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Diode-pumped solid-state lasers as light sources of Michelson-type gravitational-wave detectors

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Abstract. For the next generation of gravitational-wave detectors a laser-light source with high continuous output power in single-frequency operation, excellent frequency stability, and low amplitude noise is required. This contribution summarizes the recent progress in the development of a diode-pumped solid-state laser system with the potential to meet these requirements. Single-frequency operation at an output power of 20W cw is achieved by injection locking of a high-power laser, using a new monolithic non-planar ring laser as a master oscillator.

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New aims in high-resolution spectroscopy and laser-based metrology require reliable ultrastable laser systems, operating with high overall efficiencies at low operational costs. The laser-light source required for the next generation of gravitational-wave detectors using Michelson-type interferometers is very sophisticated [1, 2]. To achieve the desired strain sensitivity of at least 10^{-21}, the lasers have to work at high power levels ($P \cong 100$ W cw) in single-frequency operation with excellent frequency stability (FM noise $< 3 \times 10^{-7} \mathrm{Hz}/\sqrt{\mathrm{Hz}}$), and amplitude noise as close as possible to the quantum-noise limit. Beyond that, the operational lifetime of these systems must be in the range of several 10000 h. First gravitational-wave interferometers were equipped with argon-ion lasers. Because of the low single-frequency output power of a single argon-ion laser, the coherent superposition of the light from several argon-ion lasers is necessary to achieve the required power levels [3]. Diode-pumped Nd:YAG lasers have the potential to reach much higher power levels [4], and diode-pumping introduces less technical noise than conventional pumping with arc-lamps. In addition, the operational lifetime of diode-pumped systems is very high, and the overall efficiency is more than 100 times higher in comparison to argon-ion lasers.

Single-frequency diode-pumped solid-state lasers, operating in the low-power regime, have demonstrated their superiority for applications in laser-based measurement techniques, as compared to gas-discharge laser systems, because of their high intrinsic frequency stability, low amplitude noise and high overall efficiencies. The monolithic unidirectional non-planar Nd:YAG ring lasers can fulfill the required properties of an interferometer for gravitational-wave detection concerning amplitude and frequency stability in single-frequency operation [5, 6]. But the direct use of these devices in an interferometer is not possible, since their output power is limited to values below 2W in a single axial mode. Conventional amplifiers could increase the power of the monolithic ring laser, but they would amplify its technical and quantum noise as well. Therefore, the injection-locking technique has to be used in order to achieve ultrastable radiation at high power levels. By injecting the light of a stable single-frequency laser (master laser) into a high-power laser (slave laser), a combination of the stability and spectral properties of the master laser and the high power of the slave laser is possible [7]. Several experiments using arc-lamp-pumped Nd:YAG lasers as injection-locked amplifier stages have been described [8–10]. Investigations on the amplitude pump-noise transfer to the injection-locked slave laser show [11] that it is indispensible to use diode lasers as pump source of the high-power slave laser [12, 13] because of the low noise of diode lasers compared to arc-lamps.

This contribution summarizes the substantial progress in the development of a diode-pumped solid-state laser-light source for a gravitational-wave detector. Single-frequency operation at an output power of up to 20 W cw is performed by injection locking of a diode-laser side-pumped high-power laser, injecting the radiation of a new non-planar monolithic ring laser.

1 Master oscillator: Diode-pumped non-planar miniature ring laser

Diode-laser end-pumped solid-state lasers, operating in a single transverse mode, are well known as compact,

