Low-amplitude-noise laser for AURIGA detector optical readout

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We implemented a laser system to be used in an optical transduction chain for the gravitational-wave bar detector AURIGA (Antenna Ultracriogenica Risonante per l'Indagine Gravitazionale Astronomica; Ultracryogenic Resonant Antenna for Astronomical Gravitational Investigation). This system is based on a Nd:YAG laser and includes quantum-limited power stabilization in the acoustic range, deep phase modulation and near-quantum-limited rf detection for locking onto optical cavities, and coupling to a single-mode polarization-maintaining optical fiber without deterioration of performance. Such a system has wide applications in optical metrology. © 2000 Optical Society of America

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1. Introduction

Ultracryogenic resonant detectors of gravitational waves have reached a high peak spectral sensitivity, thanks to the extremely low level of thermal noise.[1] For further increasing the burst sensitivity and fully exploiting the detector capabilities an improved transduction chain must be implemented for translating the weak bar excitation into a readable signal with the smallest added wideband noise.

In the past an optical signal extraction chain was proposed by Richard[2,3] and partially implemented by Pang and Richard.[4] The basic idea is to build an optical Fabry–Perot cavity formed by a mirror attached to the bar end face and a second mirror attached to a resonant mechanical transducer (in our case, a central load on a circular elastic plate). The relative motion of the two mirrors is then converted into a frequency shift of the cavity optical resonance frequency.

In the past few years significant technical improvements have greatly extended the possibilities of frequency references based on stable optical cavities. For example, Seel *et al*. demonstrated the higher level of stability for the integration period between 1 and 100 s.[5]

In the framework of the AURIGA (Antenna Ultracriogenica Risonante per l'Indagine Gravitazionale Astronomica; Ultracryogenic Resonant Antenna for Astronomical Gravitational Investigation) collaboration[6] we are developing a fully optical readout for an ultracryogenic resonant bar detector. The AURIGA detector is based on a 3-m-long, 0.6-m-diameter cylinder, with a mass of 2300 Kg, made with Al5056, an alloy that permits obtaining a high-mechanical-quality factor Q at low temperatures. The bar is cooled to ~0.1 K, where it is characterized by a vibration frequency (first longitudinal mode) of 920 Hz with a Q of several million. The scheme of our transduction chain is based on the use of two Fabry–Perot cavities, which we call transducer and reference cavities.[7] The former is installed on a bar end face, and its entrance mirror is mounted on a second mechanical resonator with a mass of ~10 Kg. The latter is kept in an acoustically isolated and thermally stabilized (in the range 20–100 °C) environment, and, by means of changing the temperature, it can be tuned with respect to the trasducer cavity. A Nd:YAG laser is frequency locked to the transducer cavity by means of a FM sidebands technique,[8,9] and its frequency fluctuations are monitored by use of the same technique with the reference cavity. A single-mode polarization-

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maintaining optical fiber is used to carry the laser radiation into the bar vacuum chamber. The beam reflected by the transducer cavity, after an optical circulator, is collected by a second fiber and detected outside the bar chamber.

An efficient implementation of the transduction chain requires a laser system with some special characteristics. In this study we present and discuss the implementation of such a system. In particular, a high-laser-intensity stability is necessary in the kilohertz region, and the phase-sensitive detection must be performed with the highest obtainable sensitivity, i.e., with optimal phase-modulation depth and shot-noise-limited detection. Moreover, these characteristics must be conserved after the optical fiber transmission.

Even if our system is particularly designed for use in the optical transduction chain, the results we obtained are of more general interest and can be easily extended to satisfy the requirements of other metrological laser systems.

2. System Requirements

The transduction chain includes a 1-cm-long transducer cavity, with finesse 3×10^5, corresponding to the best commercially available mirror quality. With a detected power of 1 mW and an optimal phase-modulation depth ($\sim$1 rad) a shot-noise-limited detection yields a residual frequency noise of the laser locked to the cavity (with respect to the cavity itself) of 2×10^{-4} Hz/$\sqrt{\text{Hz}}$.

