction

One way of implementing a quantum computer is by building an ion-trap [2]. There the trapped ion serves as the qubit. This is achieved by exposing the ion to a magnetic field. As a consequence of the Zeeman-effect the energy levels of the ion are split and the ion can be in many different energy states. To change the state of said ion, which is crucial for manipulating qubits, one can drive a transition by exciting the ion with a laser. The ion will undergo a transition with an energy difference corresponding to the frequency of the laser. To achieve long coherence times precise frequency and line-width control is required.
The trapped ion quantum information group (TIQI) works with trapped calcium ions which have a qubit transition wavelength of 729 nm. Their current setup see (Appendix A) relies on the injection of two Fabry-Perot diodes (FP). The injection of the two diodes is achieved using 15 μW and 3 mW injection power respectively. Previous thesis ([4][5]) have found that the lower power injection is only possible using the FP-diode but not feasible using an Anti-Reflection coated diode (AR). Nevertheless, the results suggest that at higher power injection the use of the AR-diode might lead to more stability of the diode injection.
Diode injection is a technique where the light of a master laser is optically coupled (injected) into a slave diode and forcing this slave diode to lase at the frequency of the master laser. This process can be used to amplify the master laser power while keeping it spectrally pure.
The goal of this thesis is threefold. First, a theoretical background on diode lasers and diode injection is provided. Secondly, the FP- and AR-diodes are studied experimentally. The diodes are tested for stability in three injection power regimes when varying current or injection power. An attempt is made in matching theory and experimental observed phenomena. Last, the thesis should provide a guide that helps decide which way to amplify light should be chosen under given circumstances.

2. Diode injection theory

2.1 AR-diode and FP-diode

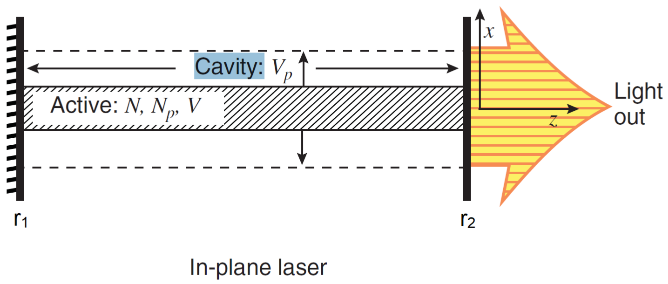

Figure 2.1: Schematic of the diode cavity, with r_1 and r_2 the mirror reflectivities for the electromagnetic field, in between the active region, N_P is the photon density occupying a volume V_P, N the density of electric carriers occupying a volume V, [1]

An ideal FP-diode is a semiconductor laser (in this thesis an InGaAsP laser). Both transverse interfaces of the diode form a cavity (see fig. 2.1). An ideal AR-diode has the same structure as a non-coated diode. The back of the diode forms a mirror as well yet the other interface (mirror r_2) is coated with an anti-reflective coating. The AR-coating reduces the reflectivity of this interface close to zero.
A simple model of such an AR-coating is given as follows: the refractive index of the AR-coating is chosen such that the light reflected at the surface of the diode and the light transmitted at this surface and then reflected upon the AR-coating and transmitted back into the diode has a phase mismatch of $\pi/2$. In the case of normal incidence and only one layer of AR-coating with thickness h= $\lambda/4$, the refractive index of the layer should be $n_{AR} = \sqrt{n_{Diode}}$. [3]
In this idealized picture the injected laser light is reflected at the back of the diode

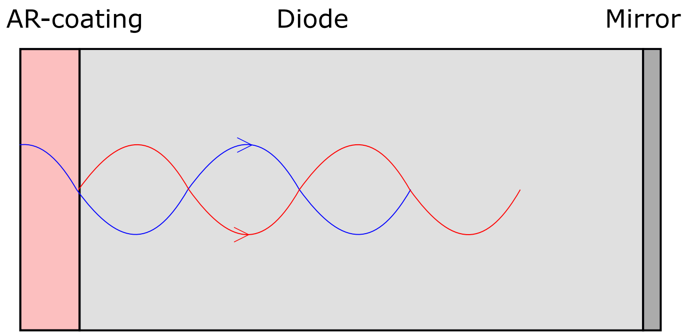

Figure 2.2: Schematic of the diode and the phase shift acquired which cancels the reflection at this surface

and exits the diode on the front side again. Since the laser beam has a beam divergence, only a part of the beam is normal incident and therefore the reflection coefficient is non-zero. In practice multiple layers form the AR-coating to achieve a bigger tolerance in terms of wavelength.[7] Nevertheless the AR-diode can be treated like a normal cavity laser with diminished mirror reflectivity r_2.
Assuming that the material between the mirrors has a loss coefficient α, the total intensity for a diode laser cavity of length L in one roundtrip is given by $I = I_0 R_1 R_2 exp(-\alpha 2L)$ where R_i is the intensity reflectivity at mirror i. It is often useful to distribute the mirror losses continuously over the total roundtrip $I = I_0 exp(-(\alpha - \frac{1}{2L} ln(R_1 R_2))2L)$. If one now uses that the intensity reflectivity R_i equals r_i^2, the total loss of intensity is given by $\alpha + \frac{1}{L} ln\left(\frac{1}{r_1 r_2}\right)$.

