Noise Behaviour of NLI and SESAM Mode-Locked Fiber Oscillators

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Abstract

This report investigates combining two known techniques for passive mode-locking of fiber lasers, in order to determine the noise behaviour and mode-locking threshold in addition to making a stable mode-locked laser as a seeder for future experiments. First nonlinear interferometry (NLI) is used to mode lock a Yb fiber laser. Then a semiconductor Saturable-Absorber Mirror (SESAM) is added to investigate the effect on the mode-locking self-starting threshold and the amplitude noise. Both laser systems are characterised and compared in terms of power, spectrum and amplitude (AM) noise. It is found that the addition of the SESAM to the NLI greatly improves the self-starting ability however also amplifies the Noise.

Contents

1 Introduction

1.1 Background

Lasers, standing for Light Amplification by Stimulated Emission, are devices that generate a beam of coherent electro-magnetic radiation. The theory of stimulated emission was first proposed by Einstein in 1916 [1]. Stimulated emission refers to a process where a photon generates an identical copy of itself (same phase, energy etc.) via interaction with an already excited electron in the gain medium. To form a laser a pump source is needed to provide energy to a gain medium. As the photons are absorbed by the gain medium, stimulated emission happens at the laser wavelength which is given by the energy levels of the gain medium. When the gain medium is placed into an resonant optical cavity the photons at the lasing wavelength are periodically amplified via stimulated emission each time they pass through the gain medium. The process repeats until there is population inversion and the laser reaches a steady-state.
Charles Townes and James Gordon demonstrated the first maser (lasing in the microwave radiation region) in 1954 and Theodore Maiman demonstrated the ruby laser at Hughes Research Labs in 1960[1]. Since then the large development in laser devices have led to numerous applications in scientific research, engineering, telecommunications, medicine, entertainment and other consumer products[1].
Mode-locking of lasers is a technique, that has been widely developed over the last 50 years, in order to create very short pulses by forcing coherence between the phases of different modes. Originally created in order to study fundamental matter and dynamics of chemical bonds with pump-probe experiments, ultra-short laser pulses have been used for research in chemistry and biology for the last 30 years, with Femtochemistry (physical chemistry studying reactions on the femotosecond scale) being largely developed in the 1980s[2]. Since then the applications of mode locked lasers have continued to expand, for example in materials processing and manufacturing, microscopy, biomedical imaging, timing and synchronization, optical communication, remote sensing and many more[3].
The main principle of mode-locking depends on balancing various effects in the laser cavity[3]. There are different techniques to achieve mode-locking. Generally, a mode-locking device is added to the cavity, this could be either an active element or nonlinear passive element such as a saturable absorber, which balances the effects influencing the circulating pulses in order to maintain the pulse parameters after each round trip, resulting in a regular pulse train[4].

1.2 Motivation

This project explores two techniques to achieve mode-locking of a fiber laser: a nonlinear interferometry and a semicondutor saturable-absorber mirror (SESAM). The two laser systems will be built with a flip mirror to easily switch between a nonlinear interferometry (NLI) and a NLI with a SESAM. Mode-locked fiber lasers are favourable due to being simple to implement, more robust and compact as well as cheaper and more stable long term than the more traditional solid-state mode-locked lasers[3]. The main aims of the project are the following:

- Build a CW Yb Fiber Laser
- Mode-lock with NLI
- Add a SESAM to NLI
- Characterise and compare the two mode-locking mechanisms in term of power, spectra and noise

This report will first expand on the theory behind continuous wave fiber lasers, NLI and SESAM mode-locking and the Noise. Then there will be a detailed account of the experimental setups and methods to build and characerise the lasers. Finally there will be a discussion of the measurements and results found and a comparison of the two systems in terms of their spectrum, power curves, AM noise measurements and mode-locking and self starting thresholds.