We use the expression *detected power* for the power impinging on the detector times the detector quantum efficiency: the detector is modeled as a beam splitter with transmission equal to the quantum efficiency, followed by a perfect detector.

When we consider the losses in the coupling of the radiation reflected by the transducer cavity into the output fiber (expected to be $\sim$20%) and the detector quantum efficiency, a laser power of $\sim$2 mW or less must be coupled to the transducer cavity. With these figures and mirror losses (absorption and scattering) of 1 part in 10^6, the laser power dissipated by the cavity is expected to be few hundreds of microwatts, which is still lower than the AURIGA refrigerator cooling power ($\sim$1.4 mW at 0.1 K). A higher power level would improve the sensitivity, but it can hardly be tolerated by the ultracryogenic cooling system.

We will operate two independent reference cavities simultaneously to reduce the possibility of spurious events. The reference cavities' detection system should allow for a sensitivity that is better than that of the transducer cavity, to maintain the above-calculated performance. Such a result will be obtained with 20-cm-long cavities with finesse near 4×10^4 and a detected power of 10 mW.

The frequency of the FM sidebands must be large enough to operate in the spectral region where the laser amplitude noise is nearly shot-noise limited. However, the need to detect a power of at least 10 mW implies the use of relatively large photodiodes, thus limiting the detection bandwidth. As a compromise, the modulation frequency is chosen between 10 and 15 MHz. The FM and the detection are discussed in detail in Section 4.

Table 1. Parameters Used for the Reported Calculations

Parameter	Value
Reference cavity finesse	4×10^4
Transducer cavity finesse	3×10^5
Transducer cavity input mirror transmission	10 parts in 10^6
Phase-modulation depth	1 rad
Laser power impinging on the transducer	2 mW
Detected power for the transducer cavity photodiode	1 mW
Detected power for the reference cavity photodiode	10 mW
Transducer thermal noise	10^{-26} N^2/Hz

A further parameter to be considered is the laser amplitude noise spectrum near 1 kHz. The fluctuations of the laser intensity in the transducer cavity are transformed into mechanical noise by the radiation pressure effect on the cavity mirrors and must be treated as a source of force noise, whose power spectrum S_{BA} is

$$S_{\text{BA}} = (4/c^2)S_{P_c}, \tag{1}$$

where S_{P_c} is the intracavity laser amplitude noise power spectrum, which can be written as

$$S_{P_c} = S_{P_{\text{in}}}(P_c/P_{\text{in}})^2. \tag{2}$$

Here $S_{P_{\text{in}}}$ is the noise spectrum and P_{in} the power of the laser beam entering the cavity, corresponding to approximately half the beam impinging on the cavity for the optimal modulation depth. P_c is the intracavity laser power, given by

$$P_c = P_{\text{in}}T_1(F/\pi)^2, \tag{3}$$

where T_1 is the input mirror transmissivity and F is the cavity finesse. To reduce the effect of the radiation pressure, we have to implement an active intensity noise reduction, described in Section 5. With the parameters of Table 1 a shot-noise-limited input beam yields a force noise spectral density of $S_{\text{BA}} = 1.6 \times 10^{-28}$ N^2/Hz, nearly 2 orders of magnitude lower than the calculated thermal noise. We note that the fluctuations due to the radiation pressure are seen as narrow-band noise at the output of the transduction chain. They can be treated as a back-action effect, and they would determine the ultimate sensitivity limit if the laser power could be increased beyond what is possible with the present technical limitations.

3. Experimental Apparatus

A scheme of our system is shown in Fig. 1. The laser source is a 100-mW Nd:YAG (Lightwave Model 126-1064-100) with internal amplitude stabilization. A −40-dB optical isolator is used to prevent scattering

