Chapter 1

Introduction

When Albert Einstein postulated his General Theory of Relativity, his main intention was to overcome the limitations of Newton's Theory of Gravity [Ein15]. One solution of the equation of general relativity revealed the theoretically existence of gravitational waves [Ein16]. These waves are ripples in space-time that travel at the speed of light. Even though these waves pass through the Earth on a daily basis most of them are much too weak to be ever noticed or detected. Only waves with a very high amplitude, created by high-mass stellar objects, like neutron star - neutron star binaries, massive black holes or collapsing massive stars, are detectable to us.
Although no detection of gravitational waves has been successful so far, various scientists over the past 80 years were eager to measure these waves as a direct experimental proof of Albert Einstein's theory. The first major break through was done when Russell Hulse and Robert Taylor investigated a pair of pulsars (PRS 1913 + 16) spinning around each other [Hul75, Tay76]. These pulsars send out a detectable radio burst that hits the Earth every 7.75 h. Measuring the period of this signal over a long time scale they found that the pulsars were slowly drawn together. The energy lost during this process perfectly fitted the predicted energy loss caused by gravitational waves. For these experiments both scientists were awarded with the Nobel Prize in Physics in 1993.
Today technological evolution has made huge progress, so that the detection of gravitational waves is within reach. Large-scale Michelson interferometers with arm lengths of up to 4 km achieve sensitivities for gravitational waves that could lead to the first detection. Measuring the distance between quasi free falling mirrors (in direction of the propagating beam), called test masses inside the L-shaped interferometer arms, a displacement sensitivity of 10^{-22} per meter per root Hertz could be demonstrated, recently [Abb09].

The largest detectors of this type are the ***L**aser **I**nterferometer **G**ravitational wave **O**bservatories* (*LIGO*). Built by a collaboration of the Californian Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT) three detectors are operated today. Two of these are located at Hanford, Washington state, and share one building. One detector with two 4 km long arms between beam splitter and the test masses and one with 2 km. Separated by 3000 km, located at Livingston, Louisiana, a third detector with 4 km arm length was constructed. These detectors are the most sensitive for gravitational waves today.

In theory, two interferometers would be sufficient to detect gravitational waves and confirm the authenticity by a coincidence measurement. Nevertheless, a deeper insight into the origin, orientation and polarization of these waves is only gained by having more than two detectors. Therefore, different groups around the world working in the same field and with their own observatories, joint together and formed a collaboration called LIGO Virgo Scientific Collaboration (LVC). Amongst these detectors are the French-Italian detector Virgo (3 km arm length) near Pisa, Italy, the German-British detector GEO600 (600 m arm length) near Hannover, Germany and TAMA300 (300 m arm length), built and located in, Tokyo, Japan.

Even though a detection is possible with the sensitivity of the today's LIGO, a plan to increase the sensitivity and hence the detection range for theses observatories was developed during the last years, called *Advanced LIGO* [Fri08]. Various groups all over the world will supply the latest in technology for this major upgrade until the end of 2014. One limitation in the interferometric detection of length variations in the sub attometer scale is the photon shot noise. As shot noise level decreases proportionally to the light source power an increase in output power of the laser system used is desired. To increase the sensitivity by a factor of 10 from LIGO to Advanced LIGO, a significant increase in laser output power is needed. Calculations showed that 200 W of light emitted from such a laser source would be sufficient (taking losses for active stabilization, filter cavities, and for sideband modulation, etc. into account).

To increase the circulating power inside the arms of the interferometer and therefore the light's storage time, resonant high-finesse Fabry Perot cavities are installed. Additional power and signal recycling mirrors furthermore increase the circulating power to a maximum of 800 kW (for Advanced LIGO) [Har10]. To couple a laser beam in such a resonant large scale cavity, the beam profile has to have a pure Gaussian shape. In addition, the emitted light should only oscillate at one single frequency.

Within the second chapter of this work, an up-to-date description of the current and future LIGO detectors is given. Considering the development of the Advanced LIGO

Project during recent years, the final design requirements for a laser system for this gravitational wave detector are presented. This section is followed by an overview of the underlying technological background which led to the development of the first laboratory laser prototype by Frede et al. [Fre05b]. Additionally, an overview of the laser technology, which is actually installed and operated inside the various observatories is given. At the end of this chapter, the final design laser concept, which was chosen as the light source for Advanced LIGO, is described.