2 Theory

2.1 Fiber Lasers

As mentioned in the introduction, to form a laser a gain medium is added to a resonant cavity. In this project a Ytterbium-Doped fiber is used as the active gain[5], optically pumped by a narrowband laser diode. Optical fibers have a core, a cladding and a jacket. The core has a different refractive index than the cladding, in order to maintain total internal reflection and thus keep the light rays propagating through the fiber. There are different types of fibers, here a polarisation maintaining (panda) fiber is used. A diagram of the cross section is shown in figure 1. Due to the two extra stress-rods in a PM fiber the relative refractive index vertically and horizontally is different introducing a birefringence with well-defined fast and slow axis. The polarisation is therefore maintained for linear polarized light coupled parallel to one of the two axis, as the strong birefringence compensates random local refractive index distortions in the fiber.
In order to fuse optical fibers together the technique of fiber splicing was used. This required the jackets of the fibers to be striped, the fiber cleaned with alcohol and cleaved at a right angle. The two ends are then fused together with an electric arc. Fiber ends can then be connected to a FC/PC (fiber connection/physical connection) before connected to a collimator. This reduces the back reflections and loss. The collimator is adjusted so that the light is collimated to reduce the divergence of the beam in the far field.
When light is absorbed by the gain fiber there is also green flourescence from two-photon absorption (515nm) seen. When the laser cavity is not aligned correctly, the inversion (population of the laser level) in the optically pumped gain medium is higher which increases the probability for two-photon absorption and thus the magnitude of green

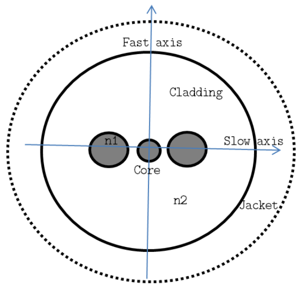


Figure 1: Cross section of a panda fiber, not drawn to scale. The diameter of the core is 5.5μm and the cladding is 125μm. The n1 is greater than n2 to maintain the precondition for total internal reflection. The added rods create a fast and slow axis due to increasing or decreasing the relative refractive index across the axis.

flourescence. The technique of minimizing the TPA flourescence of the gain fiber can be used can be used to check the alignment of the laser.
In figure 2 the emission and abosrbtion spectra of Ytterbium is shown. Ytterbium has a very broad range of emission and absorption with local peaks at 920nm, 975nm and 1030nm. In this project a pump source of 976nm is used which is overlapping with the peak in the Yb absorption cross-section to ensure an efficient energy transfer. A laser output of around 1030nm can be expected from the absorption peak of 1030nm.

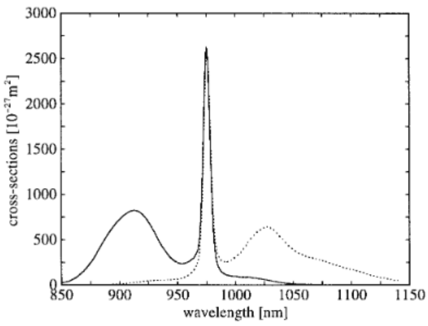


Figure 2: Ytterbium-doped fiber emission (dotted line) and absorption(solid line) spectra. Figure taken from[5].

2.2 Mode-locking

Mode-locking is a resonance phenomena to generate ultra-short pulses of lasers by enforcing coherence between difference modes' phases[6]. In a cw laser there are multiple modes and pulses propagating through the cavity that are not in phase. To mode-lock the laser, the modes are forced to become phase locked. This is done by modulating the loss/gain in the cavity[13]. Therefore a loss modulator is required. Active mode-locking can be achieved e.g., by adding a amplitude modulator. Passive mode-locking can be realised with a real saturable absorber (material-based) or an artificial saturable absorber to balance the nonlinear effects. The general purpose of SAs is to provide an intensity-dependent decrease of cavity loss, an effect known as self-amplitude modulation[14]. This influence of the SA provides a condition for the laser cavity that energetically prefers the build-up of laser pulses from a pure cw-field due to the decreased loss, enabling the build-up and stabilisation of mode-locked steady-states[14].

2.3 SESAM Mode-locking

A SESAM is a Semiconductor-Saturable Absorber mirror and can be used to passively mode-lock lasers. In a simplified picture, the SESAM consists of a mirror and saturable absorber, where the mirror is nonlinear so that the reflectance increases with increasing pulse energy[7]. This results in an intensity-dependent reflectivity of the SESAM which causes the amplitude modulations causing mode-locking. The relationship between fluence/intensity and the reflectivity is shown in figure 3. The fluence can be increased for example by adding a lens to reduce the beam area focused onto the SESAM.