2.2 Free running diode laser

A diode laser transforms electric pumping power into optical output power. To describe this process the time evolution in carrier density N and photon density N_P can be written down as a set of coupled differential equations. Additionally it is assumed that the electron density equals the hole density ($N = H$). This yields the pair of rate equations which describe the process.[1]

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \frac{N}{\tau} - v_g g N_P \tag{2.1}$$

The first term is the rate of carriers with charge q pumped into the system by the current I per volume V with efficiency η_i. The second term is the non-radiative loss rate due to various factors. The effective lifetime of this decay is τ. The last term is stimulated emission loss which depends on the photon density N_P the gain g and the group velocity v_g.

$$\frac{dN_P}{dt} = \Gamma v_g g N_P + \Gamma \beta_{sp} R_{sp} - \frac{N_P}{\tau_P} \tag{2.2}$$

The first term is the stimulated emission gain. This term is modified by $\Gamma = \frac{V}{V_{photon}}$ which accounts for the fact that the volume that the photons occupy is not equal to the volume of the diode. The second term is the gain rate due to spontaneous emission. The factor β_{sp} accounts for the part which emit at lasing wavelength. The last term is the loss rate due to the finite photon lifetime τ_P. If only a small fraction of the spontaneous emission is at lasing wavelength $\beta_{sp} \approx 0$, solving for the steady state $\frac{dN_P}{dt} = 0$ yields $\Gamma g_{th} = \frac{1}{v_g \tau_P}$. Using that the definition of Γg_{th} for a cavity laser with mirrors of reflectivity r_1 and r_2 is that the gain cancels the losses; $\Gamma g_{th} = \alpha + \frac{1}{L} ln\left(\frac{1}{r_1 r_2}\right)$. It is clear that bigger values for r_2 give smaller g_{th} and therefore bigger photon lifetimes τ_P which means that threshold photon flux can be reached for smaller I. Deriving an expression for the total output power P for currents $I > I_{th}$ making use of the fact that $N(I) = N(I_{th})$ one finds:

$$P = \underbrace{\eta_i \frac{h\nu}{q} \frac{\alpha}{\alpha + \frac{1}{L} ln\left(\frac{1}{r_1 r_2}\right)}}_{:=AI} (I - I_{th}) \tag{2.3}$$

The term A which is the slope of the line is steeper for high reflectivities r_1 and r_2.

2.3 Diode injection

In many applications one wishes to increase the power of spectral pure laser light. To do so one can use this light to inject a so called slave diode. This leads to more power having the desired spectral properties. An injection is referred to as clean if the only frequency present in the outgoing beam is the same as the injected and hence all the natural frequencies of the injected diode are suppressed [4]. However the injection is not necessarily clean for all slave-currents I_{Dio}, temperatures T_{Dio} and injection powers P_{inj}. Achieving clean injection is only feasible for certain points P$(P_{inj}, T_{Dio}, I_{Dio})$. Yet the magnitude of fluctuations allowed for the parameters are interdependent and differ by type of diode. The more sensitive a diode is the more carefully it has to be maintained. The reason why the points of clean injection are dependent on the mentioned parameters is because they change

the refractive index inside of the laser diode. This changes de facto the length of the light path. The laser diode itself forms a cavity and by changing its length the resonance condition is altered [6]. In the case of the injection frequency being off resonance, the injection power is smaller compared to the natural modes power. As a consequence the natural modes dominate. The better the cavity the bigger the power difference between injection and natural modes. Hence, it is expected that the FP-diode is less stable.
Diode injection can be viewed as a special case of optical feedback where the light of the *feedback* does not share the same wavelength and has an uncorrelated phase. Taking the assumption that the feedback power is small (this is not necessarily true in this thesis because the injection power is almost of the same magnitude as the slave laser power itself) the feedback effects can be accounted for by changing $r_2 \rightarrow r_{eff}$ to an effective reflectivity. The effective reflectivity r_{eff} accounts for two different effects:

1. A phase modification of r_2
2. Interference effects between the feedback and the light reflected at r_2 and is therefore a function of the phase difference between the two

Keeping the injection power constant and scanning the current the resonance of the slave diode is altered and thus the phase difference is changed. This causes oscillations in the observed output power P' described by

$$P' = P_{Dio}(1 - \mu cos(\beta L_P)) \tag{2.4}$$

where βL_P is the phase difference and P_{Dio} is the free running diode output power ([1] eq. 5.184). Due to *mode pulling*, an effect where β is changed unpredictably due to the feedback, the oscillations in output power are asymmetrical. The amplitude of these oscillations is μ, a variable dependent on various diode laser parameters. The analogous effect can be found for normal optical feedback (see fig. 2.3).

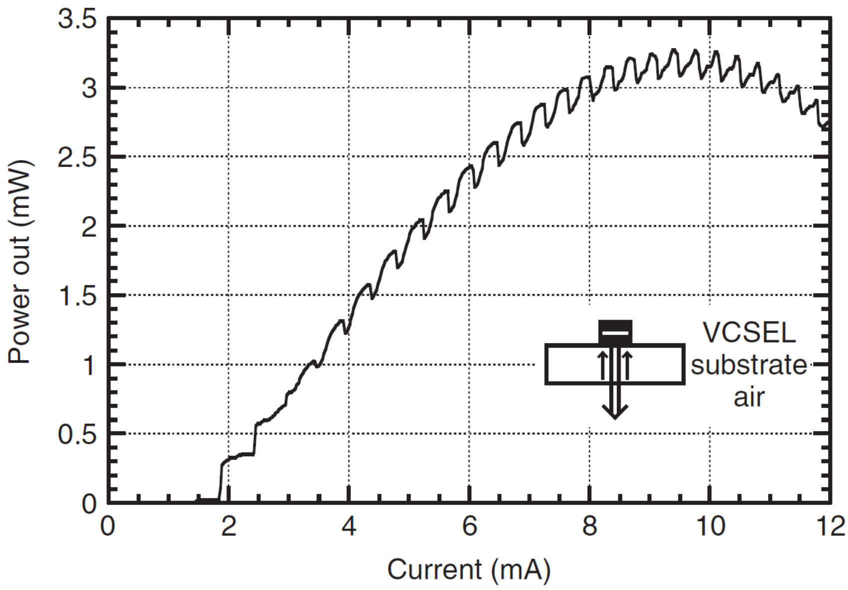

Figure 2.3: Output power of a VCSEL with feedback from the substrate-air interface, the feedback field is phase shifted by $\pi/2$ for the peaks and aligned for the valleys [1]

