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Investigation on Amplitude and Frequency Noise of Injection-Locked Diode-Pumped Nd:YAG Lasers

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Abstract. Amplitude and frequency stability of an injection-locked diode-pumped miniature Nd:YAG ring laser were measured. The mechanism of amplitude-noise transfer to the injection-locked slave laser was experimentally investigated and consequences for the injection locking of solid-state lasers operating at high output powers are discussed.

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Diode-pumped miniature ring lasers [1-4] have well been known as reliable sources of stable single-frequency radiation. Due to their low amplitude noise and high inherent frequency stability they are well suited for interferometer-based metrology. Especially high resolution is required for the detection of gravitational waves using Michelson-type interferometers [5]. The laser light source of the projected gravitational-wave interferometers must ensure single-frequency operation with high amplitude and frequency stability to accomplish the desired strain sensitivity of 10^{-21}. In order to achieve large signal-to-noise ratios, the laser has to work at high power levels in Continuous-Wave (CW) operation ($P \simeq 100$ W). A diode-pumped miniature ring laser can fulfill the requirements concerning amplitude and frequency stability. The direct use of this device in an interferometer for gravitational-wave detection is not possible since the output power is limited to values below 3 W in a single axial mode [6]. On the other hand, high-power lasers, in general, show poor stability. To arrive at the combination of high power and high stability, a high-power laser can be injection-locked to a miniature ring laser.

In the conventional use of the injection-locking technique [7], it is applied to improve mode structure and noise behaviour of a high-power laser by injecting the light of a low-power single-frequency laser with excellent stability. Applications of this technique to solid-state lasers have been demonstrated for several lamp-pumped [8-10] and diode-pumped [11, 12] Nd: YAG lasers. The highest single-frequency output power reported so far for an all-diode-pumped Nd:YAG laser system is 18 W [13]. The low noise due to diode-pumping leads to an improved amplitude stability in comparison to lamp-pumped high-power lasers. In order to guarantee excellent amplitude stability of the master/slave configuration, it is necessary to have a full understanding of possible amplitude-noise sources and of the mechanism of noise transfer to the injection-locked slave laser. Corresponding investigations have not yet been reported.

High-power solid-state lasers show large frequency fluctuation due to acoustical vibration and thermal drift and, hence, require an active frequency stabilization to accomplish injection locking. For this reason, analysis of noise transfer mechanisms is difficult because the electronic feedback loop might affect the amplitude stability of the slave laser. Therefore, we decided to investigate the amplitude-noise characteristics of an injection-locked slave laser by using a master/slave configuration with two miniature Nd:YAG ring lasers [6], which had been reported previously by Chen and Kane, to demonstrate the power scaling possibility of these devices [14]. Due to the high intrinsic frequency stability of monolithic ring lasers, injection locking can be accomplished for hours without electronic stabilization, allowing measurements of amplitude-noise transfer to the injection-locked slave laser with no interference of an electronic feedback loop. With the results obtained for the injection-locked miniature ring laser, possible amplitude-noise sources of an injection-locked slave laser are available, and consequences for locking of high-power lasers can be derived.

1. Diode-Pumped Miniature Nd:YAG Ring Lasers

The monolithic non-planar miniature ring laser first reported by Kane and Byer [1] is well known as a reliable source of stable radiation. An intrinsic optical diode enforces unidirection and, hence, single-frequency oscillation of this device. The monolithic resonator and the low noise due to diode-pumping result in a high intrinsic amplitude and frequency stability. Furthermore, high output powers and slope efficiencies are obtainable. So far a maximum single-frequency output power of 1.8 W CW with a slope efficiency of 60% were reported for diode-pumped monolithic Nd:YAG ring lasers [6].

