Development of Photodetectors for the Squeezing Experiment at the LIGO 40m GW interferometer

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Low-noise photodetectors with high quantum efficiency are needed for quantum optics experiments, especially for the application of injecting squeezed states into GW interferometers to reduce quantum noise. I have designed and fabricated a balanced photodetector which is composed of two photodiodes and a difference photocurrent transimpedance amplifier. This design symmetrizes detection responses to light onto each photodiode if a pair of photodiodes with matched quantum efficiencies are properly selected. I have also developed a single-photodiode photodetector for the purpose of the ongoing experiment on squeezing-enhanced GW interferometers at 40m. This report contains an introduction to the squeezing project at 40m laboratory and the above PD development work.

I. INTRODUCTION AND MOTIVATION

The sensitivity of next generation GW interferometers such as Advanced LIGO will be enhanced by several efforts, such as the increase of the input laser power. While the present-day interferometers (like LIGO interferometers) are limited at high frequencies (about 100 kHz) by noise of quantum-mechanical nature due to fluctuations of the vacuum fields, the next generation GW interferometers are expected to be limited by quantum noise not only at high frequencies but in almost the full range of frequencies of interest, from 100 Hz to 10 kHz. For the purpose to increase the sensitivity the quantum noise needs to be reduced. In GW interferometers the measurement processes are the interaction of light with test masses (the cavity mirrors) and counting signal photons with a photodetector. The two fundamental sources of quantum-mechanical noise are the fluctuations in number of output photons (shot noise) and the fluctuations in radiation pressure on the masses. The first arises from the uncertainty in number of photons detected and dominates at high frequencies (above 100 Hz) while the second is due to the fact that photons impart momentum to the masses so fluctuations in number of photons are translated into fluctuations in momentum transferred and is dominant at low frequencies. Both have a poissonian statistical nature. In 1981 C.M. Caves first proposed to reduce the quantum noise in interferometric GW detectors by injecting squeezed states of light or vacuum into the unused input port (dark port), to substitute the ordinary vacuum fluctuations [1].

In the last two decades this idea has been developed with world-wide efforts, both theoretical models and experiments. The experimental techniques for generating non classical states have reached a notable maturity: table-top experiment produced a high level of squeezing (over 7 dB) [2], the experimental demonstration of a table-top squeezing-enhanced power-recycled Michelson interferometer has been achieved at MHz frequencies [3] and squeezing in the GW band has been demonstrated for the first time [4]. However, in the past, only proof-of-principle demonstrations have been done and there has been no demonstration of a realistic squeezing-enhanced GW interferometer. Nowadays this is being realized for the first time. From the preliminary proposal dated October 2005, the 40m LIGO team (Caltech-MIT collaboration) is working on the ambitious project of obtaining the first experimental demonstration of a squeezing-enhanced GW interferometer at the 40m laboratory (California Institute of Technology) [5].

At present the experiment is already in an advanced state, the apparatus for the production of squeezed vacuum has been equipped and installed near the 40m interferometer dark port. Nevertheless to reach the final goal several further developments are needed. One of the most important requirements for the experiment is the possibility to measure a sufficiently high level of squeezing (a wishful goal is 10 dB) and this can be obtained by an important enhancement of the balanced homodyne detection (see II B) employed in the final configuration. I realized the design of new low-noise photodetectors to be used in the experiment starting from a previous design by Christopher Wipf (MIT) and then I produced and tested them in the actual 40m squeezing apparatus.

Section II introduces the reader with some basics about the production of squeezed states with an optical parametric oscillator (OPO) and homodyne detection. Section III gives an overview about the current status of the experiment and describes the design and production work for the new photodetectors.

II. THEORY

Here I present a brief abridgement of the theoretical background underliing the experiment. A reference for squeezed state generation and detection theory is [6]. A deepening about the theory of squeezing generation in cavities with the Langevin approach can be found in [7]. For an overview on squeezed states in general I refer the reader to [6].