3. Diode test setup

A schematic of the setup is given in fig. 3.1. It is essentially identical to the one used in Chap. 4.2 [5]. The incoming (injection) beam is split into two parts, one is sent to a photo-diode so that the power can be measured. The injection beam is spectral pure and has a wavelength of 729 nm. For the power of the injection beam a range between 20 μW and 5 mW can be used. The $\lambda/2$ plate was mounted right after the first beamsplitter. Then the beam enters the sideport of the Faraday-isolator. This way the injection beam is not affected by the isolator. There are no mirrors between the Faraday-isolator and the laser diode. After the injection of the diode, the beam travels back now through the main port of the isolator and is split into two beams one going to the experiment and the other to the optical spectrum analyser (OSA). The Faraday-isolator is used to filter any reflections from optical components back into the slave laser cavity. To be more precise the Faraday-isolator rotates the phase of the light by $\pi/4$ per travel, indifferent of the direction of propagation. Therefore the part reflected back is blocked. Two different diodes were tested. A FP-diode by Thorlabs [1], and an AR-diode by Toptica [2]. Both are specified to lase at 730 nm but have a tuning range of 720-740 nm. The diode was held by a mount [3] which keeps the diode thermalized via the temperature control element. The beam was collimated by a lens [4] built into the mount.

To make the injection work the position, height and angular orientation of the slave laser was adjusted such that the light could pass through the Faraday-isolator. Then it was fiber-coupled to the OSA. The beams of the master laser and the slave laser can be spatially overlapped by eye between m1 and m2. It was possible to see injection on the OSA, for diode currents below the threshold. From there the mirrors could be beam walked to improve the injection. To improve the injection, the wave-

[1] HL7302MG

[2] LD-0730-0040-AR-2

[3] LDM21 Thorlabs

[4] C110TMD-B Thorlabs

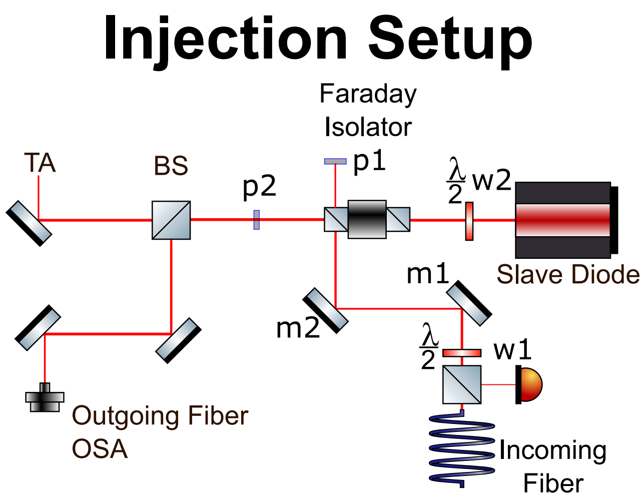

Figure 3.1: Schematic of the optical setup; w1: $\frac{\lambda}{2}$-waveplate after incoming fiber, w2: $\frac{\lambda}{2}$-waveplate between Faraday-isolator and slave diode, p1: temporary measurement point, p2: temporary measurement point, BS: beamsplitter, m1: first mirror after incoming fiber, m2: second mirror after incoming fiber, TA: Tapered amplifier, OSA: optical spectrum analyser

plate w1 was adjusted to maximize the light transmitted by the Faraday-isolator. In practice the plate was adjusted such that minimum power was measured at p1. The waveplate w2 was adjusted such that the maximal light exited the Faraday-isolator at p2. From there the light was split, sending one part to the OSA and the other to the TA [5] which will amplify the light to 0.5 W in the future setup.
The setup was not well sheltered from vibrations and other light sources. Under more favorable conditions (i.e. in a box on a separate table) the performance of the diodes may be more stable.

[5]SYST BOOSTA PRO, TA-0735-0500-5

4. Measured injection characteristics

Several measurements were performed to examine the unique properties of both diodes. The power characteristics of the free-running diodes were measured 4.1. Then a stability analysis was performed in three power regimes 4.2. In 4.3 the output power characteristics of the injected diode were measured for the three injection power regimes. The measurements are presented in comparison since the goal is to provide a guide to select the more suitable diode for specific applications.

4.1 Free-running diodes

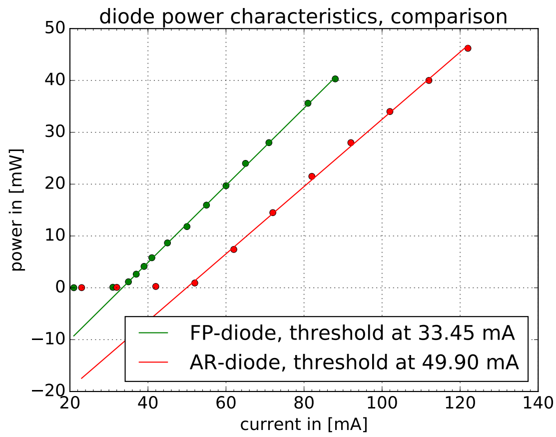

Figure 4.1: Power characteristics for the free-running diodes measured at p2 (see fig. 3.1)

The lasing threshold for the FP-diode is at 33 mA whereas for the AR-diode it is at 50 mA. The FP diode power gain curve has a slope of 0.74 mW/mA and is therefore steeper than the slope of the AR-diode (0.65 mW/mA). To obtain 40 mW of output power one needs to apply less than 90 mA for the FP diode and more than 110 mA for the AR diode respectively. This is expected as both threshold and slope depend on the cavity inside the diodes. As a result for the AR-diode the threshold is higher, the slope less steep, and the output power lower because its cavity has a diminished mirror reflectivity. One important difference is that the FP diode is allowed to lase with 50 mW output power whereas the AR-diode has not specified a maximum output power but mentions a typical output power of 40 mW. The maximal current that should be driven through the FP-diode is 100 mA and for the AR-diode it is not specified.