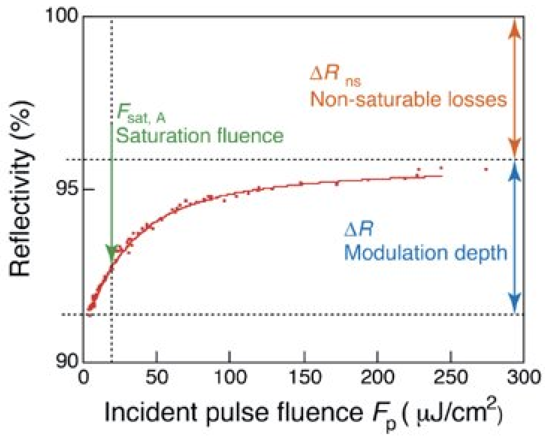


Figure 3: Relationship between fluence/intensity with the reflectivity of a SESAM. This intensity-dependence leads to mode-locking of phases in the laser cavity. Figure taken from reference[13].

2.4 NLI Mode-locking

Nonlinear interfermetry mode-locks due to an added nonlinear phase shift to create an intensity dependent polarization rotation and transmission at the polarizing beam splitter. Figure 4 shows the relationship between the phase difference and transmission. This works to balance nonlinear effects to keep pulse parameters constant after each round trip[8]. As the transmission is dependent on the pulse intensity the amplitude is modulated and the phases become coherent as long as the tunable non-reciprocal phase-bias ensures the right setting of the intensity-dependent system transmission curve.

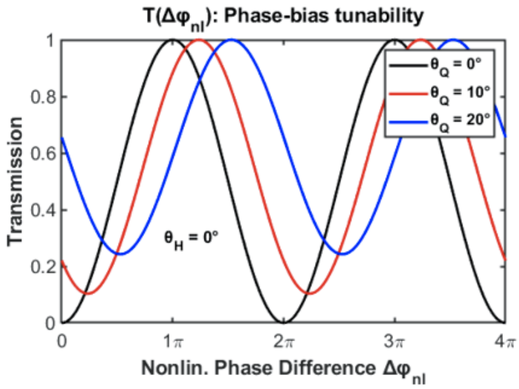


Figure 4: Relationship between pulse intensity and transmission. Adjusting the phase bias will alter the phase difference to find a stable mode-locking point. Figure taken from reference[14].

2.5 AM Noise

Intensity noise is the fluctuations in amplitude or changes in the average power. The relative intensity noise of a laser is defined as

$$RIN = \frac{\delta P(t)^2_T}{P(t)^2_T}, \tag{1}$$

where $\delta P(t)^2_T$ is the mean-square optical power fluctuation and $P(t)^2_T$ is the pulse train average optical power for a certain measurement time T[3]. It is important to measure the noise because low intensity noise is needed for high precision applications for example: optical sampling and photonic analog-to-digital converters, arbitrary optical waveform generation, seeding of optical amplifiers, optical communication systems, and laser-based materials processing[3].

3 Experimental Method

3.1 CW Fiber Laser

A 976nm, 1W diode laser was used as a pump source (refer to figure 5 for power characterization of the diode laser) to pump a Yb gain fiber and get lasing at 1030nm.
A continuous wave laser was made using a linear cavity with two dielectric end-mirrors that are highly reflective for wavelengths between 750 to 1100nm [10]. The setup is

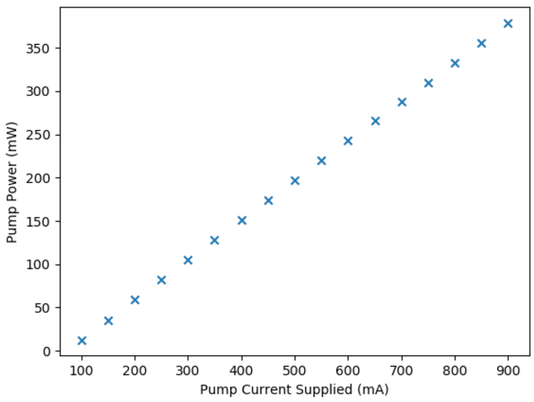


Figure 5: Diode laser's power against the current supplied for the pump.

shown in figure 6 which shows the pump is connected to the fiber to collimators via a WDM (wavelength division multiplex).