The design of our miniature Nd:YAG ring lasers used in these injection-locking experiments has dimensions of 3x8x12 mm^3 [4]. The laser radiation is reflected at the center of the front surface at the two tilted side surfaces, and at the top surface. The plane front surface is coated with a dielectric mirror of T = 3.2% transmission for the 1064 nm laser radiation and high transmission for the pump radiation at 808 nm. The total optical path length L_{opt} = 51.8 mm for one cavity round trip corresponds to a Free Spectral Range (FSR) of 5.8 GHz and a cavity decay time of $\tau_c = L_{opt}/c(T+L)$ = 3.6 ns, assuming internal round-trip losses of L = 1.6%. Transverse-mode stability of the resonator is provided by thermal-induced lensing inside the Nd:YAG crystal due to the absorption of the diode-laser radiation. The laser crystal is equipped with a thermoelectric cooler for active temperature stabilization to ensure minimum thermal drifts. This temperature controlling unit can be applied to tune the laser frequency at a rate of 3.1 GHz/K. Fine tuning at a rate of 2 MHz/V is accomplished by additional piezomechanical tuning [4].

The miniature ring laser is end-pumped by 1 W CW diode lasers (Siemens, SFH 487401). These diode lasers (emitting aperture 1x200μm^2) are equipped with a miniature cylindrical lens inside the housing in order to compensate the astigmatism of the diode-laser radiation. Hence, only spherical lenses are necessary for coupling the pump light into the laser crystal, which results in a very simple pump scheme. To increase the pump power, the radiation of two diode lasers is spatially overlapped in the laser crystal by a polarizing beam-splitter cube (Fig.2). The temperature of both diode lasers is controlled by a thermoelectric cooler to time the emission wavelength to the strongest absorption line in Nd:YAG at 808 nm. All optics are antireflection coated for this wavelength. At the maximum pump power behind the coupling optics of 2 W CW, a single-frequency output power of more than 1.1 W CW with a slope efficiency of 60% is obtained.

The amplitude noise power spectrum of the miniature ring laser is detected with an InGaAs photodiode (PD 7006) supplied by a low-noise voltage source. The power of the optical signal illuminating the photodiode is converted to a current, which is proportional to the optical power. The electrical signal from the photodiode is amplified by a 60 dB low-noise amplifier (Miteq AU-1291) and measured with an electronic spectrum analyzer (Tektronix 2756P). Hence, the electrical power detected by the spectrum analyzer is proportional to the square of the optical power at the photodiode. For example, a factor 2 increase of optical power fluctuations will increase the detected electrical signal by about 6 dB.

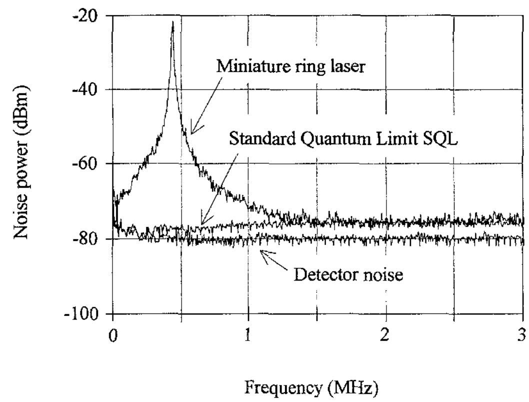

Fig.1. Amplitude-noise power spectrum of a miniature Nd:YAG ring laser

All measurements of amplitude noise in this work have been carried out with the same optical power of 500 μW on the photodetector. For rating these noise spectra, the amplitude-noise power of a white-light source with the same power at the photodiode (standard quantum limit) and the electronic noise from the detection system itself is shown in Fig.1. The amplitude noise of the miniature ring laser operating at an output power of 500 mW CW shown in the same graph is rather low, and reaches the quantum-noise limit at frequencies above a few MHz. At lower frequencies, the noise spectrum is dominated by the relaxation oscillations which are a consequence of the coupling between the laser cavity field and the atomic inversion. Because of the dynamics, even small disturbances in pump power or laser operation conditions can be strongly amplified by the active medium, resulting in a large peak in the noise spectrum, typically 40÷60 dB above the quantum-noise level (Sect.3.2). The relaxation oscillation frequency is given by [7]

$$\nu_{rel} = \frac{1}{2\pi}\sqrt{\frac{r-1}{\tau_f - \tau_c}} \, . \tag{1}$$

The pump rate is the ratio of pump power P to pump power at laser threshold P_{thres}, τ_f is the fluorescence lifetime of the upper laser level, and r_c the cavity decay time. For the miniature Nd:YAG ring laser described above, the time constants are τ_f = 230 μs and τ_c = 3.6 ns. At an output power of 500 mW CW, the pump rate is approximately r = 6.3, corresponding to a relaxation oscillation frequency of 405 kHz. This value is in reasonable agreement with the measured value of 430 kHz.