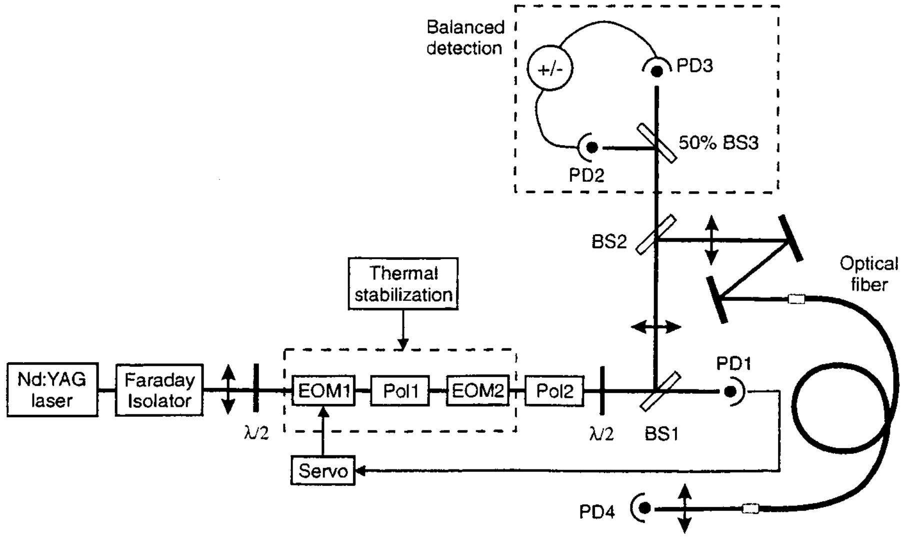

Fig. 1. Experimental setup: λ/2, half-wave plate; Pol, polarizer.

of light into the laser and to obtain a well-defined polarization.

An aluminum box contains a first electro-optic modulator (EOM1), a polarizer, and a second electro-optic modulator (EOM2). The box is slightly heated (between 30 and 35 °C) up to a selected temperature and thermally stabilized with residual fluctuations of ~0.04 °C in 24 h. EOM1 is a Gsänger Model LM0202, with a 5-mm-wide crystal and a half-wave voltage V_π of ~560 V at 1064 nm. EOM2 is a New Focus Model 4003 resonant modulator. A modulation depth of ~1 rad is obtained by application of a rf power of 20 dBm at the resonant frequency of 13.3 MHz.

After the box a polarizer is followed by a 50% beam splitter (BS1). BS1 is replaced with a variable beam splitter (i.e., a half-wave plate followed by a polarizing beam splitter) for the measurements described in Section 5. The beam transmitted by BS1 is detected by a photodiode (PD1). The signal is then amplified and filtered by the loop electronics and sent to EOM1.

Part of the beam transmitted by BS1 is coupled into a single-mode polarization-maintaining optical fiber, with integrated lenses at both ends. The overall coupling efficiency is 65%. The beam analysis is performed both before and after the fiber, by means of photodiodes followed by a rf spectrum analyzer or a digital scope with internal fast Fourier transform data analysis (LeCroy Model LT342).

For the low-frequency analysis the calibration of the shot noise is performed by use of balanced self-homodyne detection.[10] The laser beam is precisely divided into two parts of equal intensity by means of a beam splitter formed by a half-wave plate and a polarizing beam splitter. The two outputs of the beam splitter are sent to separate photodiodes (PD2 and PD3) whose ac signals are amplified and sent to a passive ± power combiner. The difference signal gives an accurate calibration of the shot noise of the beam impinging on the beam splitter, whereas the sum corresponds to the laser amplitude noise. The calibration was checked with a halogen light source.

For the rf analysis a single photodiode (PD4) is used, and a shot-noise calibration signal is provided by the thermal light source. The rf signal from PD4 is demodulated in a double-balanced mixer whose i.f. output is analyzed, after a low-pass filter and an amplifier, with use of the digital scope. The modulation signals for EOM2 and the local oscillator for the mixer are provided by two phase-locked signal generators (HP Model 33120A).

4. Phase Modulation

We analyze the laser amplitude noise spectrum at rf frequencies by means of a 2-mm-diameter p-i-n photodiode (EG&G Model C30642) with a load resistor of 150 Ω followed by an ac-coupled (frequency, >1 MHz) home-made amplifier. The quantum efficiency of the photodiodes we used is ~0.9.

The linearity of the photocurrent response versus laser power is within 1% below 20 mW, as checked with a power meter.