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Dedicated to H. Walther on the occassion of his 60th birthday reliable and highly efficient sources of stable radiation. But for many applications in high-resolution spectroscopy and metrology, single-frequency operation is required. Because of the spatial hole-burning effect, also the homogeneously broadened solid-state lasers oscillate on several longitudinal modes even at low output powers. To enforce single-frequency operation internal resonator elements can be applied. But, the additional intracavity elements strongly reduce the efficiency and stability of the laser systems. The microchip laser design permits single-frequency oscillation in a more simple way, but output powers are limited to about 100 mW. Since the frequency-locking range of an injection-locked system scales with the square root of the power ratio of master and slave laser, a single-frequency master oscillator at reasonable power level is desired for reliable performance of the laser-light source. The monolithic miniature Nd:YAG ring laser – first reported by Kane and Byer [5] – enables single-frequency operation at higher output powers. Unidirectional and hence single-frequency oscillation of this device is enforced by an intrinsic optical diode. A maximum output power of 1 W and slope efficiencies of more than 60% for a diode-pumped ring-laser system has been reported so far [6].

The design of our non-planar ring-laser system with dimensions of $3 \times 8 \times 12\ \mathrm{mm}^3$ is shown in Fig. 1. An unstable resonator design has been developed, compensating the thermal lensing within the laser crystal, which is due to the pumping process. This design allows a reliable operation at high output powers. The optical beam path is determined by three total reflections and one reflection at the negatively curved front surface. The front surface has a dielectric coating for a reflectivity of 96.8% at the generated 1.06 μm radiation, and for high transmission of the pump radiation at 808 nm. The laser is end-pumped with 1 W cw diode lasers (Siemens SFH 487401), having an emitting aperture of $1 \times 200\ \mu\mathrm{m}^2$. These GaAlAs-diode lasers are equipped with miniature cylindrical lenses in order to compensate the astigmatism of the emitted radiation. Hence, only spherical components are necessary to couple the pump light into the laser crystal. To increase the pump power, the radiation of two diode lasers is spatially overlapped by a polarizing beam splitter. Two of these pump modules are applied to realize a pump power of about 3.8 W at the laser crystal (Fig. 2). For this pump power, a maximum output power of 1.8 W in single-frequency operation is measured. These data correspond to an overall efficiency (electrical–optical) of the laser system of more than 15%. This high output power for the master laser gives a large locking range for the injection locking of the high-power slave laser and results in a high reliability of the master/slave configuration [11].

The amplitude noise power spectrum of the monolithic ring laser, operating at an output power of 500 mW, was measured by an electronical spectrum analyzer (Tektronix 2756P), and is shown in Fig. 3. The spectrum is dominated by the relaxation oscillations, which are due to the strong coupling between the laser-cavity field and the inversion. At frequencies above a few MHz, the laser is quantum-noise limited. Using an active feedback loop, the relaxation oscillation can be effectively reduced [14]. We have demonstrated the suppression of the relaxation oscillation to about 6 dB above the standard quantum-noise limit in the entire frequency range between 300 Hz and 300 kHz, in collaboration with Bachor and co-workers from ANU/Australia [15].

To investigate the spectral properties of the monolithic ring laser, the output of two independently operating lasers can be mixed on a photodiode, and analyzed with a spectrum analyzer [16]. A beat measurement between two free-running laser systems is shown in Fig. 4. Due to the monolithic structure of the resonator and the low technical noise introduced within the pumping process, the spectral linewidth of a free-running laser is typically less than 1 kHz/100 ms, and the low-frequency noise amounts to $1\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ [17, 18]. Monitoring the temporal fluctuations of the beat frequency, a thermal drift of the system of less than 10 MHz/h can be estimated [6].