Single-frequency operation of the miniature Nd:YAG ring laser can easily be detected with a Fabry-Perot interferometer. In order to investigate the spectral properties of the ring laser in more detail, a beat experiment between similar systems can be carried out. Due to the monolithic structure of the resonator and the low technical noise due to diode-pumping, a beat signal of typically a few kHz linewidth is detected [15, 16]. The thermally induced drift of the laser frequency is less than 1 MHz/min [16]. Because of this high-frequency stability, the miniature ring laser is perfectly suited for studies of amplitude and frequency stability of an injection-locked solid-state slave laser.

2. Injection Locking of Miniature Nd:YAG Ring Lasers

The experimental arrangement for the injection-locking experiments is shown in Fig.2. The radiation of the master laser is carefully matched to the transverse mode of the slave laser. Due to the unidirectional oscillation of both lasers, no optical feedback from the slave laser to the master laser occurs. Master and slave lasers are equipped with two diode lasers each, but the diode lasers were driven below their maximum operation currents. For these operation conditions, the output power of the master laser is P_m = 580 mW CW, while the output power of the slave laser is P_s = 670 mW CW.

Without injection locking the front facet of the slave laser acts as a geometrical beam combiner. The non-resonant radiation of the master laser, nearly totally reflected at the slave mirror, is spatially overlapped with the slave-laser radiation. Hence, the combined radiation of both lasers yields a power of 1250 mW CW. The amplitude-noise power spectrum from this master/slave configuration is detected with the detection system described above. The mode spectrum of the radiation is simultaneously analyzed by a Fabry-Perot interferometer with 2 GHz FSR and a finesse of 300. The combined beam includes the frequencies of both free-running lasers (Fig.3a). In the amplitude noise of the combined radiation relaxation oscillations of both lasers occur (Fig.4a).

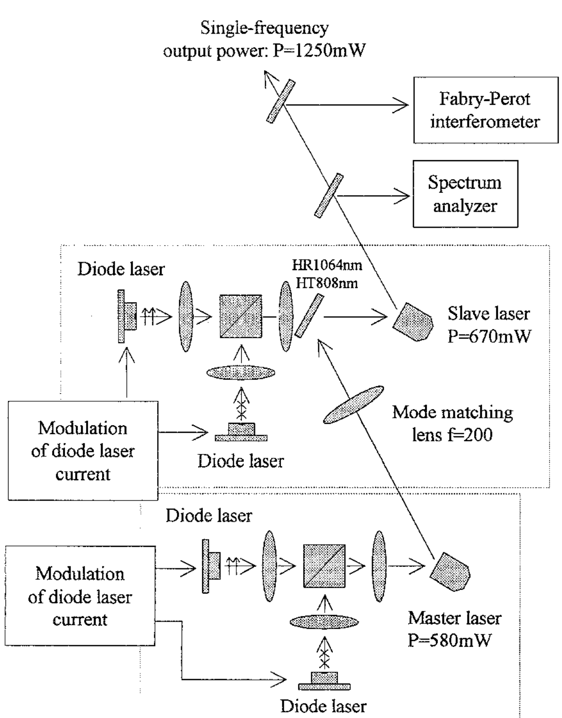

Fig.2. Experimental setup of the master/slave configuration to determine the amplitude-noise transfer