In chapter three, the theoretical background needed for the optimization of the laser system for Advanced LIGO is presented. First of all, the thermal effects inside the laser active media of a high power laser system are reviewed and two methods to obtain numerical results for the thermal lens within the laser crystals are given. With these results, a numerical model for the resonator stability and internal mode diameters is developed. The results obtained can then be used to predict the best operation point of a given dynamically stable laser configuration and for further optimization of the resonator. Furthermore, the Pound-Drever-Hall injection-locking technique is discussed, which was used to achieve a high output power in a single longitudinal mode by coupling the high power oscillator to a low power seed.

The theoretical guidelines derived with the previously mentioned models were then incorporated in the development process of the injection-locked high power oscillator. Prior to that, experimental results used to verify the suitability of an asymmetric resonator configuration for higher-order mode discrimination are presented. Based on the derived experimental data and the numerical calculations an optical setup for the high power oscillator is presented in chapter four. The derived optical scheme was then implemented into a mechanical design for the high power oscillator, which was optimized for long term operation and high stability. To compensate for thermal effects, which greatly influence the mechanical structure and thus the alignment of the laser, a cooling scheme was developed and verified by simulations and thermo optical measurements.

In chapter five all results of a full characterization of the injection-locked laser system for Advanced LIGO are presented. In contrast to industrial high power Nd:YAG lasers it is not sufficient for a laser system designed for a gravitational wave detector to measure output power and beam quality only. Special attention is paid to the power and frequency noise characteristics of the laser and especially the higher-order mode content of its output beam. Furthermore, the injection locking behavior, which has a strong impact on the long term stability of the laser system, is examined in more detail. For a concluding performance overview a short section with the latest output characteristics of the actively stabilized laser system is given. Even though these results were not generated as part of this work, they will contribute to a more detailed overview of the laser system's performance.

As described in the previous section, the laser system fulfilled the requirements and is currently installed as the next generation light source inside the Advanced LIGO observatories. From the design descriptions and pictures in this manuscript one will see that the complete laser system is a fairly large and complicated assembly. To deliver and install such a delicate optical laser system to the United States, extensive planning and foresight during the mechanical development of the laser was needed. Therefore, a short overview of the shipping procedure, on-site installation and support is given in the outlook section of this work.

Even though the development of advanced gravitational wave detectors will result in the detection of such waves on a yearly basis, a detailed description of astrophysical phenomena will need a more sensitive detection method for the future. Although, the newest generation of LIGO detectors and others are not operational at this time, a project to build a third generation detector called *Einstein Telescope* was formed. This Earth bound observatory also relies on an interferometric detection of length variations caused by gravitational waves, but with much higher sensitivity. For this observatory, new lasers with even higher output power levels in a fundamental mode beam or in a different wavelength regime are desired. As a foresight what comes next in the field of gravitational physics, an outlook of these new technologies is presented in chapter six.

At the end of this work a conclusive overview of the achievements during the development of the Advanced LIGO high power oscillator will be given in chapter seven.

Chapter 2

Light sources for gravitational wave detectors

The essence of Albert Einstein's General Theory of Relativity is that mass and energy produce a curvature of four-dimensional space-time, and that all matter will move in response to that curvature. Similar to Maxwell's equation describing the interaction of an electric charge and an electromagnetic field, Einstein's equations characterize the interaction of mass and space-time curvature. Gravitational waves (GW) are time-dependent vacuum solutions for curvatures field equations. A similar structure can be seen in Maxwell's time-dependent in vacuum solution, which describes electromagnetic waves. GWs can be imagined as ripples or strain oscillations perpendicular to a reference flat, or Minkowski, space-time metric.
Experimentally, the variation of this metric could be detected as a delay of light traveling from one free falling test mass to another. If the orientation of these test masses is well adapted to the orientation of the GW, the relative distance change can be described as [Sau94]

$$\frac{\delta L}{L} = \frac{|h|}{2}, \tag{2.1}$$

with h being the amplitude of the GW or GW strain, as it describes the fraction of stretch and compression of the space-time. Similar to electromagnetic waves, GWs travel at the speed of light. Because their interaction with the surrounding masses is relatively low, they can pass objects without being perturbed. In comparison to electromagnetic waves, which are dipole in nature, GWs are quadrupole. This means that the strain pattern of these waves contracts and stretches space-time along the propagation pass. The transverse strain field of the GW comes in two different polarizations. The basic +-polarization and the rotated by 45° ×-polarization can be observed. Normally, the astrophysical GW comprises both orientations.