A. Squeezing in optical parametric oscillator

Parametric amplification is one of the most useful processes for the production of squeezed states. A parametric amplifier consists of a nonlinear crystal having a $\chi^{(2)}$ coefficient on which is directed a light beam acting as pump for the system; when a light beam travels across a nonlinear medium new harmonics can be generated, in the present case the interaction between the pump beam and the nonlinearity generates two new modes called signal and idler, whose sum of frequencies is equal to the pump frequency. The pump is usually a large amplitude coherent state.

It is a general use to put the nonlinear medium in a resonance cavity, in this case we speak about an optical parametric oscillator (OPO). This method for generation of squeezed state is preferred because the interaction is weak and confining the field in a cavity increases the interaction time and allow to obtain a bigger effect. In what follows, to give a more realistic description of the squeezed states generation process in presence of a cavity, I will use the Langevin approach (see [6], [7]).

We describe an optical cavity by a Hamiltonian of the form $H_{tot} = H_{sys} + H_b + H_{int}$, where H_{sys}, H_b, H_{int} are the internal mode, bath, and interaction between cavity field and bath Hamiltonians respectively. The quantum Langevin equation for a single mode cavity is $\frac{da}{dt} = -\frac{i}{\hbar}[a, H_{sys}] - \frac{\gamma}{2}a + \Gamma$, where a is the cavity field annihilation operator, γ is the cavity damping constant and Γ is the noise operator. For a OPO cavity at the fundamental frequency the Langevin equation is

$$\dot{a} = (i\omega_c - \gamma_{tot})a + \epsilon a^\dagger b + \sqrt{2\gamma_{in}} v_{in} e^{i\omega_0 t} + \sqrt{2\gamma_l} v_l e^{i\omega_0 t} + \sqrt{2\gamma_{out}} v_{out} e^{i\omega_0 t} \quad , \tag{1}$$

where ω_c, ω_0 are the cavity resonance frequency and the carrier frequency respectively, a, b are the cavity modes of the fundamental field and second-harmonic field, v_{in}, v_{out}, v_l are the input, output field and the field that couples into the cavity due to intra-cavity losses, ϵ is the nonlinear coupling constant, γ_{in}, γ_{out}, γ_l are the decay rates associated with the input, output mirrors and the intra-cavity losses and $\gamma_{tot} = \gamma_{in} + \gamma_{out} + \gamma_l$. In our case $\omega_c = \omega_0$. If we now transform into the rotating frame with the fundamental field by substituting $z \to z e^{-i\omega_0 t}$ for all operators and treat b as a classical field, $\beta = |\beta| e^{i\phi}$ with $\phi =$ squeezing angle, we obtain

$$\dot{a} = -\gamma_{tot} a + \epsilon \beta a^\dagger + \sqrt{2\gamma_{in}} v_{in} + \sqrt{2\gamma_l} v_l + \sqrt{2\gamma_{out}} v_{out} \quad . \tag{2}$$

In the frequency domain we define the quadrature field amplitudes as

$$\tilde{a}_1(\omega) = \frac{\tilde{a}(\omega) + \tilde{a}^\dagger(\omega)}{\sqrt{2}} \quad , \quad \tilde{a}_2(\omega) = \frac{\tilde{a}(\omega) - \tilde{a}^\dagger(\omega)}{\sqrt{2}i} \tag{3}$$

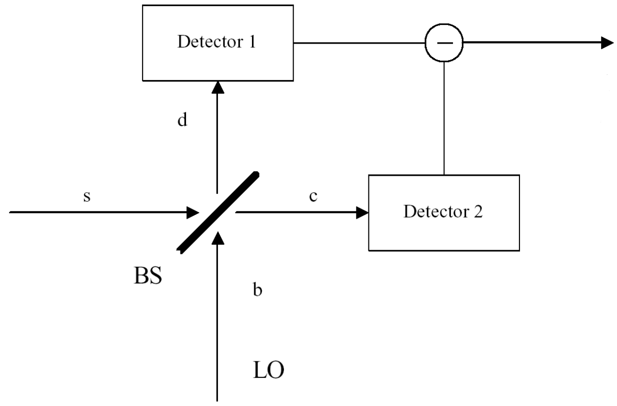

FIG. 1: Balanced homodyne detection schematic diagram.