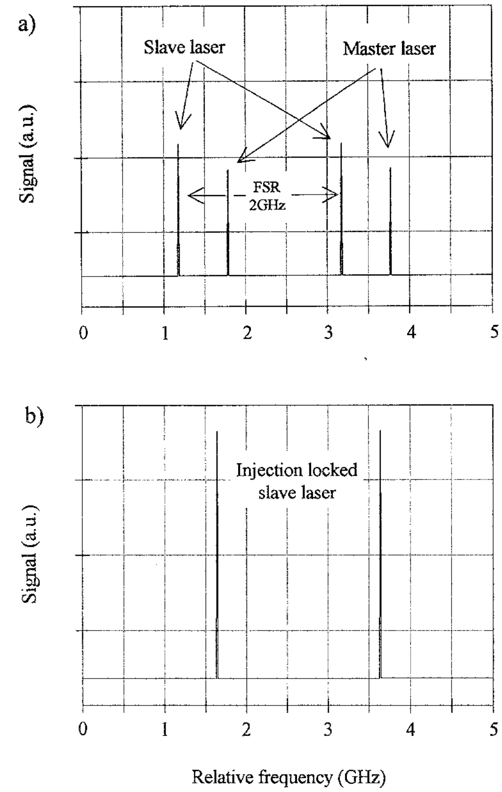

Fig.3. Mode spectra of the master/slave configuration. (a) Free-running slave laser; (b) injection-locked slave laser

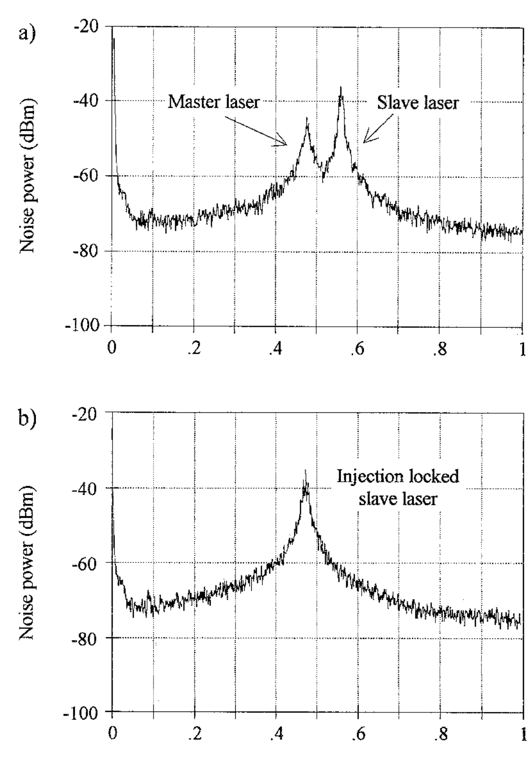

Fig.4. Amplitude-noise power spectra of the master/slave configuration: (a) Free-running slave laser and (b) injection-locked slave laser

The relaxation oscillation frequency of the master laser is 475 kHz, whereas the slave-laser frequency of 570 kHz is higher, due to a higher transmission T = 10.0% of its output-coupling mirror (see below). At frequencies beyond a few MHz the amplitude noise corresponds to the quantum-noise limit of a white-light source with an output power of the sum of master and slave laser.

With the frequency-timing elements of the miniature ring laser described above, the injection-locking condition can be satisfied. In order to realize injection locking, the locking range has to be taken into account. The locking range depends on the FSR = c/L_{opt} of the slave laser, on the transmission T of its output-coupling mirror and on the square-root of the master-to-slave output power ratio $(P_m/P_s)^{1/2}$:

$$\Delta\nu_{lock} \simeq \frac{FSR \cdot T}{\pi} \sqrt{\frac{P_m}{P_s}} \,. \tag{2}$$

Our coating, optimized for maximum output power, has a transmission of T = 3.2% for the 1064 nm laser radiation. To enlarge the locking range, the transmission of the output-coupling mirror of the slave laser was increased, compared to our standard dielectric coating, to a value of T = 10.0%. With this value, and for similar output powers of master and slave laser, a locking range of approximately 200 MHz is predicted. Therefore, by applying temperature-controlling units to the laser crystal, injection locking can be accomplished over hours without electronic stabilization.