As mentioned above, the interaction of gravitational waves with matter is very weak. From astrophysical considerations, the largest strain that can reach the Earth would have to be produced by a catastrophical event, such as a nearby supernova or the merging of two black holes. Estimates say that this strain could reach levels of $h \approx 1 \cdot 10^{-18}$. As such events are very rare, an approximation of the amplitude and hence displacement generated by a gravitational wave which is more likely to be detected on a daily basis was performed. Therefore the amplitude h of a GW that is created by two neutron stars (NS) orbiting around each other in a distance R to the Earth can be described as [Sau94]

$$h \approx \frac{r_{S1} r_{S2}}{r_0 R}, \tag{2.2}$$

with r_0 the distance in between the two stars and $r_i = 2GM_i/c^2$ the corresponding Schwarzschild radii. As an example the gravitational constant is given as $G = 6.67259 \cdot 10^{-11}\mathrm{Nm}^2/\mathrm{kg}^2$ and the mass of one of the two stars is 1.44 times the solar mass $M_\odot = 3 \cdot 10^{30}$kg. With a distance of 50 million light years located in the Virgo cluster these NS binary stars rotate within a distance of 80 km to each other. Under these conditions the estimated GW strain would be $h \approx 1 \cdot 10^{-21}$. Hence the sensitivity of a gravitational wave detector (GWD) should be in the range of $h \approx 1 \cdot 10^{-21}$ to $h \approx 1 \cdot 10^{-22}$. This corresponds over a distance of 1 km to a length displacement of 1 – 10 attometers. The first attempts to measure a GW were made by Weber in 1960 [Web60]. For his detector he used a large (approximately 1 t) aluminum cylinder, hanging suspended in a vacuum chamber. A GW that passes through the detector will cause the cylinder into oscillate. These oscillations can be detected by high precision transducers attached to the cylinder. With this setup a GW strain sensitivity of $h \approx 1 \cdot 10^{-16}$ was achieved. With the development of new cooling techniques to temperature levels of 0.1 K for the oscillating cylinder the sensitivity of these GWD was improved significantly [Ast97]. Even though the sensitivity of this device is in the range to detect a GW it only has the ability of detecting these waves at discrete resonant frequencies.

To measure in a more broadly spread range of frequencies and thus increase the probability of detecting a GW, a concept based on the optical measurement of length variations was chosen. Used to study the impact of the ether on light waves by Michelson in 1881 and further on in a more sensitive experiment by Michelson and Morley in 1887 [Mic87], a light interferometer was developed. Based on the ability to measure length deviations of two orthogonal arms with high precision, Pirani, Weiss and Forward proposed the use of an interferometer as a gravitational wave antenna [Pir56, For78, Wei72].