and the quadrature field amplitudes of the cavity output field are then given by

$$\begin{pmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{pmatrix} = \sqrt{2\gamma_{tot}} \begin{pmatrix} \tilde{a}_1 \\ \tilde{a}_2 \end{pmatrix} - \begin{pmatrix} \tilde{v}_1^{out} \\ \tilde{v}_2^{out} \end{pmatrix} \quad . \tag{4}$$

We assume that the intra-cavity losses are negligible with respect to the mirror losses and the frequency of the cavity length modulation/demodulation used to lock the squeezing angle is much smaller than the cavity length; in this case $\gamma_l/\gamma_{in} \approx 0$ and $\omega \ll \gamma_{tot}$. With the above assumptions and imposing the squeezing angle to be $\phi = 0$ we find the squeezing quadrature variances as

$$\tilde{V}_1(\omega) = \langle |\tilde{s}_1(\omega)|^2 \rangle = 1 + \frac{4\eta x}{(1-x)^2}$$

$$\tilde{V}_2(\omega) = \langle |\tilde{s}_2(\omega)|^2 \rangle = 1 - \frac{4\eta x}{(1+x)^2} \quad , \tag{5}$$

where $x = \epsilon|\beta|/\gamma_{tot} = \sqrt{P/P_{th}}$, $\eta = \gamma_{out}/\gamma_{tot}$. P, P_{th} are the pump power and the OPO threshold while η is the efficiency of the OPO cavity. P needs to be under the P_{th} limit hence $x < 1$.

This result shows that, depending on the x and η quantities, the two squeezing quadrature variances are always over and under the shot noise level ($\tilde{V}_1(\omega) = \tilde{V}_2(\omega) = 1$) respectively.

B. Detection of squeezed states: balanced homodyne detection

The detection of squeezed states requires a phase-sensitive system which allows the measurement of one quadrature of the field. Here we are interested in a particular kind of detection useful for our purpose, the balanced homodyne detection, based on a two-port detection. The schematic diagram for the balanced homodyne detection is shown in Figure 1. The input s field is superposed to the b field, a coherent state of amplitude $|\alpha_l|$ and phase ϕ_l coming from the local oscillator (LO), at a lossless 50/50 beam splitter (BS) ($T = R = 1/2$). Let us call the annihilation operators for the different fields s, b, c, d respectively. The BS acts as a matrix,

$$\begin{pmatrix} c \\ d \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} & i/\sqrt{2} \\ i/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \begin{pmatrix} s \\ b \end{pmatrix} \quad , \tag{6}$$

hence the signals detected by the two photodetector are given by the operators

$$c^\dagger c = \frac{1}{2}(s^\dagger s + |\alpha_l|^2) + \frac{i}{2}(s^\dagger b - b^\dagger s) \quad , \tag{7}$$

$$d^\dagger d = \frac{1}{2}(s^\dagger s + |\alpha_l|^2) - \frac{i}{2}(s^\dagger b - b^\dagger s) \quad . \tag{8}$$

It is important to underline that in the previous equations the noninterference terms have the same sign while the interference terms have an opposite sign, hence if we take the difference between the two photocurrents developed in the two photodetectors we obtain a signal containing only the interference contributions

$$n_{cd} = c^\dagger c - d^\dagger d = -|\alpha_l|(s_1 \sin\phi_l + s_2 \cos\phi_l) \quad . \tag{9}$$

If the input s field is the ordinary vacuum the output signal variance will be $\langle |n_{cd}|^2 \rangle = |\alpha_l|^2$. Let us suppose s to be a squeezed field and fix the value of ϕ_l, which in this case plays the role of the squeezing angle. The output signal variance is found to be

$$\langle |n_{cd}|^2 \rangle = |\alpha_l|^2 (V_1 sin^2\phi_l + V_2 cos^2\phi_l) \quad . \tag{10}$$

As a result by locking the squeezing angle to the convenient value it is possible to obtain a noise signal under the shot noise level. When $r = 0$ we have $V_1 = V_2 = 1$ and this gives again the result $\langle |n_{cd}|^2 \rangle = |\alpha_l|^2$.