4.2 Stability analysis

Injection was obtained for both diodes. The stability analysis was performed in three power regimes (0.25 mW, 1 mW, 3 mW) while maintaining a steady diode temperature of 24.2 °C. In each regime the clean injection points for varying current, were found by looking at the spectrum in the OSA. The height of the main frequency peak served as a measure to find the point of cleanest injection. The bounds of the clean injection point were defined as the limit beyond which natural modes could be seen. If there were no natural modes observed between two points of cleanest injection, the point with the lowest main frequency peak served as bound between these two injection points. After determining these current intervals for each injection point, the current was set to each cleanest injection point. From there the injection power was lowered until the natural modes could be seen. Turning the power up again to the starting point, it was noted whether the main peak could reestablish the same height as in the start. From there the power was turned up until natural modes could be observed. In order to protect the diodes the maximal power tested was 5 mW. If there was no upper bound detected, the range is not fully displayed in fig. 4.2-4.4. If there were no natural modes observed for the lowest possible injection power, the points are displayed in red.

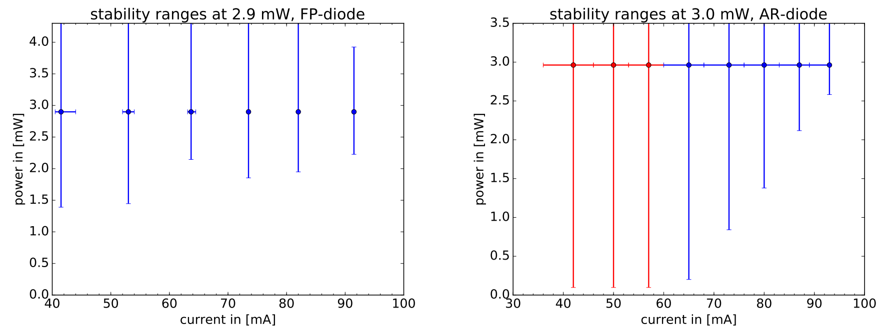

Figure 4.2: Stability analysis in the high power regime, points where no natural modes were observed upon lowering the power are displayed in red

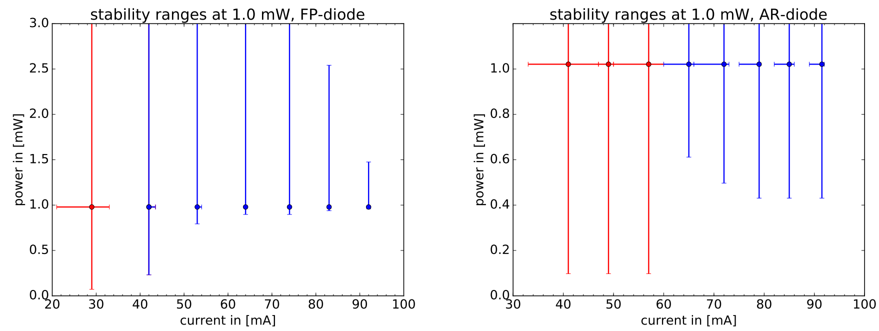

Figure 4.3: Stability analysis in the medium power regime, points where no natural modes were observed upon lowering the power are displayed in red

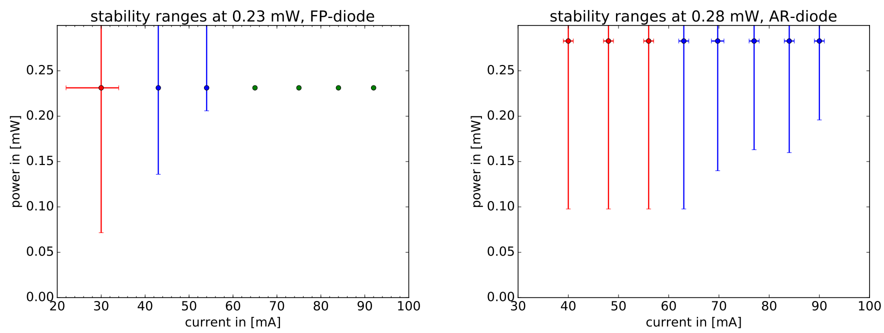

Figure 4.4: Stability analysis in the low power regime, points where no natural modes were observed upon lowering the power are displayed in red

4.2.1 Stability at 3 mW injection power

The measurements are displayed in fig. 4.2. The stable injection current ranges observed for the diodes vary greatly. For the AR-diode the points of clean injection are lined up without a gap. That means that the injection is clean over the entire current range. The point of cleanest injection is shifted towards the upper current boundary.

For the FP-diode this is substantially different. The range of clean injection for higher current becomes smaller. The lower end of the current ranges is sharp. The lasing mode locks abruptly. The upper end of the current ranges is soft. More and more natural modes start lasing upon increasing of the current. Above 70 mA the range of clean injections is smaller than the precision of the current controller used. In terms of power the diodes are less sensitive. The power can be altered by at least $1 - \frac{2.6\,\mathrm{mW}}{3\,\mathrm{mW}} \approx 15\%$. For high currents both diodes have equal tolerance to varying power. The injection power was increased to 4.7 mW. Only for the FP-diode at 91 mA an upper bound could be found. For all the other points there was no upper bound up to 4.7 mW.

4.2.2 Stability at 1 mW injection power

In this regime the same behavior in terms of current ranges continues compared to the 3 mW injection power. However the current ranges of the injection point are smaller for both diodes. For the AR-diode this causes small gaps between areas of clean injection for high currents. In terms of minimal and maximal injection power, the AR-diode only has a lower bound. This is at 0.4 mW for the 5 highest clean injection points. These lower bounds exhibit additional poorly understood phenomena. It is not that there could be seen natural modes for them, but when turning the power back up the main peak of the injection did not have the same height as before. For the remaining ones there were no lower bounds observed. For the FP-diode only the two highest points had an upper bound. The lower bound could be found for all but the lowest point. It is notable that the tolerance especially for high currents is very small in this regime. For them even the power fluctuations of the injection laser power could trigger natural modes.

4.2.3 Stability at 0.25 mW injection power

The current ranges observed for the AR-diode shrank even more. Leaving not more than ± 1 mA of tolerance for clean injection. As in the last two sections (4.2.1 and

4.2.2) no upper bounds were observed. For the three lowest points also no lower bounds could be found.
For the FP-diode only the three lowest points were actual clean injections. For them no upper bounds in power could be found. The lower bounds are very close to the starting power. The rest of the points, displayed in green, did only have injection but the natural modes could not be fully suppressed.