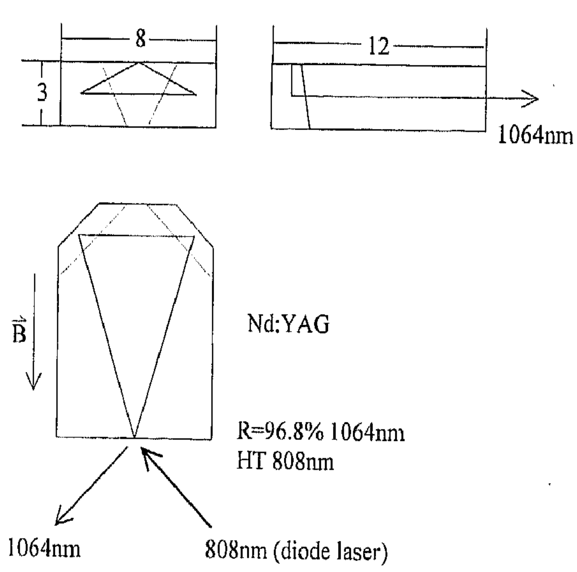

Fig. 1. Design of a monolithic Nd:YAG ring laser

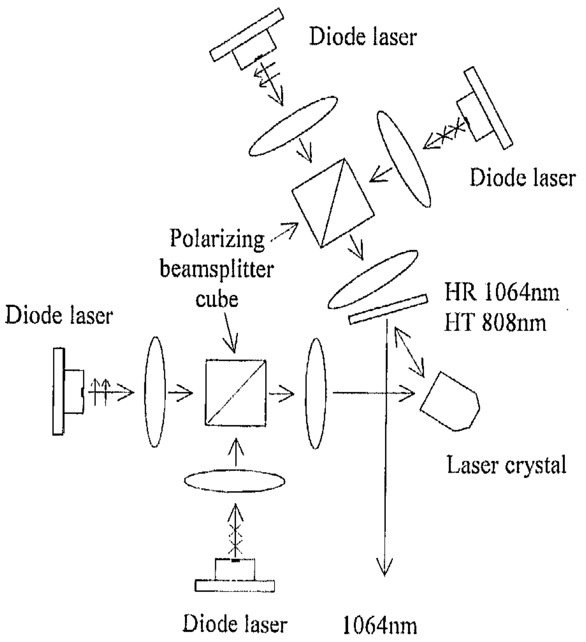

Fig. 2. Longitudinal pump scheme for miniature ring lasers applying 4 diode lasers with a nominal output power of 1 W cw each at 808 nm