III. EXPERIMENT AND RESULTS

A. Squeezer apparatus

The schematic of the actual experimental setup is shown in Figure 2. The laser source is the MOPA laser , a Nd:YAG laser with a wavelength of 1064 nm and a power of 1.5 W, prestabilized in intensity and frequency by the LIGO 40m PSL (Pre-Stabilized Laser) system which includes two photodetectors (PD4, PD5), an electro-optic modulator (EOM) and a reference cavity (RC).

The SHG (Second Harmonic Generator) is pumped by 1.5 W of the 1064 nm from the MOPA laser and generates 580 mW at 532 nm (visible green light). It is a cavity composed by a 5% MgO:LiNbO$_3$ crystal with a high reflection (99.5% at both 1064 nm and 532 nm) curved surface and an anti-reflection flat surface. A piezo-electric transducer (PZT1) controls the length of the SHG cavity which is locked by the PDH (Pound-Drever-Hall) technique [8]. The SHG work temperature is 114.5^{0}C.

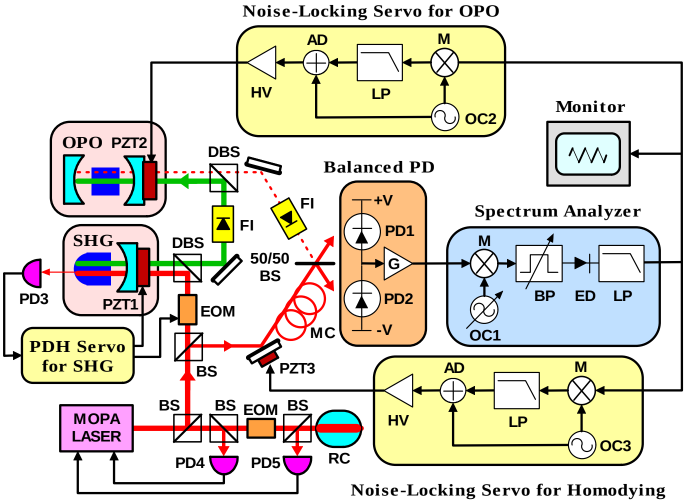

FIG. 2: Actual setup of the experiment.

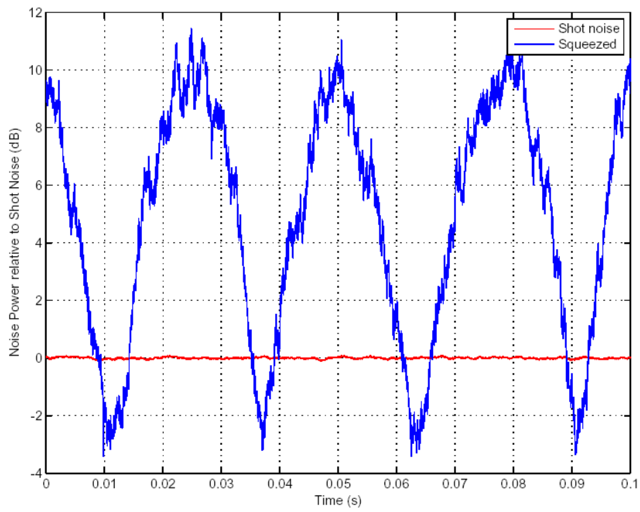

FIG. 3: Best level of squeezing reached in the 40m squeezer apparatus.

The 532 nm radiation is used as a pump for the OPO cavity, which is composed of a periodically-poled KTiOPO$_4$ crystal with anti-reflection flat surfaces and two coupling mirrors (radius of curvature of 10 mm). The input and output coupling mirrors have a reflectivity of 99.95% and 92.0% respectively (at both 1064 nm and 532 nm). The crystal is maintained at the optimal work temperature which is about 37^{0}C. To lock the OPO cavity a coherent-light-free technique is used [9], that assures a long term stability of both the OPO cavity locking and the squeezing angle locking (PZT3). Squeezed vacuum (dotted line in Fig. 2) is generated by the correlation between the upper and lower quantum sidebands around the carrier frequency operated by the OPO. A useful description of this process is given by the two-photon formalism [10]. A Faraday isolator (FI) is placed between the the OPO cavity and the homodyne detector to protect the OPO from back scattering of the LO field from the photodetector.