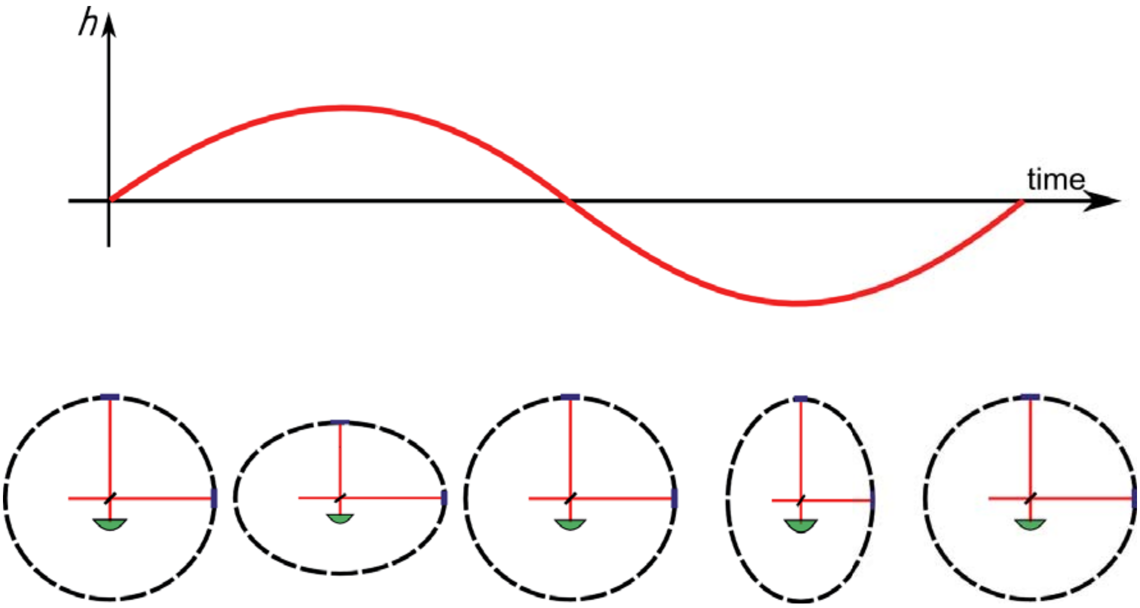

Figure 2.1: Gravitational wave with the strain h perpendicular to the plane of the diagram. A figurative circle of particles around a Michelson interferometer is transformed into an ellipse. One arm gets elongated during one half-cycle while the other gets compressed. In the next half-cycle the other direction is stretched and the orthogonal one compressed. The oscillation can be measured as a light modulation at the output of the interferometer (**green**).

In a Michelson interferometer the injected light is divided by a beam splitter into two beams traveling in orthogonal directions. These two rays are reflected by mirrors and interfere when being overlapped at the beam splitter. If a GW passes the interferometer the arm lengths are compressed or stretched, respectively. In Fig. 2.1 an incident GW with a sinusoidal oscillation and its impact on the interferometer is shown. Sending light with a single frequency into the interferometer, a phase shift of

$$\Delta\Phi(t) = \frac{4 \cdot \pi \cdot L}{\lambda} \cdot h(t), \tag{2.3}$$

corresponding to strain $h(t)$ of the GW can be detected at the output. To increase the signal to noise ratio the arm lengths of the basic Michelson interferometer configuration are chosen so that the light will interfere destructively at the output port. Under this so called *dark fringe condition* the phase modulated sidebands, which are caused by the passing GW, will interfere constructively with an amplitude depending on the GW strain, as shown in Fig. 2.2.