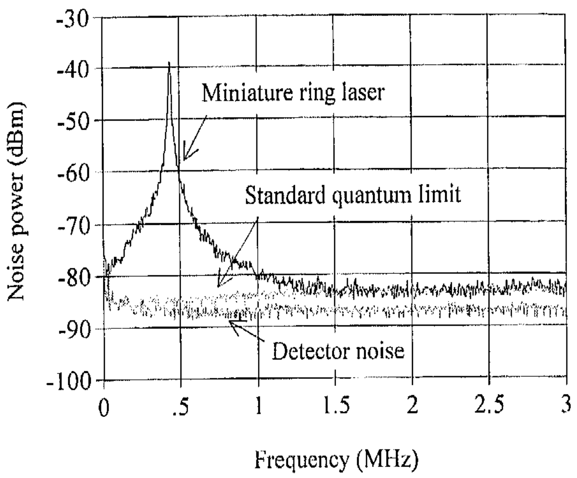

Fig. 3. Amplitude-noise power spectrum of a miniature Nd:YAG ring laser

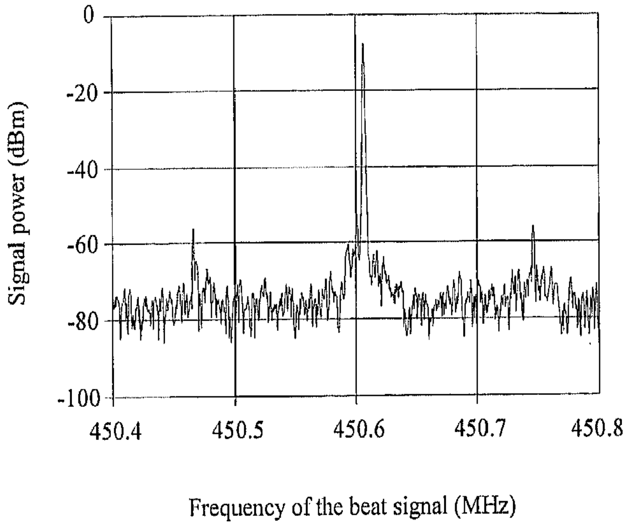

Fig. 4. Beat signal between two independently operating miniature ring lasers

To increase the frequency stability and reduce the spectral linewidth of the laser, the laser has to be locked to optical [19, 20] or atomic resonances [21], which requires a fast and precise frequency control. For monolithic ring laser systems the laser frequency can be tuned either by temperature, with a tuning coefficient of 3.1 GHz/K, or by stress-dependent changes of the index of refraction due to piezomechanical forces [22]. We realized typical tuning coefficients of a few MHz/V [6]. A reduction of the spectral linewidth to 330 and 200 mHz, respectively, has been observed by use of this frequency-tuning method [19, 23].

To further increase the stability, the modulation bandwidth and the gain of the feedback loop can be enlarged, which can be accomplished by the use of electrooptical modulators. Based on the monolithic non-planar ring laser design, several electroptically tunable ring lasers have been developed, which permit tuning via the longitudinal or transverse electrooptical effect [16]. In Fig. 5, the design of an electrooptically tunable quasi-monolithic miniature ring laser is shown, applying the transverse electrooptical effect. The center part of the Nd:YAG-laser material is replaced by a $3 \times 2 \times 8\,\mathrm{mm}^3$ $LiTaO_3$ crystal, which is applied because of its small birefringence compared to other modulator materials (1/20 of $LiNbO_3$).

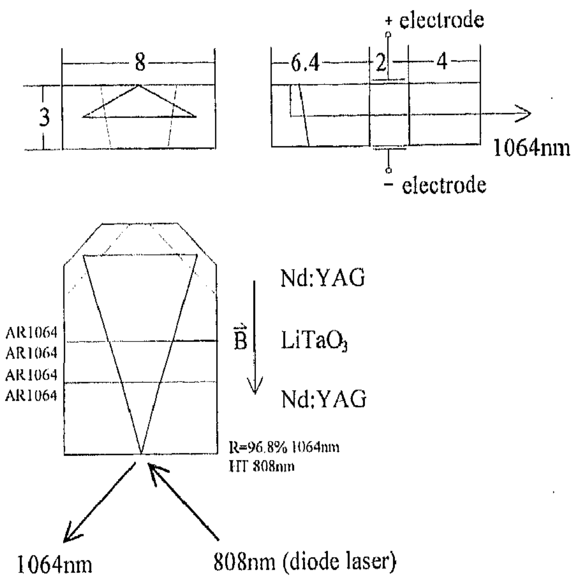

Fig. 5. Design of a electrooptically tunable ring laser using the transverse electrooptical effect

Due to the insertion of the modulator crystal, the optical beam passes eight surfaces during one round trip. To reduce the reflection losses, these surfaces are antireflection coated for the laser wavelength of 1064 nm (transmission per surface: $T > 99.8\%$). For pump powers of 2 W, output powers of 760 mW were measured. Electrodes are placed at the top and at the bottom surface of the ring laser in order to realize a homogeneous electrical field inside the modulator crystals. In laser operation, a tuning coefficient up to 1.1 MHz/V was determined. This value is similar to piezomechanical tuning, whereas the tuning range is greatly enhanced up to 1 GHz. To investigate the spectral properties and the noise behaviour of the tunable laser, the output was compared with an independently operating monolithic ring laser. In these experiments, no significant decrease of the laser stability was observed in comparison to the monolithic non-planar ring-laser system.

With its intrinsic amplitude and frequency stability at output powers in the range of 1 W in single-frequency operation, this laser represents an attractive, fast tunable master oscillator as the laser-light source of a Michelson-type gravitational-wave detector. Presently, investigations are in progress to increase the frequency stability of our laser system to the desired values by locking the laser to a high-finesse cavity and a $X \rightarrow B$ iodine-dimer transition.