4.2.4 Discussion

The injections is more susceptible to the expected current variations than expected power variations. This is in good agreement with the theoretical picture. The injected photons (i.e. the injection beam) do not directly affect the charge carrier density and therefore the change in refractive index is small [6] which leads to low sensitivity on power fluctuations of the injection beam. In return, this means that a small current difference can change the power boundaries by a lot.
Generally it is observed that for lower currents the power boundaries are lower. This makes sense since the diode lases less strongly and therefore the power to suppress the natural modes decreases. The AR-diode is much more stable for both parameters in all three regimes. This is explained by the fact that the AR-diode forms a weaker cavity, which decreases the mean roundtrip length. On the other hand the weaker cavity results in less output power compared to the FP-diode. Additionally, the AR-diode displayed a hysteresis effect. When tuning the current the boundaries of clean injection depend on whether the current gets increased or decreased. For the measurements all points were measured while increasing the current. Similarly at 1mW injection power; when the injected power falls below a certain value, the starting peak height of the main frequency i.e. output power cannot be obtained when increasing the injected power back to starting value.
This phenomena might be explained as follows: It seems that when some intrinsic modes begin to lase, then the injected power may not be enough to suppress them again. This phenomena was not observed for 3 mW injection power.

4.3 Power characteristics

In this section the power output of the diodes at cleanest injection are displayed. This was done in similar manner as in section 4.2 for the same three regimes of injection power.

4.3.1 Power characteristics of the FP-diode

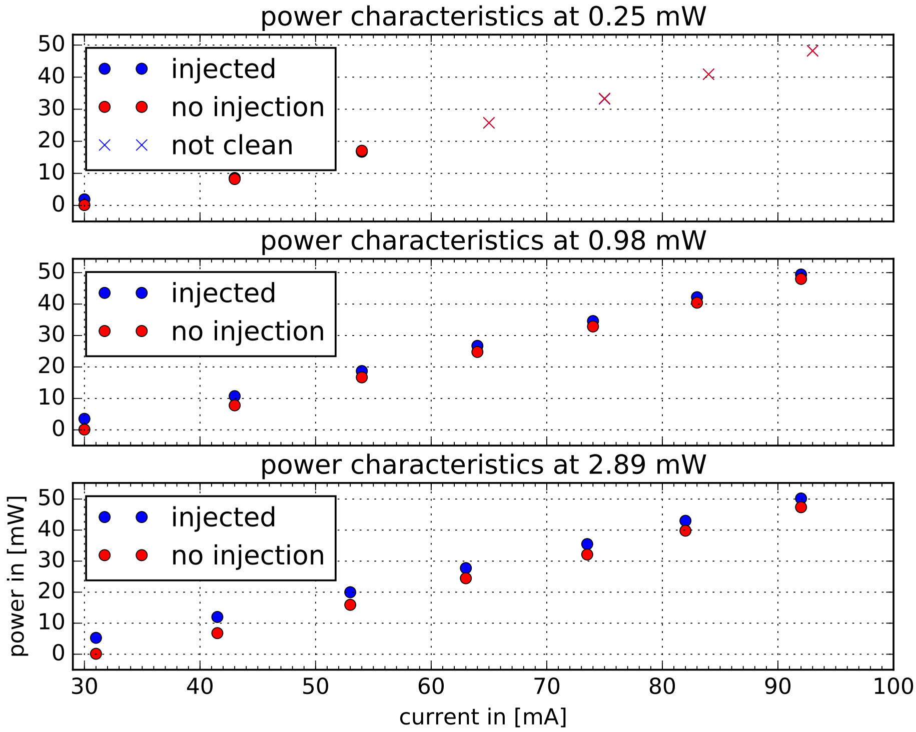

Figure 4.5: Power characteristics for the FP-diode

It is remarkable that for all three regimes the output power at cleanest injection compared to no injection barely differs. However it seems that this difference grows with higher injection power. For higher currents at constant injection power the difference shrinks.
The points of cleanest injection may slightly shift towards lower currents upon increasing the injection power. However this shift is never bigger than 1 mA.

4.3.2 Power characteristics of the AR-diode

For this diode-type the output power differs between injection and not injected. Yet the difference increases with higher injected power and for higher current it seems not to decrease. The points of cleanest injection may slightly shift towards higher currents upon increasing the injection power. However this shift is never bigger than 2 mA.