Under injection locking, the frequency of the master radiation is resonant with the slave laser, and the slave-laser mode is suppressed. The output power of the master/slave configuration is not changed but, as predicted by theory, the spectrum of the output signal now contains only a single line (Fig.3b), with the frequency determined by the master laser. The linewidth of the injection-locked slave laser was measured by a beat experiment with an independently operating free-running miniature Nd:YAG ring laser. The linewidth of the beat signal is in the range of a few kHz, similar to results obtained for free-running miniature ring lasers. Hence, within the accuracy of this beat signal measurement, no increase of the linewidth due to the injection locking can be detected. In the amplitude-noise power spectrum, the relaxation oscillation of the slave laser at 570 kHz disappears (Fig.4b), while the amplitude noise at the relaxation oscillation of the master laser is amplified in the injection-locked slave laser. The amplitude noise at frequencies beyond a few MHz is not changed by injection locking, and corresponds to the quantum-noise limit of a white-light source at the same output power level.

These preliminary results might suggest that all technical amplitude noise from the free-running slave laser is suppressed by injection locking. But it is obvious that there has to be a contribution from noise at low frequencies, because, for example, low-frequency changes in the pump rate will influence the stimulated emission inside the slave-laser cavity.

3. Amplitude-Noise Transfer to the Injection-Locked Slave Laser

There are two fundamental sources of amplitude noise in the output signal of the injection-locked slave lasers. The first source is power fluctuation in the injected signal, the second source is fluctuations in the excitation of the slave laser. The results described in the previous section illustrate that the contributions of these sources are changed under injection locking. In order to determine possible amplitude-noise sources of the slave laser, a detailed experimental investigation of the noise transfer is required. This is accomplished by introducing an additional amplitude modulation in the radiation of the master laser (Sect.3.1) and the slave laser (Sect.3.2) and comparison of the amplitude-noise spectra of the master/slave configuration for the free-running and the injection-locked slave laser.

3.1 Noise Transfer from Power Fluctuations in the Injected Signal

The amplitude-noise transfer of power fluctuations in the injected signal to the output of the injection-locked slave laser was measured by introducing a pump-power modulation of the master laser, which generates an amplitude modulation of the master-laser radiation. For instance, current modulations were applied to both diode lasers at different frequencies (for example: 100 kHz and 900 kHz), with modulation amplitudes that give the same peak of 50 dBm in the amplitude-noise power

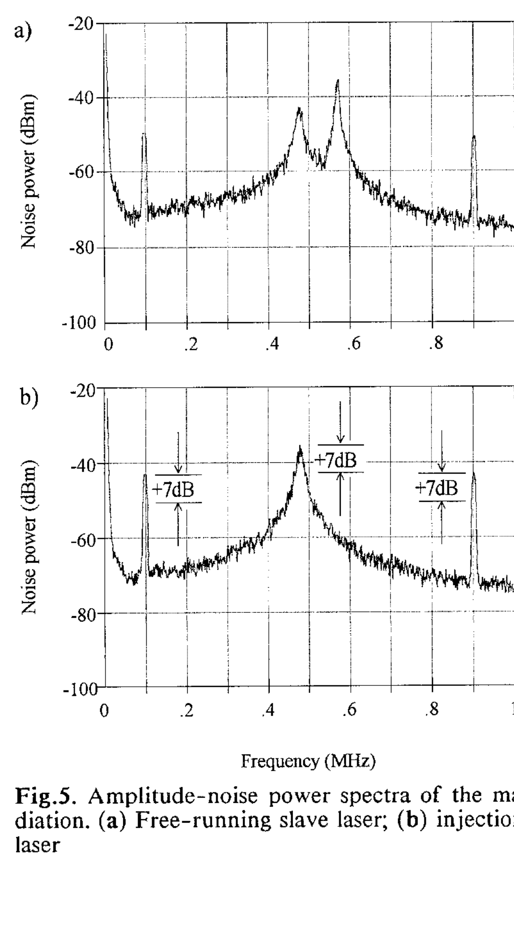

Fig.5. Amplitude-noise power spectra of the master/slave radiation. (a) Free-running slave laser; (b) injection-locked slave laser