2 Slave oscillator: Diode-laser side-pumped Nd:YAG ring laser

High output powers of diode-pumped solid-state lasers in cw and pulsed operation have been demonstrated in end-pumped and side-pumped configurations using rods and slabs as active media [24–30]. Power-scaling possibilities of end-pumped configurations are limited. At a pump-power level of approximately 400 W, the stress fracture of a Nd:YAG laser rod is reached [31]. Hence, the highest reported cw output power of an end-pumped laser with a single Nd:YAG rod so far is below 50 W [24]. Therefore, the transverse pump geometry has to be used for output powers beyond 100 W cw.

We developed and investigated cw diode-pumped Nd:YAG-rod lasers with output powers up to 200 W cw in multimode operation, which are optimized for operation at a high overall efficiency in a single transverse mode. The basic arrangement of the high-power Nd:YAG laser is shown in Fig. 6. A 110 mm laser rod (diameter: 4 mm; Nd-doping level: 1.1 at.%) with polished barrels is mounted inside a flowtube, which is antireflection coated at 808 nm, for direct laminar water cooling, in order to avoid additional technical noise due to the water cooling. 54 linear diode arrays (Jenoptik Laserdiode, OPUS 3237) with a nominal output power of 10 W each at 808 nm are arranged in a nine-fold symmetry around the laser rod. The optical emission of the diode lasers is temperature controlled within an accuracy of ± 0.1 °C to avoid fluctuations of the absorbed pump power, and tuned to the strongest absorption line of Nd:YAG. The total spectral envelope of the diode-laser output is approximately 2.2 nm. To increase the pump efficiency, reflector elements are used to reflect back the transmitted pump light into the laser crystal. By applying these reflector elements, the slope efficiency is increased by about 5% to a value of more than 35%. The calculated and measured pump-light distribution is shown in Fig. 7. In the center of the rod, the pump light of the diode lasers is superimposed, yielding a non-uniform inversion density. For a total pump power of 500 W cw, an output power of 175 W in multimode operation at a beam-parameter product of less than 15 mm · mrad is observed.

For the light source of the gravitational-wave detector a high-power laser in single-frequency operation is required. TEM_{00} operation of the high-power diode-pumped rod laser is necessary in order to apply this laser as a slave laser in an injection-locking setup. Theoretical and experimental investigations concerning the pump-light distribution and the resulting thermally-induced lens and non-spherical aberrations of the lens showed that the best laser performance with the considered pump geometry for single transverse-mode operation is given for pump powers of about 340 W. In order to optimize the TEM_{00} operation, a resonator has to be chosen which is stable against both focal-length fluctuations and misalignment. For high output powers, the design criteria for dynamically stable resonators, first reported by Magni [32], can be applied. In a linear cavity, which was insensitive against focal-length fluctuations of about ± 10%, a maximum output power of 33 W at a pump power of 340 W was measured for a laser rod of 4 mm diameter. Because of spatial hole burning, the laser oscillates in several longitudinal modes with large frequency fluctuations.

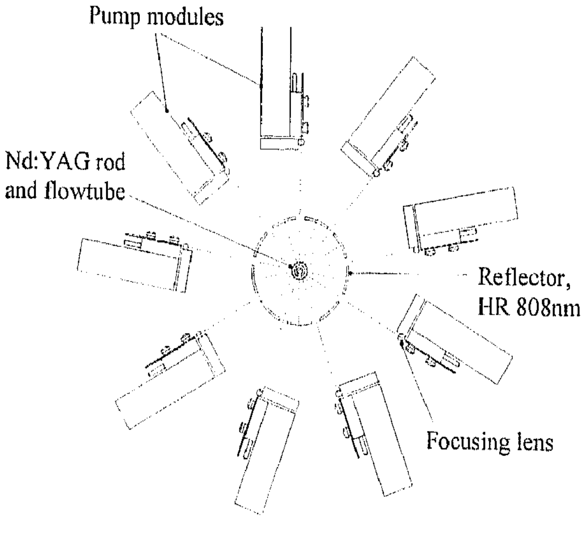

Fig. 6. High-power laser head, side-pumped by 54 diode lasers (9 pump modules with 6 diode lasers each)