In Fig. 2 we show the recorded amplitude noise spectrum of the laser, for a power of 9 mW impinging

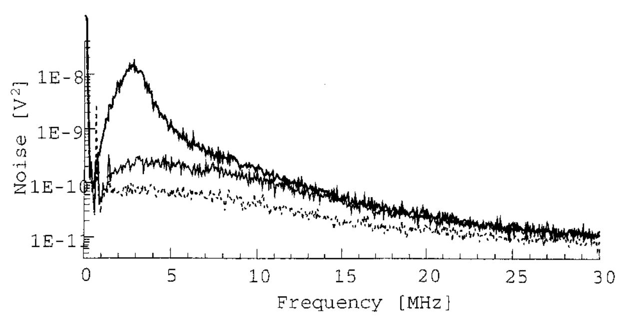

Fig. 2. Upper curve, intensity noise power for 9 mW impinging on the detector; middle curve, shot-noise calibration obtained with a halogen lamp; lower curve, detector electronic noise.

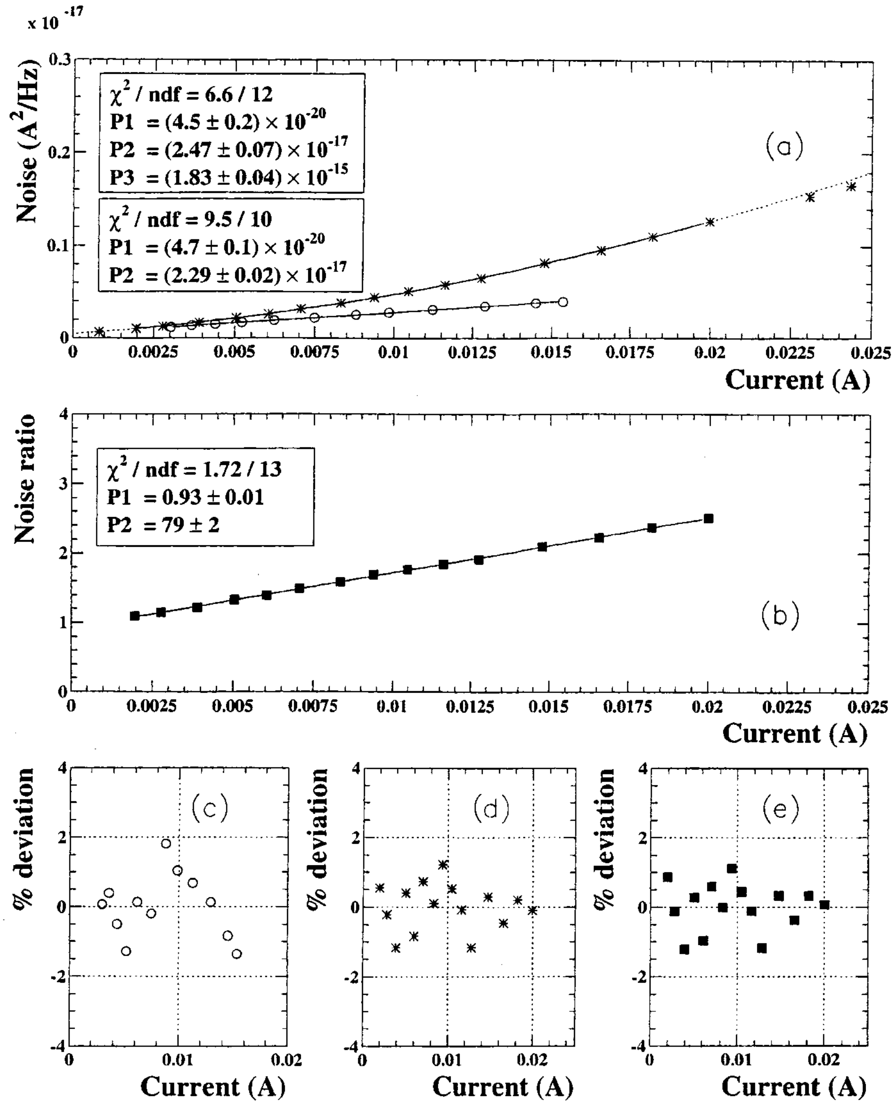

Fig. 3. (a) Power spectral density at 10 MHz of the intensity noise as a function of the photocurrent generated by a halogen lamp (lower curve, fitted with a straight line) and by the laser (upper curve, fitted with a second-order polynomial). P1, P2, and P3 are the coefficients of the zero-, first-, and second-order terms in the fitting function, respectively. (b) Laser power density normalized to shot noise as a function of the photocurrent. Percentage deviations from the fitting curves are shown on the bottom: (c) halogen lamp, (d) laser, (e) noise ratio.