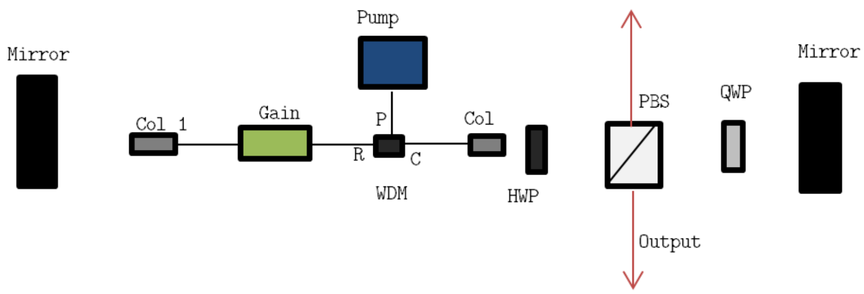
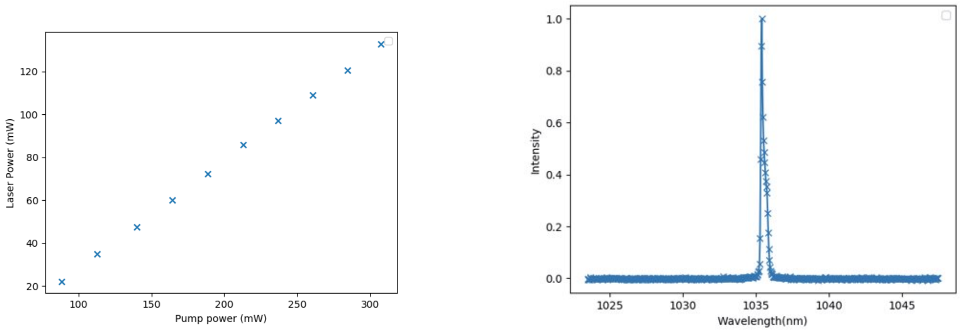


Figure 6: Experimental setup for a CW Yb fiber laser. Col: Collimator, WDM: Wavelength-division multiplexer, R:reflected input of WDM, P: pass input of WDM, C: common output of WDM, HWP: half wave plate, QWP: quarter wave plate, PBS: polarising beam splitter.

In order to find efficient cw-lasing with low loss in the cavity to lase, the coupling between free-sapce and fiber segement through the collimators has to be optimized. To ensure they were aligned the power at one collimator (considered as the feedback) was measured while adjusting the mirror position at the other side of the cavity as well as the tunable collimator, until the power was at a maximum. In addition the TPA fluoresence from the gain fiber was used to see whether the beams were aligned. The fluoresence is expected to be less when there is less loss, meaning a lower probability for TPA due to efficient decrease of inversion based on stimulated emission. The half wave plate (HWP) rotates the polarization and was adjusted for maximum transmission through the polarising beam splitter (PBS) for linearly polarised light and set to 153 °to align the PBS transmission axis to the fast axis of the PM fiber segment. The purpose of the



(a) CW fiber laser power against the pump power

(b) CW fiber laser spectrum

Figure 7: Characterising a continuous wave Yb-doped fiber laser in terms of power and spectrum.

HWP is to establish an axis of the polarization. A quarter wave plate (QWP) converts linearly polarized light to circularly polarized light and is used here to determine the output coupling ratio. Then the PBS will split the laser to the output proportional to the QWP rotation angle. As the QWP is rotated the power of the laser increases and decreases. Figure 7 shows the power curve and spectra of the resulting CW laser at a constant output coupling ratio with QWP set to 124°.