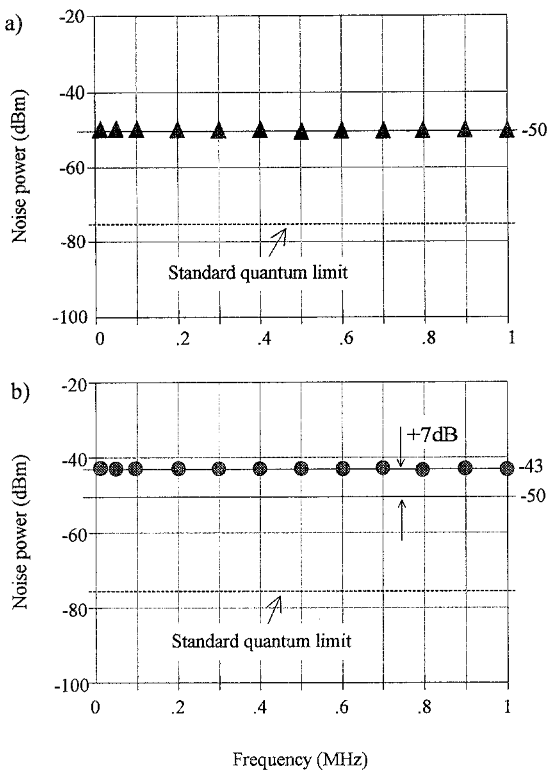

Fig.6. Frequency response of the master/slave configuration to a constant power modulation of the injected signal. (**a**) Free-running slave laser; (**b**) injection-locked slave laser

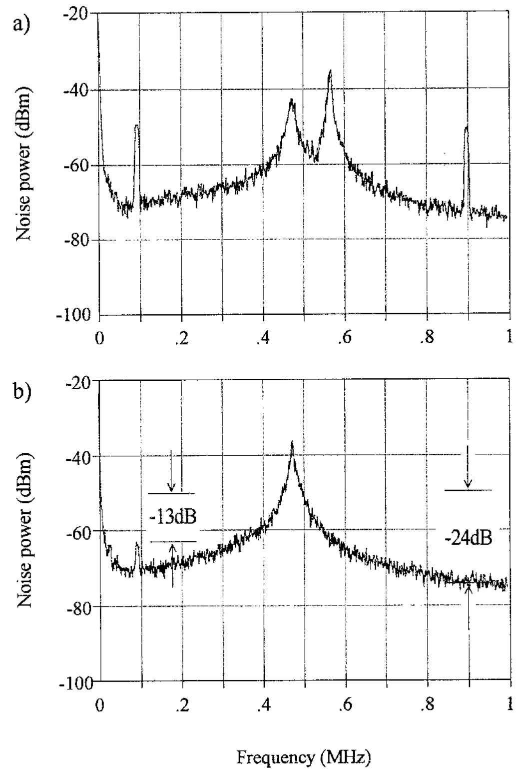

Fig.7. Amplitude-noise power spectra of the master/slave configuration with additional amplitude modulations introduced in the slave-laser radiation. (**a**) Free-running slave laser and (**b**) injection-locked slave laser

spectrum of the master/slave configuration when injection locking is not accomplished (Fig.5a). The amplitude-noise power spectrum now contains three peaks corresponding to amplitude modulations of the master laser, including its relaxation oscillations.

Under injection locking, these three peaks are amplified by the same value (Fig.5b). As the electronic signal measured by the spectrum analyzer is proportional to the square of the optical power at the photodiode, the detected increase of 7 dB corresponds to an amplification of the optical power modulation of 2.2. This is exactly the power ratio of the injection-locked slave laser to the injected signal. The same measurement was repeated for other frequencies between 10 kHz and 1 MHz. Figure 6 shows the frequency response of the master/slave configuration to power modulations of the signal injected from the master laser. The additional noise power of the introduced amplitude modulation was determined by measuring traces as in Fig.5b, and subtracting the trace without additional amplitude modulation. No dependence of the amplitude modulation upon the power modulation frequency of the injected singal is observed (Fig.6b). Even at the relaxation oscillation frequency of the slave laser, no resonant enhancement occurs.

To conclude, the injection-locked slave laser acts similarly to a conventional optical amplifier with no inherent dynamics at the relaxation oscillation of the free-running system. All technical noise from the master laser is amplified in the radiation of the injection-locked slave laser. The amplification is given by the power ratio of the injection-locked slave laser to the injected signal.