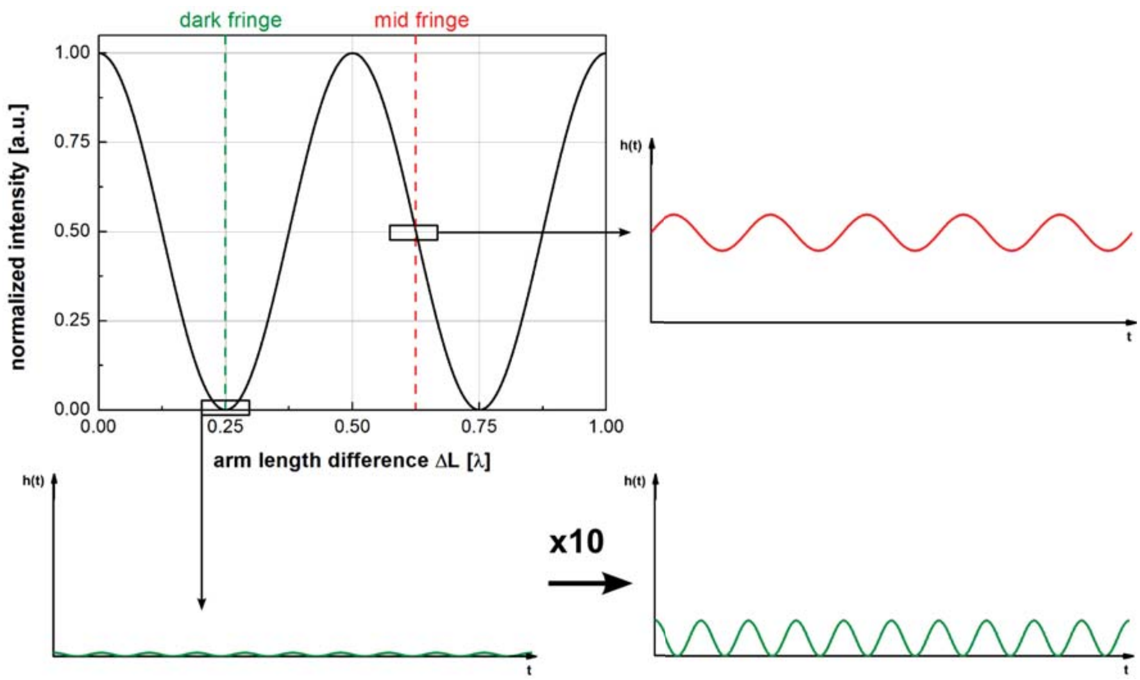

Figure 2.2: GWD response to a differential displacement of the interferometers end masses to a gravitational wave in dark fringe condition.

To increase the sensitivity of the interferometer for GW signals additional changes apart from the standard Michelson configuration have been introduced. Two different parameters of the interferometer configuration have a direct very high impact on the sensitivity of the detector: the power incident on the beam splitter and the light storage time inside the interferometer. Both parameters reduce the limiting sensing noise above 10 Hz, which is dominated by shot noise. The ideal shot noise limited strain can be described as [Abb09]

$$\tilde{h}(f) = \sqrt{\frac{\pi \hbar \lambda}{\eta P_{BS} c}} \frac{\sqrt{1 + (4\pi f \tau_s)^2}}{4\pi \tau_s}, \tag{2.4}$$

where η is the photodetector's efficiency, f the GW-frequency, λ the wavelength of the light-source, τ_s the light storage time, P_{BS} the laser power at the beam splitter, $\hbar$ the Planck's constance, and c the speed of light. To raise the light storage time τ_s, resonant Fabry-Perot cavities (FPC) are installed in each of the interferometer's arms as shown in Fig. 2.3. These cavities cause the light to perform several round-trips in the arms, which increases the carrier power and phase shift for a given GW strain amplitude and frequency [Mue03]. To scale the power inside the detector even more a scheme, called power recycling, is applied. When the Michelson interferometer is operated in the *dark fringe configuration* all optical power reflected from the end test masses / mirrors (ETM) of the detector arms is send back in direction of the light source. To recycle this power a power recycling mirror (PRM) is placed in between the light source and the beam splitter (BS).

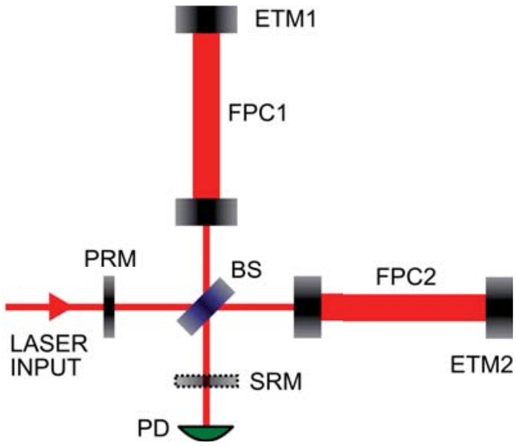

Figure 2.3: Schematic of the LIGO interferometer with end test masses (ETM1 and ETM2), Fabry-Perot cavities (FPC1 and FPC2), beam splitter (BS), power recycling-mirror (PRM), signal recycling mirror (SRM) and photodetector (PD).

Another method of increasing the sensitivity is the installation of a signal recycling mirror (SRM) [Str91, Hei98]. First introduced in the GEO600 detector, it sends the sidebands produced by GWs back into the interferometer. Inside the detector the signal is amplified even more, picking up more phase from the passing GW. Additionally this scheme offers one the ability to control the frequency range, in which the detector is most sensitive to GW [Wil02]. Although this mirror was not included in the LIGO detectors, it is planned to be installed in Advanced LIGO [Fri08].