The homodyne detection system mixes the local oscillator (LO) signal and the squeezed vacuum coming from the OPO at a 50/50 BS and reads the difference of the two photocurrents developed in PD1 and PD2. LO field is mode cleaned by an optic fiber.

At present time the best level of squeezing reached is about 3 dB (Fig. 3). When all the enhancements of the squeezing apparatus will be completed it will be adapted to inject the squeezed vacuum into the dark port of the 40m interferometer.

B. Photodetection

For the purpose of getting the first experimental demonstration of a squeezed-enhanced GW interferometer one of the most tightening requirements is to produce a sufficiently high level of squeezing. One of the improvements needed is the enhancement of the homodyne detection with a new low-noise balanced photodetector (BPD). I took part in the project with the design, fabrication and test of this new device.

1. *Design and preliminary tests*

I worked on the production of three different devices specifically designed for the balanced homodyne detection, two balanced phtodetectors (BPD) and one single photodetector (SPD), which can be used in pair as an alternative to the balanced detector. The only relevant difference between the two BPDs is a different distance between the two photodiodes, which is about 8.5 cm and 13.5 cm respectively. A different distance between the photodiodes is useful to adapt the homodyne detector to different possible configurations in the squeezer apparatus. This design will also be used by Shailendhar Saraf in a different experiment at Rochester Institute of Technology.

For the BPDs I used a previous BPD design by Christopher Wipf (MIT) dated January 2006, properly adjusted for our necessities, while the Single PD amplifier design has been obtained from the BPD amplifier design with a few changes. In the following figures are shown schematic (Fig. 4) and printed circuit board (PCB) layout. (Fig. 5) for the different devices.

All the devices are inverting transimpedance amplifiers, in which the low-noise high-bandwidth operational amplifier OPA847 is used. If the total current produced by a photodiode is I the output signal is $V_{out} = -R_1 I$ (in the high gain approximation), where R_1 is the feedback resistor. For the balanced photodetector case the current produced is the difference between two currents, say $I_1 - I_2$, and then the output voltage is $V_{out} = -R_1(I_1 - I_2)$. In the design both positive and negative

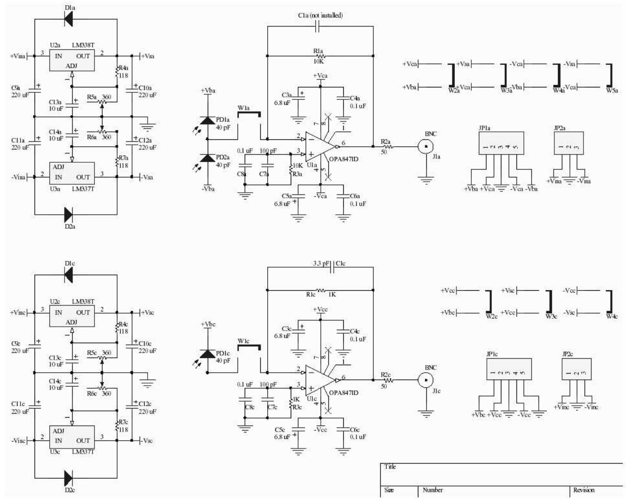

FIG. 4: Schematic design of BPD (top) and SinglePD (bottom) amplifiers.