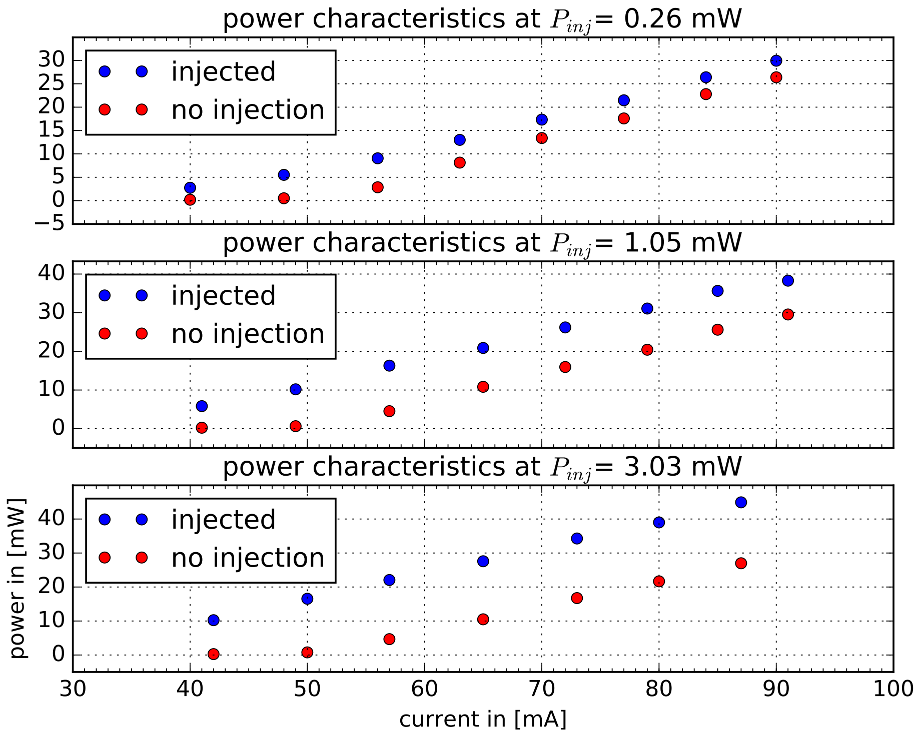

Figure 4.6: Power characteristics for the AR-diode

4.3.3 Precise current scan

Given the hysteresis behavior of the AR-diode mentioned in 4.2.4, the diode's output power was measured as a function of I while keeping the injection power constant at 1 mW. This yield the following saw-tooth pattern (fig. 4.7). The red and blue points in the lower diagram are the consistency check with the data in fig. 4.6. This shows that behavior within the range of clean injection is very asymmetric.

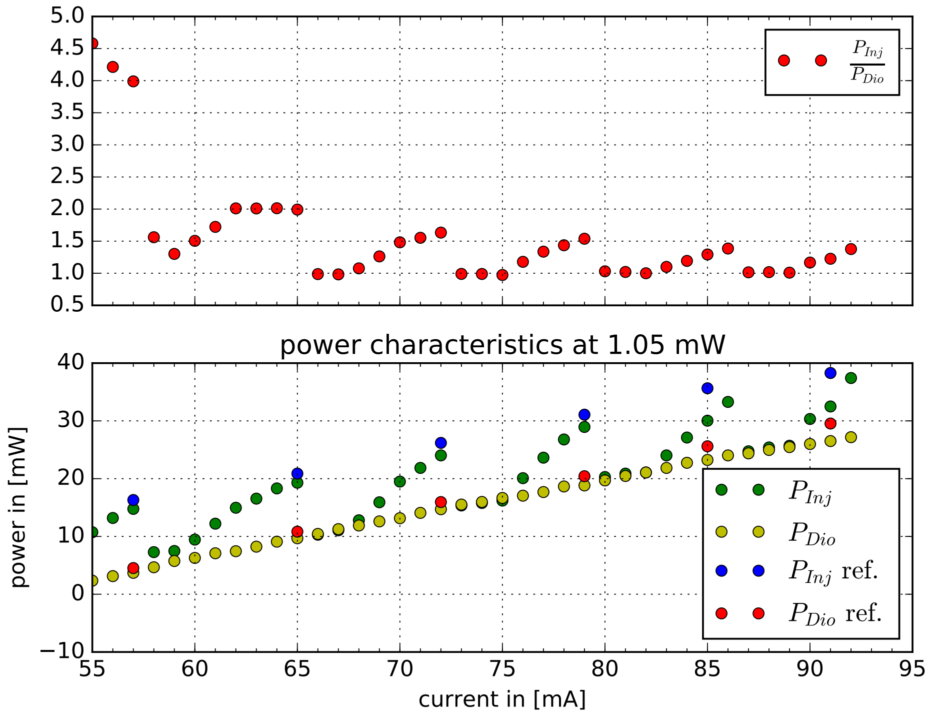

Figure 4.7: Current scan for the AR-diode at 1 mW injection power, relative gain (upper), absolute value (lower), P_{Inj} is the output power of the injected diode, P_{Dio} is the output power of the free running diode

The point of maximal power output (i.e. cleanest injection point), relative as well as absolute, is very close to the upper bound. This is in good agreement with the points of cleanest injection found in the stability analysis.
In order to understand whether this is a behavior that all diodes display, the same scan was done for the FP-diode. Since this diode has very narrow injection ranges the scan was performed with 3 mW injection power to achieve the best resolution possible. Again with the consistency check from fig. 4.5. This yield the following

wave-pattern (fig. 4.8).

Here the injection points are still very narrow and therefore it is not possible to

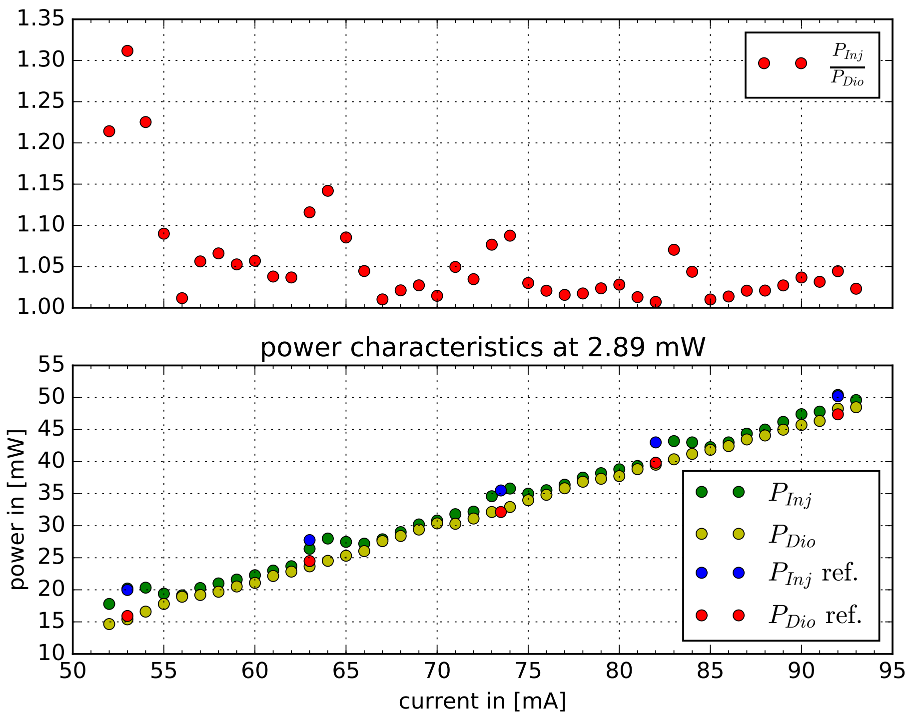

Figure 4.8: Current scan for the FP-diode at 3 mW injection power, relative gain (upper), absolute value (lower), P_{Inj} is the output power of the injected diode, P_{Dio} is the output power of the free running diode

analyze the behavior in detail. Yet the diode's amplification seems not to be saw-tooth shaped like the AR-diode is. It could even be that the two lowest point hint at a reversed saw-tooth pattern. What can be seen is that while already lasing with natural modes the main peak is still slightly amplified.