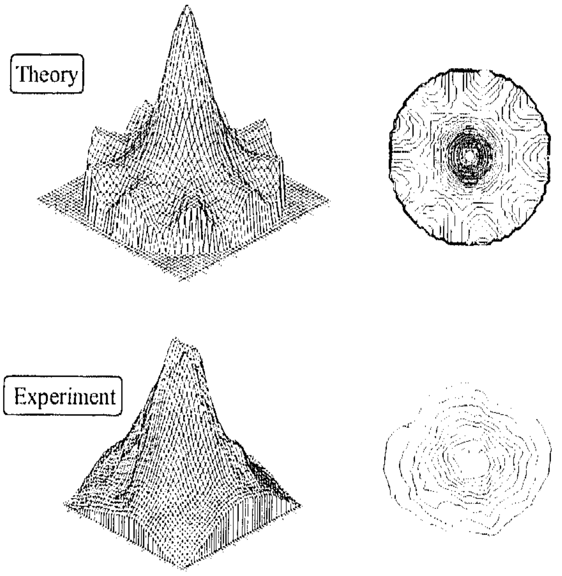

Fig. 7. Calculated and measured pump-light distribution of the diode-pumped rod laser excited by 9 pump modules

3 Injection locking of a diode-pumped high-power Nd:YAG laser

Injection locking of high-power lasers to an ultrastable single-frequency master oscillator can be applied to improve the mode structure and the noise behaviour at a high output-power level. The technique has been applied to several cw laser systems, including, e.g., ion lasers and dye lasers. For Nd:YAG lasers, injection locking has been demonstrated first for lamp-pumped systems [8–10]. Due to the low noise of diode lasers, it is desirable to use diode-laser-pumped Nd:YAG lasers for the frequency-stable master laser as well as for the high-power laser. The first realization of an injection-locked all-diode-laser-pumped Nd:YAG laser used a rod geometry and yielded an output power of 15 W [12]. In the following, an injection-locked diode-pumped slab laser was described with an output power of 5.5 W [13]. This laser was equipped with fiber-coupled laser-diode pump sources, which offer great flexibility of the laser-head design and enhance the reliability of the system.

To injection lock the diode-pumped high-power laser system to a miniature ring laser, a dynamically stable ring

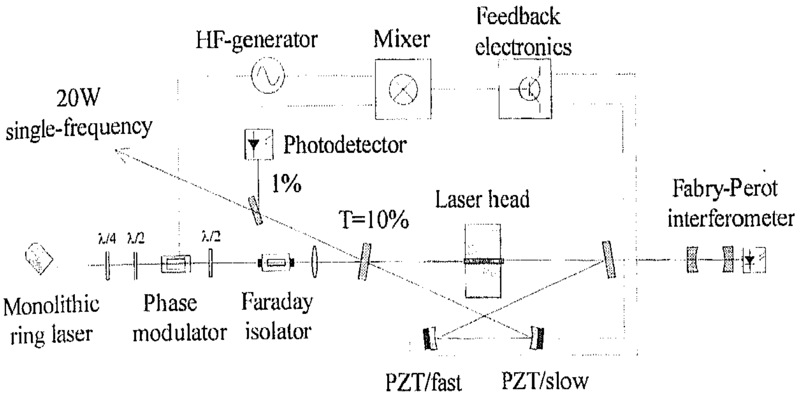

Fig. 8. Schematic of the injection-locking setup consisting of a diode-pumped miniature ring laser (master oscillator) and a high-power diode-pumped rod laser (slave oscillator)