on the detector. The noise approaches the shot noise for frequencies higher than a few megahertz. The electronic noise corresponds to the shot-noise level for a power of 3.5 mW on the detector. It is thus negligible for a power that is sufficiently larger than this value.

Figure 3 shows the measured noise power density at 10 MHz for different values of the photocurrent, for both the laser and the white light. The linearity of the latter curve demonstrates that the rf response of the photodiode is linear (up to 20 mA, corresponding to a detected power of ~25 mW). The curve of the laser amplitude noise has a quadratic behavior,

$$S_L = D + aI + bI^2, \tag{4}$$

where S_L is the detected noise power density, I is the photocurrent, and, on the right-hand side of Eq. (4), the first term is the electronic noise, the second term is the shot noise, and the third term is the excess noise. The fit of the experimental curve with Eq. (4) gives an excess noise of $a/b = 75\ I$ (A).

At our detection frequency (13.3 MHz), for a power of 11 mW impinging on the detector (10-mW detected power, the value used for the calculation of the system sensitivity in Section 2), the total noise power density is 1 dB above the shot-noise level.

The phase modulation introduces a residual amplitude modulation (RAM) because of laser amplitude modulation by the EOM2, polarization modulation transformed into amplitude modulation by the polarizer, and interference of scattered and reflected light with the main beam (etalon effects). The dc offset produced by RAM after phase-sensitive detection gives rise to a displacement of the locking point from

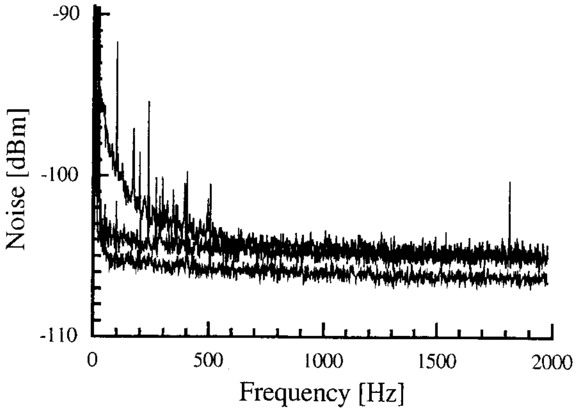

Fig. 4. Intensity noise spectrum measured after detection at 13.3 MHz and demodulation in a double-balanced mixer. Upper curve, phase-modulated laser; middle curve, without modulation; lower curve, electronic noise.

the real line center. The offset we measured is lower than 0.3% of the peak-to-peak signal amplitude, giving a frequency shift of less than 50 Hz.

What is more important, the fluctuations of the RAM signal must have a negligible spectral power near 1 kHz to avoid decreasing the sensitivity. In Fig. 4 we report on the spectrum of the demodulated signal, after the mixer. This spectrum is compared with the one without modulation: The RAM introduces no excess noise near 1 kHz, whereas it is effective at lower frequencies. The results are worse after the signal passes through a 12-m-long fiber. In that case (owing to interference effects in the fiber) we measured a noise power at 1 kHz that is ~9 dB higher than the quantum level, for a laser power of 5 mW. For 1-mW detected power we deduce an excess noise of 2 dB, leading to a 30% decrease in sensitivity.

5. Amplitude Stabilization

The photodetectors used for the 1-kHz amplitude noise reduction and measurement are the same as described in Section 4, with a load resistor of 240 Ω. The laser power is controlled by means of EOM1 and the following polarizer Pol1. The polarization axis of the laser at the entrance of the EOM1 is rotated by an angle α of ~0.12 rad with respect to one axis of the EOM1. The polarizer is oriented along the input polarization direction.