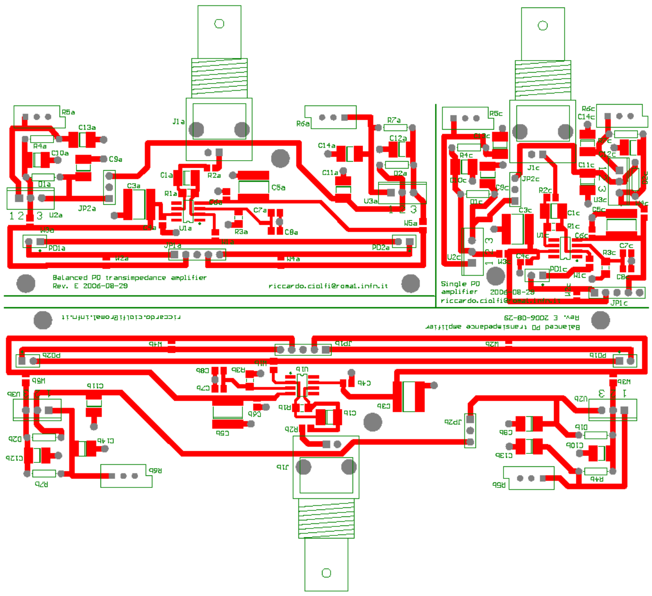

FIG. 5: PCB design of the three devices.

voltage regulators are used to reduce noise from the voltage supply fluctuations (LM338, LM337 National Semiconductor).

For the preliminary tests on the circuit and the characterization of the performances of the twelve photodiodes that I used (C30641 *EG&G* Optoelectronics) I prepared the Single PD amplifier circuit on a breadboard. The first important step is the measure of the quantum efficiency of the photodiodes, given by the ratio $\eta = r(\lambda)/r_{ideal}(\lambda)$ where $r(\lambda) = I_0/P_r$ is the measured responsivity (current generated per received watt) and $r_{ideal} = e\lambda/hc$ (e = elementary charge) [11]. Quantum efficiency determines the performance of the photodetector in terms of losses and shot noise level and in particular a balanced photodetector requires pairs of photodiodes with matched quantum efficiencies. For each photodiode I measured the output voltage of the circuit for different incident powers and I obtained the quantum efficiencies by double-weight linear fits. The power has been measured using a power meter (835 Newport) cross-calibrated to a calibrated calorimeter (Vector S310) within uncertainty of 3%. Figure 6 shows the results of the measurement. All the quantum efficiencies are found to be in the range between 81% and 88%.

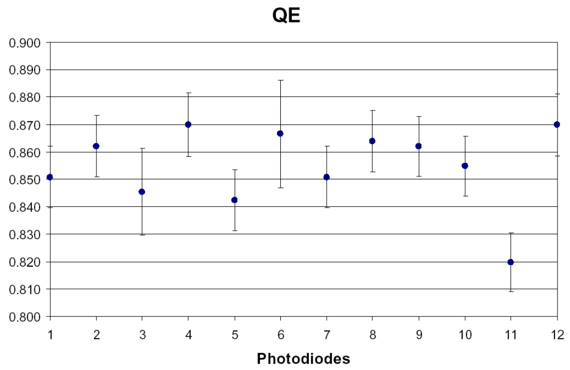

FIG. 6: Quantum efficiency of the twelve photodiodes.

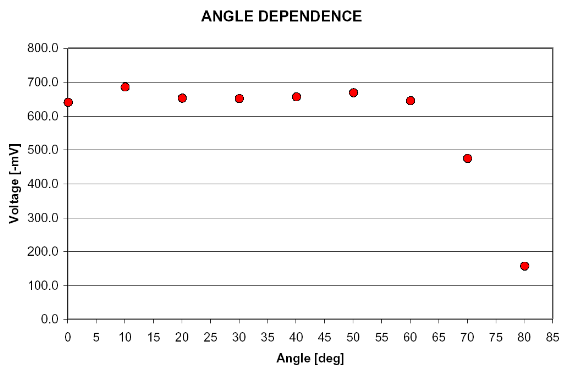

FIG. 7: Incident angle dependence of the responsivity.

In the final setup, it is planned that the light will be incident on the photodiodes at angles up to 40 degrees. Therefore, I measured the response of the photodiodes as a function of incidence angle. The variation of responsivity arises from the fact that the reflectivity of both the photodiode active surface and the thin glass layer in front of it depend on the light beam incident angle (increases with increasing angle). I verified that the responsivity is constant enough and then falls for incidence angles larger than 60 degrees. Results are shown in Figure 7. The statistical errors obtained from large set of measurements, about 50 values for each angle, are smaller than the red points. I used only one photodiode for this measurement, assuming that this angle dependence is the same for all the photodiodes.