3.2 NLI Setup

The same setup and fiber segment are used with an addition of a few optics in order to mode-lock the laser using nonlinear interferometry. Figure 8 shows the complete setup. The flip mirror is switch down for pure nonlinear interferometry. The phase bias added is made up of a Faraday rotator (FR), which rotates the polarization by 45°and a QWP. The QWP is the parameter that can be tuned to find a stable mode-locking point through adjusting the nonlinear transmission at the PBS. There is also a pair of diffraction Grating (GP) added after the PBS. This adds negative dispersion to compensate for the positive dispersion from the fiber to reduce the pulse being stretched in time. If the GP does not cancel out the dispersion the pulse will broaden each roundtrip and the intensity will decrease uncontrollably. Another FR is added to the other side of the cavity. With the mirror, this will rotate the polarization of the beam by 90°. When the light travels through the fiber, a lag is introduced between the different components of the polarization due to there being a fast and a slow axis in the PM fiber. This delay is cancelled out when the beam travels through the fiber the second time as the FR rotates the polarization by 90°.
The QWP in the phase bias was adjusted to find a stable mode-locking point at 300°. The laser output comes out of the PBS at port T. The port R is the output of the laser without having gone through the GP and can be thought as the opposite of the port T due to the inverse nature of transmission and reflection. A stable pulse train

was generated with a repetition rate of 38Mhz and a 9.4nm gap with the self start mode-locking threshold value found to be 1300mA.

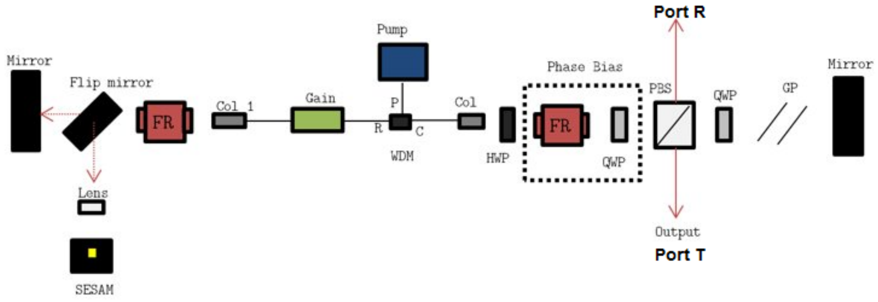


Figure 8: Experimental setup used for mode-locking using nonlinear inteferometry. With a flip mirror to connect to SESAM arm for comparative measurements with pure NLI and SESAM with NLI. Col: Collimator, WDM: Wavelength-division multiplexer, R:reflected input of WDM, P: pass input of WDM, C: common output of WDM, HWP: half wave plate, QWP: quarter wave plate, PBS: polarising beam splitter, FR: Faraday rotator, GP: grating pair.

3.3 Adding SESAM

A flip mirror was added, as seen in figure 8, to focus the light, with a lens of focal length 11mm, on to the SESAM. Once the cavity was aligned with the SESAM a value of 167 degrees on the Phase Bias QWP was found to cause stable mode locking with a threshold current supply of 430mA needed to self-start. A stable pules train with repetition rate of 38MHz was generated.

4 Results

4.1 Charactersing pure NLI and NLI with SESAM lasers

4.1.1 Power

The average power was measured at both ports with a power meter and Thorlabs software[12]. Power measurements are a useful and experimentally straight-forward way to analyse laser systems. The power was measured at both outputs for decreasing current supplied to the pump, starting at the maximum value of 1500mA and taking more measurements at lower pump current to determine the threshold for mode locking and continuous wave lasing. Figure 9 shows the resulting power curve for the pure NLI laser. As the current decreases the laser power decreases as expected. However there are also multiple jumps in the power curve, especially noticeable at port R. These can be explained by considering the behaviour of the pulses. When the laser is first formed it is in the multi-pulse regime due to the nonlinearity in the fiber and to having a large distance between diffraction grating pair thus overcompensating the dispersion from the fiber. Also having more pump power than necessary to mode-lock can lead to multiple pulses. Then as the power of the pump is decreased the pulses recombine at different thresholds causing these jumps in the power curve. Once the power is low enough and there is a single pulse the behaviour acts as in the cw case.