The EOM changes the input polarization to elliptical, thus reducing the transmitted power P according to

$$P = P_0(1 - \sin^2 2\alpha \sin^2 \phi/2), \tag{5}$$

where ϕ is the phase-retardation difference between the two EOM axes. To work in a linear response region, we set the temperature of the EOM for an offset phase ($\phi_0 \sim \pi/2$) in one of the EOM axes with respect to the other; i.e., we work around a slightly elliptical polarization (giving an average transmission of 92%). This phase is then changed by the voltage applied to the EOM in order to correct the laser power fluctuations.

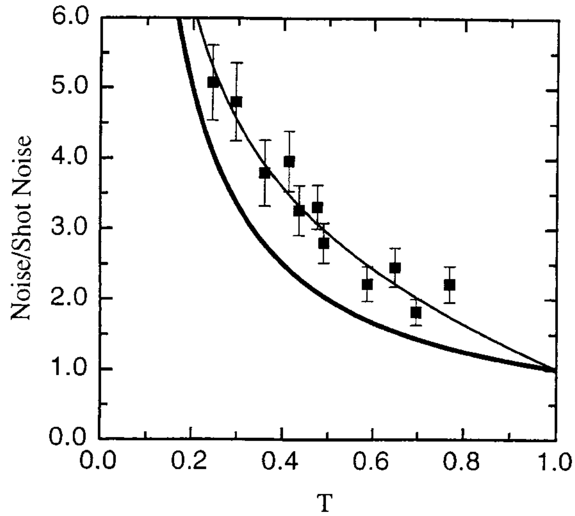

Fig. 5. Ratio of intensity noise spectral density to shot noise, as a function of the transmissivity of BS1. The experimental data are fitted with Eq. (9). Thick curve, theoretical limit for infinite gain.

The temperature of the EOM is actively stabilized within 0.04 °C, to reduce the fluctuations of ϕ_0 to less than 0.04 rad. The laser relative amplitude changes induced by the EOM and the polarizer system, for a small applied voltage ΔV, are

$$G_{\mathrm{EOM}} = \frac{1}{2}\frac{\pi \Delta V}{V_\pi} \sin^2 2\alpha \sin \phi_0. \tag{6}$$

The photodiode signal is amplified (with a bandpass filter between 500 Hz and 2 kHz) and sent to the EOM. We can define an electronic gain as

$$G_{\mathrm{el}} = G_{\mathrm{pd}} G_{\mathrm{loop}} G_{\mathrm{EOM}}, \tag{7}$$

where G_{pd} is the photodetector gain (in volts per watt) and G_{loop} is the loop amplifier transfer function, and a total loop gain,

$$G_{\mathrm{tot}} = T G_{\mathrm{el}}, \tag{8}$$

where $T = 1 - R$ and R is the reflectivity of BS1.

The calculation of the obtainable noise reduction requires a quantum mechanical approach that takes into account the vacuum fluctuations introduced by the beam splitter. It was shown by Giacobino *et al.*[11] that the noise spectrum of the transmitted beam, normalized to its own shot noise, is

$$\frac{S_0 R}{(1 + T G_{\mathrm{el}})^2} + \frac{T(1 + G_{\mathrm{el}})^2}{(1 + T G_{\mathrm{el}})^2}, \tag{9}$$

where S_0 is the input noise spectrum normalized to shot noise. For high T the output noise approaches the shot-noise level, at the expense of a lower transmitted power. In the limit of infinite gain the output noise spectrum reduces to $1/T$.