4.3.4 Discussion

More incident power yields bigger amplification of the injection frequency when looking at a clean injection point. This is valid for both diodes but the effect is stronger for the AR-diode. The points of cleanest injection seem to drift slightly upon increasing power yet the direction of drift differs by type of diode. However as seen in sec. 4.2, one does not leave the range of clean injection upon increasing the injection power. The current scan showed that the relative amplification is a lot smaller for the FP-diode.

This can be linked to the theoretical description developed in sec. 2.3 where the oscillation in power is proportional to μ. The experimental data shows that the AR-diode with its diminished r_2 yields a bigger amplitude μ.

5. Summary

As seen in section A.1, one important question is how to amplify light efficiently while preserving its spectral properties. The optimal solution to this problem is a method which fulfills all the experimental requirements and is the most stable concerning the operational parameters.

This can be done by injecting a diode or by seeding a Tapered amplifier (TA). Their field of application is separated. The TA is used if more than the minimum seeding power required is available. Below this level diode injection is the only possibility to amplify the light. One can choose either a FP-diode or an AR-diode. In this thesis two laser diodes are tested for stability when altering the slave current or the injected laser power while keeping the other parameters fixed. To understand their range of application, the power characteristics with different injection powers are measured.

Concluding from the constraining parameters on the diodes' specifications sheet, the previous works and the results presented here, the area of application for the three types of amplification divides as follows, see fig. 5.1. For very low injection powers (below approx. 100 μW) the AR-diode has no clean injection points for high currents [5]. It is only possible to use the FP-diode running at high temperature (ca. 35 °C). The dotted lines b) and e) are not confirmed and are just an interpolation of the measured points at (0.25, 1, 3) mW. However it is likely that the diodes will follow such a behavior. In order to guarantee high stability for the AR-diode, one must consider the effect of mode pulling (discussed in sec. 2.3, measured in sec 4.3.3) when choosing the point of operation. It is recommended to choose the diode current 1 mA below a point of cleanest injection in order to prevent *running of the edge*. An expected loss in output power is already included in b). For the FP-diode between 0.25 mW and 1 mW the prediction is to cautious because upon increasing the injection power the additional injection points which were not clean at 0.25 mW will become clean one after the other. Generally speaking the FP-diode generates more output power than the AR-diode at the expense of stability. One exception is the range of injection powers between 0.25 mW and ca. 0.7 mW. The maxima c) and d) given on the spec. sheets should be respected otherwise the diodes are at risk.

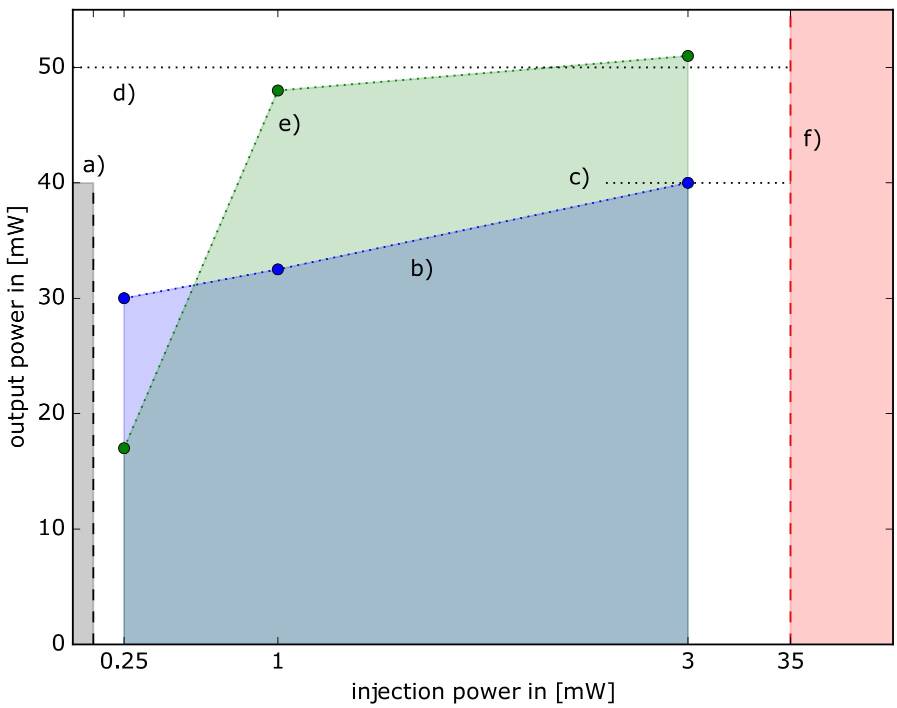

Figure 5.1: Visualization of the field of application; a) below the 0.1 mW injection power only the FP-diode at high temp. ca. 35 °C is possible, b) maximum output for the AR-diode while having a high stability (1 mA safety from the edge) and clean injection at $T = 24$ °C, c) maximal allowed power output of the AR-diode, d) maximal allowed power output of the FP-diode, e) maximum output for the FP-diode while having clean injection at T= 24 °C, f) 35 mW is the usual power to inject a TA

6. Conclusion

In this semester project the injection locking of a FP- and an AR-diode were aligned, tested and compared. It was confirmed that the stability of the AR-diode with respect to control current and injection power fluctuations is higher. Further, the output powers that the two diodes could generate while keeping a clean injection were analyzed. From the found stabilities and available output powers a selection guide for when to use which diode was given. Additionally, the important effects on *mode pulling* that should be kept in mind when selecting the operation points are measured and discussed. A recommendation on how this effect should be addressed to keep high stability is given.

When knowing the available injection power and the required output power one can check with 4.3.2 and the specs. mentioned whether the AR-coated diode can fulfill the conditions. These ranges of application are visualized and discussed in detail in chapter 5.