Besides these sensitivity scaling techniques for the interferometric GWDs, much more technical issues have to be solved to achieve the performance of today's gravitational wave observatories. Seismic isolation, featuring multiple pendulum constructions, isolate the test masses from the Earth's motion to guarantee the quasi free-falling characteristic in the direction of the propagating laser beam. The mirrors themselves are temperature controlled and positioned by actively stabilized contact-free actuators. All beams and optics are positioned into vacuum to compensate for air fluctuations coupling into the detector's signals. This vacuum system for LIGO, with its tubes running 4 km in one and 4 km in the other direction, is the largest ultra-high vacuum (UHV) system in the world. In fact, various groups all over the world worked with much effort to reach the initial LIGO sensitivity of $h = 3 \cdot 10^{-22}$ at 100 Hz.

2.1 Laser requirements

From Eq. (2.4) in the previous section one can see that the shot noise of a GWD is directly proportional to the inverse square root of the power incident on the beam splitter. This power is directly defined by the laser power that is coupled through the power recycling mirror into the interferometer setup. Because the arms of the Michelson interferometer are equipped with resonant high Finesse Fabry-Perot cavities, only laser beams with a pure Gaussian intensity profile oscillating in a single longitudinal mode can be used. To guarantee that the light incident on the beam splitter has a pure TEM_{00} beam profile, passive filtering cavities are installed upstream of the entrance window to the interferometer input [Wil98].
For the next generation of the LIGO GWD – Advanced LIGO – a laser output power increase of a factor of 20 compared with the laser used in the initial setup is desired. First estimations showed that a power level of 125 W at the beam splitter is needed to achieve a significant reduction of the limiting shot noise of the GWD. With a light source capable of supplying such power levels in a single-frequency pure TEM_{00} beam, the sensitivity for the detection of inspiral NS-NS binaries can be increased by a factor of 10 compared with the initial detector [Fri08]. Consequently, this will lead to a 1000 times higher detection rate for GWs.
In fact, an output power of more than 165 W in a pure Gaussian intensity distribution is needed to compensate for the losses at the input of the interferometer and for the generation of side bands, which are required for interferometer control loops. This sets the power requirements for a laser system for Advanced LIGO to more than 200 W of output power in a single-frequency fundamental mode. As specified, only 10% of this power can be tolerated in higher-order modes. These higher-order modes can be filtered out by passive filter cavities directly after the laser system and in front of the interferometer input.
Besides the output power and modal characteristic of the laser beam, the fluctuations of the laser frequency and power are limiting factors in optical GWDs. A frequency shift of the laser light inside the Michelson interferometer causes a phase shift at the output port. For an interferometer with arms having exactly the same length, this differential effect would cancel out. Unfortunately, it is technically not possible to build a 4 km Michelson interferometer with equal arm length. When an arm length difference of $\Delta L = L_x - L_y$ is assumed, the frequency differences $\delta\nu$ of the laser with a carrier frequency ν_L causes a phase shift

$$\delta\Phi = \frac{2\pi}{c}\left[\delta\nu\Delta L + \nu_L\delta\Delta L\right], \qquad (2.5)$$

which directly couples into the GW-detection signal as described in the previous section. Thus, the signals from the frequency fluctuations have to be kept lower than that caused by the arm length variation δL caused by a passing gravitational wave. Estimations of this value over the detectors frequency range led to a requirement for the frequency stability of the laser system which is given in Table 2.1. Furthermore, a Michelson interferometer can only be tuned to the dark fringe operation point described in the section above to a certain extent. Because of small offsets inside the electronic control loops, which keep the interferometer locked at the dark fringe point, small phase offsets are generated. In combination with a slightly mis-aligned beam, imperfect coatings of the test mass surfaces and the radiation pressure on these masses, laser output power variations can couple into the phase signal of the interferometer, causing a frequency dependent strain variation. As a consequence, the requirements for laser output power variations are well defined. Presumed values for the power fluctuations of the laser beam for specific frequency ranges of the GWD can be found in the requirement Table 2.1 as well.