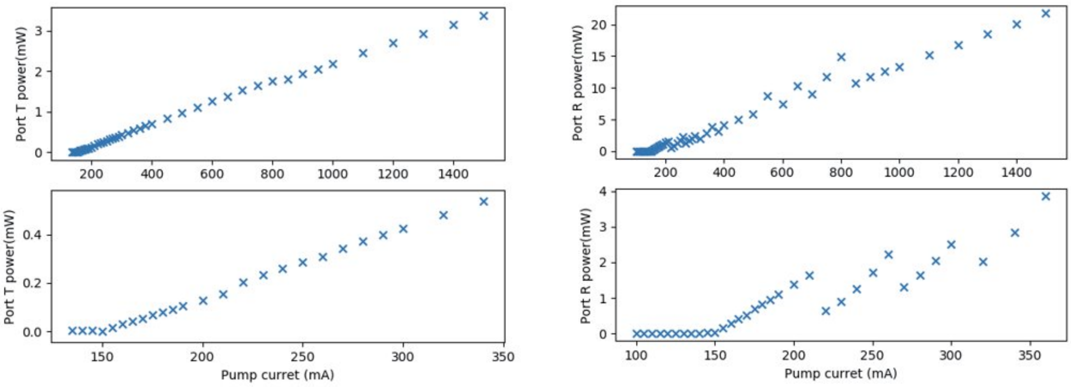


Figure 9: Power curves of the NLI laser at both ports.

A value of 1300mA was recorded as the threshold current supplied needed to be able to self start the mode-locked laser. This was found by slowly reducing the power until the mode-locking was not self starting anymore.
The power was also measured for the NLI with SESAM laser which is shown in figure 10. The overall trend is the same as for the pure NLI however there are even more jumps in the power seen in both outputs. The self-starting threshold for mode-locking was greatly reduced by adding the SESAM with a value of 430mA recorded.

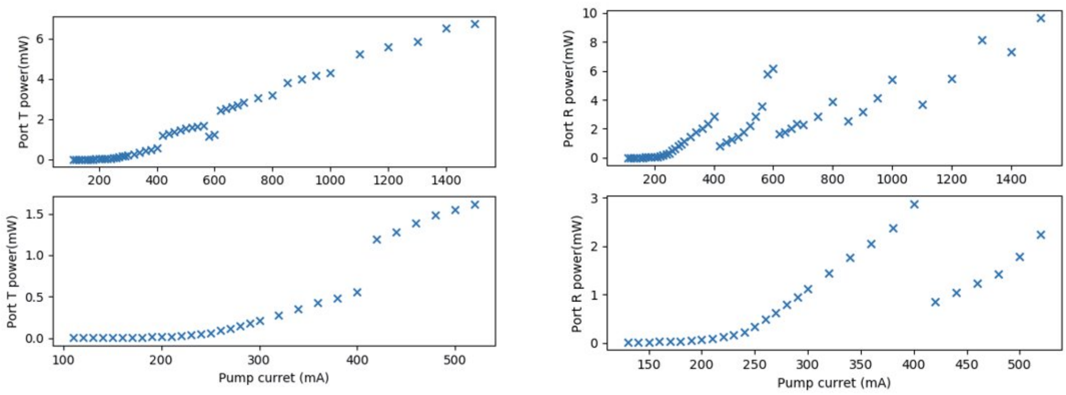


Figure 10: Power curves of the NLI with SESAM laser at both ports.

4.1.2 Spectra

A spectrometer and Oceanview software were used to take measurements of the spectra of both outputs of PBS for both laser systems[11]. Figure 11 shows the two spectra for both lasers found. As shown, the center wavelength of the output spectrum is shifted when the SESAM is added. The spectra at port R seem wider and more modulated. The spectral modulations could be caused by the nonlinear transmission at the PBS or slight misalignment of the grating pair.