In the current 729 nm setup the constraints are: 5 mW input power available and an output power which needs to be enough to seed a TA (ca. 35 mW). To improve the existing setup, an injection of the AR-diode could be used. The diode should be injected with at least 3 mW. The current should be chosen such that one is sitting at either the highest (88 mA) or the second highest clean injection point (80 mA). This may vary for the individual diode. Yet due to the saw-tooth like behavior, these points are very close to the upper bound of clean injection. To prevent running of this edge the current should be lowered a bit (approx. 1 mA). This will lead to a slight decrease in output power but improves the stability of the diode while preserving the clean injection.

7. Outlook

The AR-coated diode lacks intensive testing in the experiment. The FP-diode has a long term stability of about one day in badly sheltered environment. It is expected that the AR-diode will remain stable for longer, but this has not been tested yet.
Initially it was also planed to test the stability of the FP-diode at high temperatures ($T = 40°\text{C}$) since better performance at higher temperatures is observed [5]. The hypothesis that the diode behaves more stable for these temperatures seems likely. Both diodes are made of the same material, analogous thinking could as well be applied to the AR-diode. However the used mount is not suitable in keeping such high temperatures and the hypothesis could not be put to test in this thesis.
The photon lifetime inside the AR-diode cavity is smaller than in the FP-diode cavity which leads to a smaller circulating electromagnetic field. Therefore it should be possible to inject the diode with substantially more injection power. The measurements in sec. 4.3.2 showed, that this will increase the total output power. When treating the diode like an optical cavity the following estimation for the AR-diode can be made:

$$P_{circ} = \frac{P_{Out}}{T_2} = \frac{40mW}{T_2} = \frac{40mW}{1 - R_2} \geqslant 40mW. \tag{7.1}$$

Where 40 mW is the typical output power mentioned on the spec. sheet, T_2 the intensity transmission coefficient and R_2 the intensity reflection at mirror 2. Equation 7.1 is always valid because $1 \geqslant T_2 \geqslant 0$. Using additionally that the total energy is conserved, it is possible to find a upper bound for $P_{inj}(U_{Dio}, I_{Dio})$ for all currents.

$$P_{tot} = P_{inj} + P_{Dio} \leqslant P_{inj} + \eta_i U_{Dio} I_{Dio} \tag{7.2}$$

$$\Leftrightarrow P_{inj} \leqslant P_{tot} - \eta_i U_{Dio} I_{Dio} = 40mW - \eta_i U_{Dio} I_{Dio} \tag{7.3}$$

The efficiency η_i must be measured. Out of fear destroying the diode the injection power was never higher than 5 mW. The current 729 nm setup has approx. 5 mW at disposal, it should be possible to inject the AR-diode with more than 3 mW. With this configuration the diode should easily be able to produce 40 mW output power with comparatively low slave currents which will again improve stability.

A. Appendix

A.1 The TIQI 729 nm laser setup

The current setup consists of a 729 nm laser Toptica Model, frequency stabilized through locking it to a high finess cavity via the Pound-Drever-Hall scheme. But instead of the conventional application, the light transmitted through the cavity is used. In this particular case the cavity filters two by ± 1.2 MHz detuned servo Bumps from the laser spectrum which stem from the PDH-lock and would drive unwanted transitions. However the cavity transmission power is not more than 10-20 μW. From there an injected Fabry-Perot diode (FP) amplifies the laser light to ca. 30 mW. After the transfer via fiber and the fiber-noise-cancellation which jointly causes a loss of about 1/3, the light is then again injected to a diode of the same type. To seed a Tapered amplifier, this extra step is required since 20 mW injection power is not enough. The Tapered Amplifier then provides ca. 0.5 W in power.[4][5]

List of Figures

2.1 Schematic of the diode cavity, with r_1 and r_2 the mirror reflectivities for the electromagnetic field, in between the active region, N_P is the photon density occupying a volume V_P, N the density of electric carriers occupying a volume V, [1] 2
2.2 Schematic of the diode and the phase shift acquired which cancels the reflection at this surface 3
2.3 Output power of a VCSEL with feedback from the substrate-air interface, the feedback field is phase shifted by $\pi/2$ for the peaks and aligned for the valleys [1] 6

3.1 Schematic of the optical setup; w1: $\frac{\lambda}{2}$-waveplate after incoming fiber, w2: $\frac{\lambda}{2}$-waveplate between Faraday-isolator and slave diode, p1: temporary measurement point, p2: temporary measurement point, BS: beamsplitter, m1: first mirror after incoming fiber, m2: second mirror after incoming fiber, TA: Tapered amplifier, OSA: optical spectrum analyser 8

4.1 Power characteristics for the free-running diodes measured at p2 (see fig. 3.1) 9
4.2 Stability analysis in the high power regime, points where no natural modes were observed upon lowering the power are displayed in red 11
4.3 Stability analysis in the medium power regime, points where no natural modes were observed upon lowering the power are displayed in red 11
4.4 Stability analysis in the low power regime, points where no natural modes were observed upon lowering the power are displayed in red 11
4.5 Power characteristics for the FP-diode 14
4.6 Power characteristics for the AR-diode 15

4.7 Current scan for the AR-diode at 1 mW injection power, relative gain (upper), absolute value (lower), P_{Inj} is the output power of the injected diode, P_{Dio} is the output power of the free running diode 16
4.8 Current scan for the FP-diode at 3 mW injection power, relative gain (upper), absolute value (lower), P_{Inj} is the output power of the injected diode, P_{Dio} is the output power of the free running diode 17

5.1 Visualization of the field of application; a) below the 0.1 mW injection power only the FP-diode at high temp. ca. 35 °C is possible, b) maximum output for the AR-diode while having a high stability (1 mA safety from the edge) and clean injection at $T = 24$ °C, c) maximal allowed power output of the AR-diode, d) maximal allowed power output of the FP-diode, e) maximum output for the FP-diode while having clean injection at T= 24 °C, f) 35 mW is the usual power to inject a TA 21

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