Parameter	**Specifications**
wavelength	1064 nm
output power	> 200 W
power in higher-order modes	< 20 W
frequency fluctuations	$< 1 \cdot 10^4 \mathrm{Hz}/\sqrt{\mathrm{Hz}} \cdot [1\ \mathrm{Hz/f}]$ between 1 Hz and 10 kHz (same as NPRO free running)
relative power fluctuations	$< 10^{-2}/\sqrt{\mathrm{Hz}}$ between 0.1 Hz and 10 Hz $< 10^{-5}/\sqrt{\mathrm{Hz}}$ between 10 Hz and 10 kHz $< 3.6 \cdot 10^{-9}/\sqrt{\mathrm{Hz}}$ for $f > 9$ MHz (3 dB above shot noise of 50 mA photocurrent)

Table 2.1: Target specifications for the final free-running Advanced LIGO laser.

To understand the development process for the Advanced LIGO laser presented in this work, one has to distinguish between a free running laser system and an actively stabilized laser. With a free running laser, the requirements regarding frequency and amplitude noise given by the system parameters of the Advanced LIGO detector are not achievable. To reach the desired specifications of the laser an active stabilization scheme developed by the Max Planck Institute for Gravitational Physics in Hannover is applied to the laser system described in this work. Even though all data presented in this work are only related to the free running laser, special consideration was taken during the development process to be able to reach the requirements for a stabilized laser in the end.

Besides the specifications given in Table 2.1 the laser system has to be operable in an environment with a varying temperature of 3 K peak-to-peak and a pressure variation of 50 hPa around the average atmospheric pressure. The requirements for long term stability can be derived from the intended availability of 90% of the GWDs with a minimal continuous period of operation of 40 hours over many years. Therefore, special attention was paid to the mechanical and optical design of the laser system, which influences the long-term stability and the ease of maintenance.

2.2 Best available laser technology in GWDs

Various different laser light sources are used inside ground-based GWDs around the world. All of these laser systems have one thing in common: They use a highly stable single crystal laser as frequency reference. These non-planar ring oscillators (NPRO) are based on a monolithic ring resonator design, where the cavity is formed inside the active media [Kan85]. Because of the laser's fairly small resonator length, the emitted light is oscillating with a single frequency. Furthermore, the laser line width of a few kHz of these devices is advantageous for the development of a laser for GWDs.

Unfortunately, the output power of commercially available laser's based on this design is limited to approximately 2 W. To further increase the optical power two different approaches have been followed. The first is the direct amplification, passing the beam through multiple active media. In this so called *Master Oscillator Power Amplifier* (MOPA) configuration the NPRO serves as the frequency and beam profile reference and though is the *Master Oscillator*. In most cases the *Power Amplifier* consists of longitudinally pumped solid-state laser crystals, in which the low power beam of the *Master Oscillator* gets amplified in a single pass. As active media for this kind of amplifier Nd:YVO_4 was found to be most suitable. Offering a very high gain it is widely used in MOPA systems.

The second approach, injection locking, is based on the resonant coupling of a high power oscillator to a low power seed laser. For this purpose, a piezo actuated mirror is introduced into the high power oscillator's cavity. Moving the piezo actuated mirror, the resonance frequency of this cavity is brought near the carrier frequency of the injected low power seed. At that point, the good frequency properties (longitudinal single-frequency, low frequency noise, etc.) are imprinted on the high power beam. The injection-locking process of both laser systems is performed by an automated

analog servo system following the Pound-Drever-Hall (PDH) scheme [Dre83]. In most cases ring lasers with two or more laser crystals are used as high power oscillators. As active media Nd:YAG and Nd:YVO_4 are the most common. However, the thermal properties of Nd:YVO_4 make its use for high power laser systems above the 100 W level unfeasible.
A list of all laser systems used in today's GWDs and their concept is given below in Table 2.2.

Detector	Gain media	Concept	Output power	Reference
Initial LIGO	Nd:YAG	MOPA	10 W	[Sav98]
Enhanced LIGO	Nd:YAG+Nd:YVO_4	MOPA	35 W	[Fre07b]
Virgo	Nd:YVO_4	Inj.–Lock.	20 W	[Ace08]
GEO600	Nd:YAG	Inj.–Lock.	10 W	[Zaw02]
TAMA300	Nd:YAG	Inj.–Lock.	10 W	[And05]

Table 2.2: Overview of laser systems used in Earth bound gravitational wave detectors.