3.2 Noise Transfer from Pump-Power Fluctuations of the Slave Laser

The noise transfer from pump-power fluctuations in the slave laser to the output of the injection-locked system was measured by a current modulation of both diode lasers of the slave. In a first experiment, the modulation amplitudes at 100 kHz and 900 kHz were chosen to give a peak of 50 dBm in the amplitude-noise power spectrum of the master/slave configuration for the free-running slave laser (Fig.7a). In this case, a strong suppression of the amplitude modulations is observed under injection locking (Fig.7b). The peaks at 100 kHz and 900 kHz are decreased by 13 dB and more than 24 dB down to the quantum-noise limit, respectively, hence indicating a frequency dependent response of the master/slave configuration to pump-power fluctuations of the slave laser.

A measurement of the amplitude-noise transfer for constant power modulations in the output of the free-running slave laser, similar to that described for the master laser, is of minor use. Due to the coupling between atomic inversion and laser cavity field, the slave laser is very sensitive to pump-power fluctuations at the relaxation oscillation frequency. Hence, for this frequency only a very small modulation of the pump power is required to achieve a noise peak of 50 dBm in the

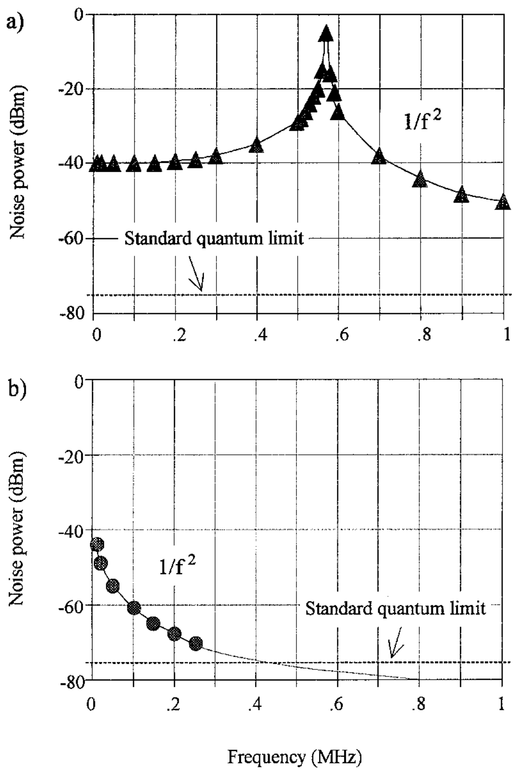

Fig.8. Frequency response of the master/slave configuration to a constant modulation of the slave-laser pump power. (**a**) Free-running slave laser and (**b**) injection-locked slave laser

output of the Nd:YAG laser, making the physical interpretation of the noise transfer difficult.

A more instinctive result to understand the physical behaviour of the slave laser is the transfer from constant modulations of its pump power to the radiation of the master/slave configuration for the free-running and the injection-locked slave laser. To measure this noise transfer, the pump-power modulations of the slave laser are measured with a second detection system. The diode-laser current modulation is chosen to give a constant pump-power modulation for all applied frequencies. Figure 8 displays the frequency response of the master/slave configuration to these pump-power modulations. As for Fig.6, the additional noise power of the introduced amplitude modulation was determined by measuring traces with additional amplitude modulation, and subtracting the trace without this modulation.

Without injection locking, there is a resonant enhancement of the frequency response of the master/slave configuration due to the relaxation oscillation of the free-running slave laser at 570 kHz (Fig.8a). The relaxation oscillation has the dynamics of a high-quality oscillator with the noise power decaying as $1/f^2$ for frequencies beyond resonance. For frequencies well below resonance, the noise power of the peak is constant.

Under injection locking, the physical behaviour of the slave laser is completely changed (Fig.8b). No resonant enhancement at the relaxation oscillation frequency at 570 kHz is observed. Modulations of the slave-laser pump power are strongly damped in the signal of the injection-locked slave laser. The damping increases with higher frequencies, due to the time constant of the active medium. The time constant responsible for the damping effect is the fluorescence lifetime of the upper laser level, which is 230 μs for Nd:YAG. The theoretically expected $1/f^2$ noise-power reduction for frequencies beyond a few kHz is in good agreement with the experimental data. For frequencies above 250 kHz, the amplitude modulation is already reduced to a value below the amplitude noise of the undisturbed master/slave configuration, and cannot be detected within the accuracy of this measurement.

