Advanced Virgo Squeezing Cavity

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Chapter 1

OPO cavity

Introduction

The choice of the OPO cavity is essentially based on its geometry and its locking configuration.

The cavity geometry can have a standing-wave (linear) or a travelling-wave (triangular, bow-tie...) design . In particular linear cavity can be monolithic, hemilithic or composed by a plane and parallel faces crystal inside an external resonator.

For both standing and traveling wave configurations one can choose between a singly or doubly resonant cavity. In a singly resonant cavity only the beam at the squeezed light frequency resonates; otherwise in the doubly resonant configuration both the pump beam and the produced beam resonate and this allows to lower the required threshold power.

Among all the possible choices we focused our attention on the OPO cavity developed by GEO600 and LIGO-ANU collaborations, being these the only that reached a good level of squeezing into the audio-frequency band for long time.

The GEO600 cavity, developed at the AEI (Albert Einstein Institute) is a singly resonant linear cavity, with a hemilithic geometry. While the LIGO cavity is doubly resonant with a bow-tie geometry, developed by the Australian National University (ANU). The German-British detector was the first to be enhanced by a squeezing technology. Both these configurations showed very good results [**khalaidovski2012long**] [**stefszky2012balanced**], reaching a squeezing level of roughly 10 dB. After a careful investigation, we concluded that there is no deep scientific motivation to choose a configuration rather than the other.

For Advanced Virgo we chose to reproduce a GEO-like cavity, being this consolidated for a longer time.

1.1 OPO optical design

To produce squeezed vacuum, at the wavelength used in Advanced Virgo interferometer (1064 nm), the OPO must be pumped at 532 nm (i.e with a pump beam at twice of the produced beam frequency).

The OPO is a singly resonant hemilithic cavity: the cavity is not resonant on the pump but only on the signal wavelength (1064 nm) and the geometry is linear with the two mirrors constituted by an input/output coupler mirror and by one of the faces of the nonlinear crystal, HR coated and curved with a suitable radius of curvature (RoC).

The coupler mirror is plano-concave with a RoC equal to 25 mm and a diameter of 0.5 inches. It has a fused silica substrate, a scratch-dig ratio of 10/5 and a rms roughness of $\lambda/10$ for both surfaces. Its IR power reflectivity is $R_{1064} = 92\%$. For a suitable value of the pump power, taking into account the system losses, this is the best value for which our OPO is able to reach both our goal of 10 dB of squeezing (see section 1.3) and a good finesse (see the following table).

IR Power Reflectivity	Squeezing Level	Finesse
90%	-10.31	59.4
91%	-10.19	66.29
92%	-10.06	74.9
93%	-9.89	86.0

Table 1.1. With an IR power reflectivity of 92% it is possible to have the maximum value of finesse, according to the requirement to reach 10 dB of squeezing. Calculations performed using a ratio between pump power and threshold power equal to 0.64 (see section 1.3).

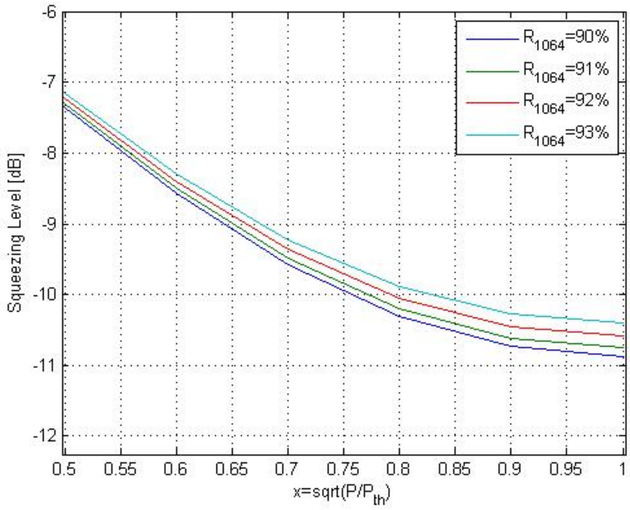

Figure 1.1. Levels of squeezing for several values of the outcoupler mirror IR power reflectivity. Value in table ?? are for x=0.8.

For green light the power reflectivity is $R_{532} = 20\%$. The curved face of the crystal, that is the rear mirror of the cavity, has a RoC of 12 mm and it is HR coated ($R > 99\%$) for both the wavelengths. The resulting cavity finesse value are, respectively, $\mathcal{F}_{1064} = 75$ and $\mathcal{F}_{532} = 3.7$, according to the choice to have a singly resonant cavity.