Both concepts, injection locking and the MOPA design, offer different advantages and disadvantages. From the technical side the MOPA concept is the most reliable and easiest to maintain, because it does not use an active resonator length stabilization scheme. Furthermore, fluctuations of the surrounding environment (temperature, air pressure and humidity) have a lower impact on the output performance compared to a laser with a length stabilized cavity. Unfortunately, the output power achievable with solid-state MOPA systems is limited, because the beam gets distorted by the thermal lens in each laser crystal, picking up more and more distortions with every additional active media of a multi-stage amplifier. By comparison, high power oscillators in an injection-locked system offer a beam filtering ability due to their resonator. For this reason, Frede et al. decided at the beginning of the design and development process of a laser system for the next generation of LIGO to combine a high power solid-state oscillator with a low power seed [Fre07a].
During the first stage of this development phase an injection-locked two head laser system with a single-frequency output power of 87 W was presented [Fre04]. In the following experiments, the power was scaled by doubling the number of laser crystals resulting in the first prototype of a four head ring laser setup. With this laser an output power of 213 W with a fundamental mode beam profile, but without injection-locking, was achieved in a table-top laboratory experiment [Fre05c].
Similar to the two head laser, the four head ring laser was injection-locked following the Pound-Drever-Hall scheme. By comparison to the two head experiments the low output power of several hundred mW of the NPRO was not sufficient to es-

tablish a stable injection lock for the high power slave laser. As shown in Fig. 2.4, an intermediate stage was introduced into the setup. This stage is an exact copy of the GEO600 slave oscillator, which is injection-locked to the low power NPRO by a second set of Pound-Drever-Hall locking equipment. The single-frequency output beam with a power of approximately 10 W was then coupled into the high power slave oscillator. With this multi-staged laser an output power of 196 W in single-frequency operation was demonstrated [Fre05b]. Furthermore, the laser system passed the *Conceptual Design Review* [Fre05a], which was the first evaluation phase to verify the laser concept's suitability for use in Advanced LIGO.

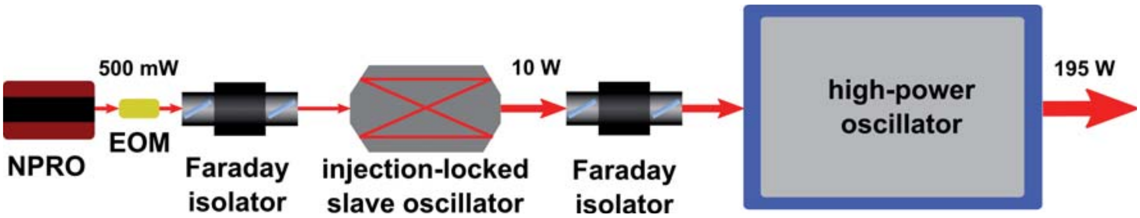

Figure 2.4: Schematic of the laboratory setup developed by Frede for the first demonstration of the feasibility as a laser for the next generation of GWD.

2.3 Laser concept

The final development process of the Advanced LIGO laser system, which will be described in this thesis, started immediately after the successfully passed conceptual design review phase. In this phase, the use of a multi-staged injection-locked setup incorporating a four head high power oscillator stage was defined. Even though the performance level of the first experimental laboratory setup was able to supply the required output power, the final Advanced LIGO requirements on higher-order mode content, frequency and power stability as well as long term stable operation could not be demonstrated. Thus the development of the Advanced LIGO laser concentrated on the optimization of the following laser output parameters to fulfill the requirements for the GWD's light source (see Table 2.1):

- Low power levels in residual higher-order modes, consequently optimization for highest power in TEM_{00} mode, which requires a laser resonator or spatial filter to control the higher-order mode content.

- Acceptable frequency and power noise levels, which can be controlled to the required range with an active stabilization scheme in a second development step (performed at the Max-Planck Institute for Gravitations Physics in Hannover).