The free-running slave-laser dynamics at the relaxation oscillation are caused by the coupling between the slave-laser cavity field and its atomic inversion. Hence, a suppression of the slave-laser mode leads to the depletion of this coupling and, therefore, to a suppression of the relaxation oscillations. The suppression of the slave-laser mode does not occur instantaneously, but depends on the power of the master-laser mode inside the slave-laser cavity. Therefore, while tuning the master-laser frequency to the slave-laser resonance, the slave-laser mode and its relaxation oscillation does not vanish at once, but are slowly decreased. In addition, a shift of the relaxation oscillation frequency to lower frequencies is observed, indicating the slave-laser mode reduction. With the injected signal on the slave-laser resonance, the slave-laser mode is completely suppressed and the injection-locked slave laser acts similarly to a conventional optical amplifier, with no inherent dynamics due to the relaxation oscillation.

4. Consequences for the Injection Locking of High-Power Solid-State Lasers

With the results obtained above for the miniature ring laser, some consequences for the injection locking of high-power solid-state lasers are obvious. In the conventional use of the injection-locking technique, the power ratio of slave laser to master laser is in the range of several tens or even higher. Any noise existing in the radiation of the master laser is amplified by this ratio and leads to a substantial contribution to the amplitude-noise spectrum of the injection-locked slave laser. Therefore, it is important to reduce the amplitude noise of the master laser to the lowest possible level over the entire frequency domain.

For a high-power Nd:YAG slave laser, pump-noise sources in the frequency region beyond a few 100 kHz are of minor interest as they are strongly damped under injection locking. However, at lower frequencies, noise sources have to be carefully considered. Especially in the frequency range between 100 kHz and 10 kHz, interesting for the detection of gravitational waves, pump-power fluctuations of the high-power laser are efficiently coupled to the radiation of the injection-locked slave laser. The use of diode lasers for the excitation of master and slave laser is therefore indispensable because of the more than three orders of magnitude lower amplitude noise of diode lasers compared to the conventionally used flashlamps.

5. Conclusion

Amplitude and frequency stability of an injection-locked diode-pumped miniature Nd:YAG ring laser at a power level of more than 1 W CW have been investigated, and the amplitude-noise transfer to the injection-locked slave laser determined. As a consequence of the injection locking, the slave laser acts similarly to a conventional optical amplifier, with no inherent dynamics at the relaxtion oscillation frequency of the free-running system. All technical noise from the master laser is amplified in the radiation of the injection-locked slave laser. The amplification is given by the power ratio of the injection-locked slave laser to the injected signal. Effects of pump-power fluctuations of the slave laser are strongly damped with increasing frequencies compared to the free-running system. The time constant responsible for the damping effect is the fluorescence lifetime of the upper laser level, which is 230 μs for Nd:YAG. A theoretical laser model describing the amplitude-noise transfer is currently under investigation [17]. First predictions from this model are in good agreement with the experimental results discussed.

For the reasons described in Sect.4, we have developed several diode-pumped high-power Nd:YAG lasers [11, 13, 18] to achieve high single-frequency output powers with extremely high amplitude and frequency stability. By injection locking, a diode-pumped Nd:YAG rod laser to a miniature Nd:YAG ring laser, a single-frequency output power of 18 W CW has already been achieved [13]. In agreement with the discussion above, the amplitude-noise power spectrum of the injection-locked slave laser is dominated by the relaxation oscillation of the miniature ring laser. A substantial suppression of the noise of a diode-pumped miniature ring laser caused by the relaxation oscillation has already been demonstrated [16, 19]. By active control of the diode-laser current with an electronic feedback loop, the amplitude noise has been suppressed close to the quantum-noise limit over the entire frequency domain. Hence, a laser light source with a single-frequency output power of several tens of watts and an amplitude noise close to the quantum-noise limit seems to be possible in the near future.

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