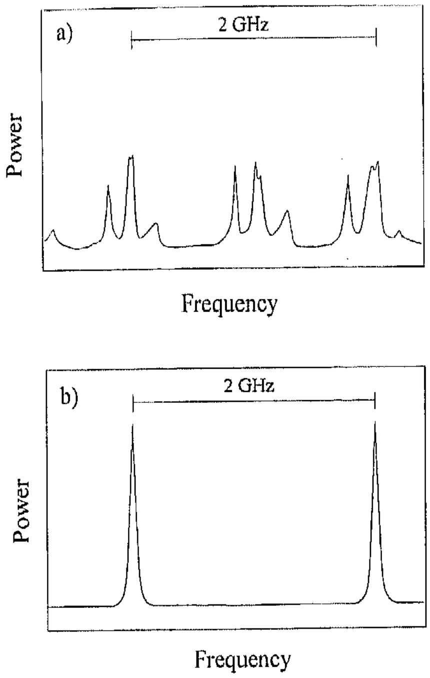

Fig. 9a, b. Mode spectra of the high-power diode-pumped Nd:YAG ring laser: (**a**) under free-running conditions , (**b**) under injection locking

cavity is used. Therefore, in the case of unidirectional oscillation, the feedback to the master laser is eliminated, and spatial hole burning is avoided. Under free-running conditions, the ring laser oscillates in both the forward and backward direction with multiaxial-mode output. The single transverse-mode output is about 12 W in both directions. The output of the master laser is coupled into the ring cavity of the high-power laser (Fig. 8), and the transverse modes of both lasers are matched by an optical system.

To realize the injection locking, the locking range has to be taken into account. It depends on the free spectral range of the slave-laser cavity and the square root of the master to slave laser output-power ratio [7]. Injection locking is observed when the difference between the frequencies of the master oscillator and the slave oscillator is within the locking range. With the parameter of the above-described lasers, a locking range of 1 MHz is predicted. Because of the large thermal drift and acoustical fluctuations of the high-power laser cavity, a stabilization of the slave-laser frequency to the master-laser frequency is necessary. The frequency stabilization is accomplished by the Pound-Drever sideband technique [33], which produces a dispersive-signed error signal. A feedback loop controls the cavity length with piezoelectric transducers. A slow piezoelectric transducer with a large dynamic range compensates for thermal drift, while a fast piezoelectric transducer eliminates the high-frequency fluctuations.

The mode structure of the high-power laser was observed with a Fabry-Perot analyzer. Without injection locking, the high-power laser oscillates in both directions with several longitudinal modes, but under injection locking, unidirectional single-frequency operation is observed (Fig. 9). Output powers up to 20 W are detected. A measurement of the amplitude-noise power spectrum shows that the injection-locked diode-pumped high-power laser is quantum-noise limited above 2 MHz. Below 1 MHz, the amplitude noise is dominated by the relaxation oscillation of the master laser. This problem can be solved by an active feedback loop, as mentioned above. Evaluating the beat signal of the superimposed outputs of the injection-locked rod laser and an independently working monolithic ring laser yields a spectral linewidth of less than 10 kHz/100 ms [34].

4 Conclusion

We have reported on high-power single-frequency operation of an all-diode-pumped Nd:YAG-laser system. The output power of a frequency-stable diode-laser-pumped monolithic Nd:YAG ring laser has been amplified in a high-power diode-laser side-pumped Nd:YAG-rod laser conserving the stability and spectral properties of the master laser. A maximum single frequency output power of 20 W cw was obtained, quantum-noise limited above 2 MHz. Power scaling can be achieved by applying a two-laser-head configuration and by reducing the thermally-induced effects inside the active-medium. These diode-pumped high-power single-frequency Nd:YAG lasers will satisfy the requirements for the laser-light source of the planned gravitational-wave detector.

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