Other tests on the breadboard circuit such as the spectral response measurement have been done, as preliminary checks that the performance is in good agreement with design.

2. Device production and test

After obtaining all the components I first produced the single phtodetector (SPD). I used it for testing the performances of the real circuit. I measured the transfer function both at high frequencies and low frequencies using the bands 10 kHz-400 MHz and 10 Hz-100 kHz. Figures 8, 9 show the results of this measurement. At

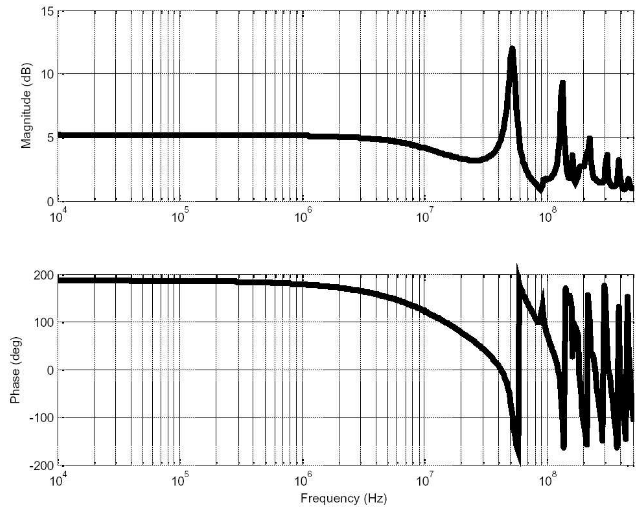

FIG. 8: Transfer function at high frequencies.

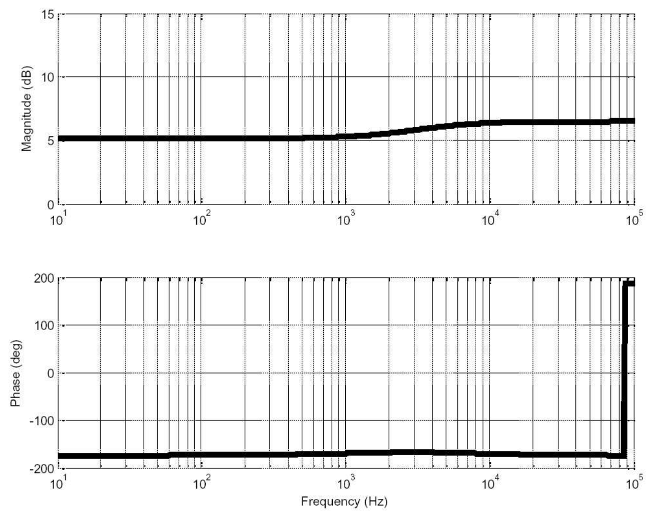

FIG. 9: Transfer function at low frequencies.

low frequency the response is expected to be flat. There is an apparent increase in the gain above about 2 kHz probably due to a measurement error. At high frequency the gain is flat with the same value of the flat part of the low frequency case and starts decreasing over 10 MHz. Instabilities occur after 20 MHz. The phase is flat as expected from 100 Hz to 1 MHz and starts decreasing very fast above 10 MHz.

With the purpose of having a complete characterization of the photodetector I measured spectral responses for different incident powers with a 1064 nm laser shining the photodiode and a frequency modulator. Because of high laser noise and spectrum analyser noise I didn't get reasonable results. These measurements will have to be repeated in the future.

Meanwhile a 13.5 cm BPD is being produced. The next step is to verify that this new device works well and respects the performances expected from the tests on the SPD.

IV. CONCLUSION

To reach the final goal of the 40m squeezing project several further development are needed. One of these is to achieve and measure a higher level of squeezing, which can be obtained only with the enhancement of balanced homodyne detection. For this purpose improved low-noise photodetectors has been designed and produced in two different configurations, BPD and SPD. Tests on SPD has been done and are still in execution, while the BPD will be tested in the future. The installation of the BPD (or a pair of SPD as a possible alternative) on-site is expected as a final result to enhance the actual homodyne detection, allowing to reach a higher level of squeezing.

V. ACKNOWLEDGMENTS

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