We measured the output noise versus BS1 transmissivity, keeping constant the total loop gain $G_{\mathrm{tot}} =$

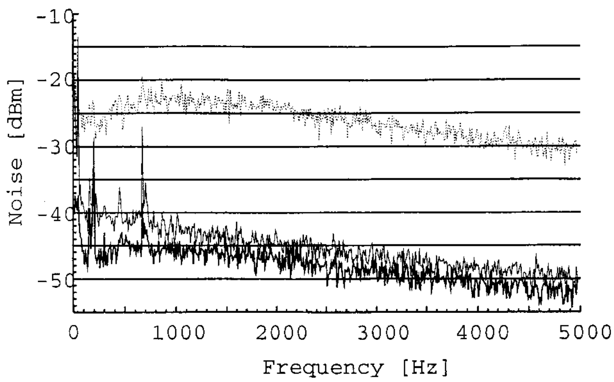

Fig. 6. Intensity noise spectra in the acoustic range, taken with the balanced detection for 30-mW laser power. Upper curve, laser noise (balanced detection in the sum position) without active stabilization; middle curve, the same, with the stabilization loop on; lower curve, shot-noise reference, measured with the balanced detection in the difference position.

15. Indeed, for a fixed loop frequency response, G_{tot} is limited by stability requirements. The results are shown in Fig. 5, together with the theoretical prediction of Eq. (9). The input noise was measured independently, giving $S_0 = 500$. The thick curve gives the theoretical limit with infinite gain.

In our transduction chain we will use a 50% beam splitter for BS1, yielding an amplitude noise 5 dB above the quantum level in the transmitted beam, near 1 kHz, with the present active stabilization. Figure 6 shows the amplitude noise spectrum in this configuration. The laser power is 30 mW, giving a relative intensity noise of -164 dB/Hz.

The coupling to the optical fiber deteriorates the laser amplitude stability, above all at low frequencies, probably because of mechanical noise in the coupling system. Figure 7 shows the noise spectrum measured after a 2-m-long fiber for both a free-running and an actively stabilized laser, compared with the shot noise. The measurement is performed with a detected power of 15 mW and gives an excess noise, after stabilization, of 7 dB at 1 kHz.

For a laser power of 2 mW or less (the planned laser power at the input of the transducer cavity) the excess noise reduces to less than 2 dB, corresponding to amplitude fluctuations lower than 1.2×10^{-21} mW^2/Hz. The back action, according to Eqs. (1) and (2), will be less than 2×10^{-28} N^2/Hz, i.e., 50 times lower than the transducer thermal noise.

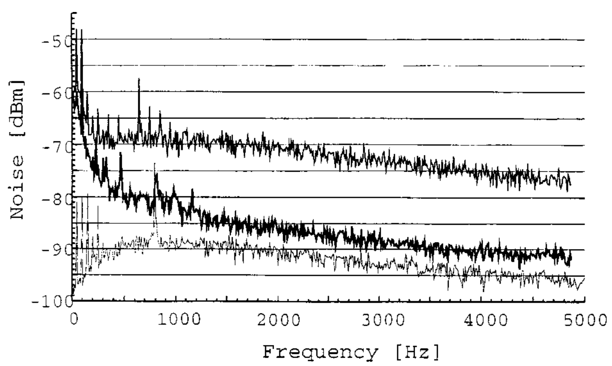

Fig. 7. Same spectra as in Fig. 6, measured after the optical fiber for 15-mW laser power.

6. Conclusions

We have implemented a laser system with the following characteristics. The beam is phase modulated at 13.3 MHz, with a modulation depth of $\sim$1 rad. The RAM is below 0.3%. The noise power of the detected and the demodulated signal, near 1 kHz, is 1 dB above the shot-noise level for 10-mW detected power and 2 dB for 1-mW detected power after a 12-m single-mode polarization-maintaining optical fiber.

The intensity is stabilized near 1 kHz, with a residual excess noise of 5 dB for 30-mW laser power and 2 dB for 2-mW laser power after the fiber.

Such a system, when used in a transduction chain such as the one described by Conti *et al.* in Ref. 7 (see also Section 1), would allow the AURIGA detector to reach a burst sensitivity of 2×10^{-20} with a bandwidth of 80 Hz. These results are the first step toward realizing a prototype optical transduction chain for gravitational-wave resonant detectors.

The characteristics of our laser system compare well with the fundamental limits given by quantum theory. Even if this study is particularly focused on the AURIGA optical readout, the results reported here are of wider interest in the field of high-performance metrological laser systems.

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