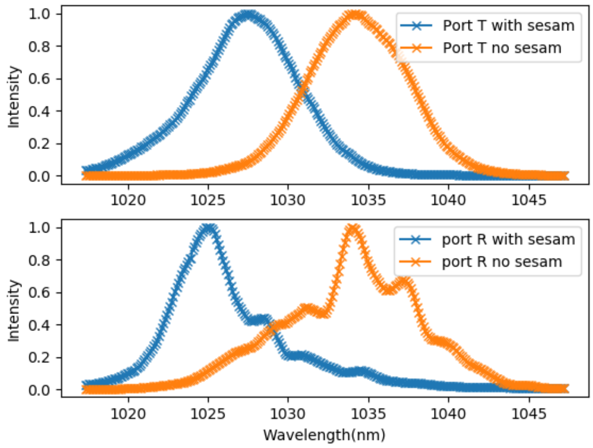


Figure 11: Comparing the spectra of pure NLI with NLI with SESAM at both ports at 460mA.

The power of both lasers was also measured when taking these spectra. Table 1 shows the power measured. The power of laser with the SESAM is very much lower than without the SESAM. This could be due to the SESAM introducing additional non-saturable loss and correlated changes in gain dynamics as well as the wavelength-depenent reflectivity of the SESAM.

Table 1: The Power measured for both outputs of the PBS for both laser systems at a pump current of 460mA and a output coupling QWP value of 240 degrees.

	Without SESAM (mW)	With SESAM (mW)
Port T	8.3	1.1
Port R	4.9	0.9

4.1.3 AM Noise

The Noise measurements were taken using a photodector connected to a bandpass filter and an amplifier then connected to a signal source Analyser (SSA). The pulse train is photodetected and transferred to the electrical domain. Here, a RF-bandpass filter is applied to filter out the first harmonic of the resulting comb. The harmonic is phase-locked to a stable reference signal in the SSA and the fluctuations are measured relative to the reference amplitude[14]. To ensure a comparable short-noise floor for the AM-noise measurements, the optical power infront of the photodetector is attenuated to ensure a constant RF power of -11 dBm reaching the SSA input. In addition, all measurements are done with identical oscillator pump current of 460mW. The noise measurements of both lasers at both ports are shown in figure 12. In general adding the SESAM seems to increase the Noise. For port T the Noise is amplifyed for frequencies above 100Hz. However there are some frequencies for port R where the noise is reduced by adding the SESAM. Therefore further research would be needed with detailed parameter studies and simulations to be able to improve the noise performance of the NLI with SESAM laser.

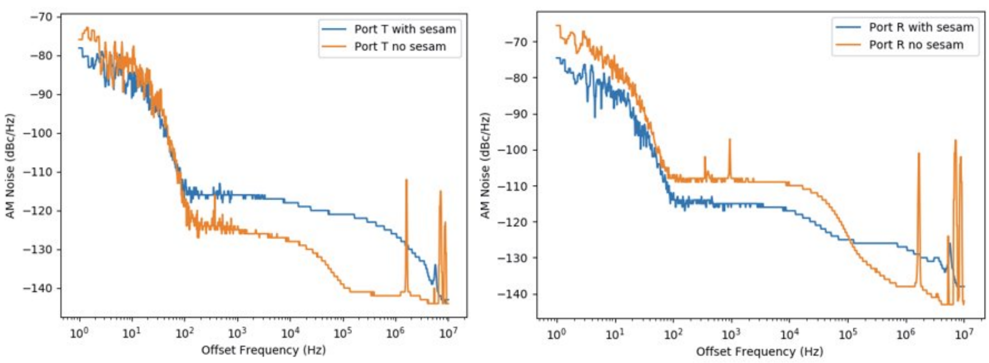


Figure 12: Comparing the AM Noise of pure NLI with NLI with SESAM spectrum at both ports at 460mA.

5 Conclusion

A Yb-doped fiber laser was built and mode-locking using nonlinear interferometry and a SESAM. The two laser systems were characterized and compared to one another. It was found that adding the SESAM to the NLI greatly reduced the self-starting mode-locking threshold from 1300mA to 430mA and that adding the SESAM amplified the AM Noise especially for port T. The experimental setup will be used for further systematic measurements. The next steps for this project would be to research more to improve the noise performance of the NLI with SESAM laser and try lenses of different focal length to focus onto the SESAM to investigate how this will affect self-starting and noise. The design for a stable and low noise oscillator can be used for applications in high power laser systems.

6 References

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