The chosen nonlinear medium is a PPKTP (Periodically Poled $KTiOPO_4$) crystal produced by Raicol Crystals Ldt; its intra-cavity face is an AR coated plane surface (with a residual reflectivity less than 0.1%). The crystal dimensions are 9.3 mm$\times$ 1.5 mm$\times$ 1 mm.

Using a periodically poled material it is possible, not only to achieve the phase-matching condition without strong requirement on the crystal temperature, but also to reach the working point of the crystal by the Quasi-Phase-Matching technique that makes possible to have a conversion efficiency greater than that obtained using only a birefringent bulk. This is due to the fact that this technique allows to interact with the larger nonlinear coefficient of the crystal (d_{33}), that can be accessed only if all the interactive waves are polarized in the same direction. The resulting effective nonlinear coefficient is

$$d_{eff} = \frac{2}{\pi} d_{33}.$$

For KTP it has a value of [7.5-9.5] pm/V, greater than that of many other non-linear crystals. This make able to obtain a good non-linear conversion also using a lower pump power. Another advantage is that the KTP is less sensitive to pump power fluctuations, due to its low optical absorption at the wavelength of 532 nm.

The air gap between the outcoupler mirror and the AR coated intra-cavity crystal face, chosen to have a stable cavity, is 22.5 mm long.

A FINESSE [**finesse**] simulation was used to find the cavity parameters: for the infra-red (IR) light the beam waist dimension is of 33 µm and the FWHM of 50 MHz; for the green light the beam waist dimension is of 23 µm and the FWHM is of 1.01 GHz.

wavelength	**waist**	**FSR**	**FWHM**	$\mathcal{F}$	R_1	R_2
1064 nm	33 µm	3.80 GHz	50 MHz	75	92%	> 99%
532 nm	23 µm	3.74 GHz	1.01 GHz	3.7	20%	> 99%

Table 1.2. Cavity optical parameters. R_1 and R_2 are the power reflectivities of the coupler mirror and of the rear cavity mirror, respectively.

1.2 Estimated threshold power

The value of the threshold pump power depends on the cavity parameters and on the non-linear conversion efficiency of the crystal [**wu1987squeezed**]:

$$P_{th} = \frac{\pi^2}{4F^2 E_{NL}} \tag{1.1}$$

where F is the cavity finesse at 1064 nm and E_{NL} is the *nonlinear conversion efficiency.* This parameter is defined as

$$E_{NL} = \frac{8\omega^2 d_{eff}^2 l^2}{\pi\epsilon_0 c^3 w_{0s}^2 n_s^2 n_p} sinc^2\left(\frac{\Delta kl}{2}\right)$$

where d_{eff} is the *effective nonlinear coefficient*, l the crystal length, $n_s = 1.8302$ and $n_p = 1.8894$ the refractive index (respectively at 1064 nm and 532 nm), Δk the momentum mismatch between the pump beam and the beam at the fundamental frequency and, finally, w_{0s} is the pump beam waist for IR light.

In case of perfect match ($\Delta k = 0$) the resulting threshold power is equal to 14.7 mW.

1.3 Maximum achievable level of squeezing

The level of squeezing that an OPO can produce depends on the ratio between the pump power P and the threshold pump power P_{th}. In terms of the *normalized pump power* $x = \sqrt{P/P_{th}}$ the squeezing (V_-) and anti-squeezing variancies (V_+) are:

$$V_\pm = 1 \pm \eta_{tot}\rho\frac{4x}{(1 \mp x)^2 + \Omega^2} \tag{1.2}$$

where η_{tot} is the product of the propagation efficiency η_{prop}, the photodiodes quantum efficiency $\eta_{q.e.}$ and the homodyne detection efficiency η_{hom} ($\sqrt{\eta_{hom}}$ is the *fringe visibility*); ρ is the *escape efficiency* given by

$$\rho = \frac{T}{T + L}$$

where T is the outcoupler mirror transmittivity, L is the total intra-cavity losses and Ω is the measuring frequency normalized to the Full Width Half Maximum (FWHM):

$$\Omega = \frac{f}{FWHM}.$$

Since we are interested in audio-frequency band, in our calculation Ω is negligible.

In theory, squeezing is possible at threshold, but in practice is better to choose a value of $x = 0.8$ [**bachor2004guide**], that corresponds to a ratio between pump power and threshold power of 0.64.

Considering $\eta_{prop} = 0.97$, $\eta_{q.e} = 0.99$, $\eta_{hom} = 0.98$ and $L = 0.0025$ (corresponding to an escape efficiency $\rho = 0.97$), our goal of 10 dB is the maximum achievable level of squeezing.

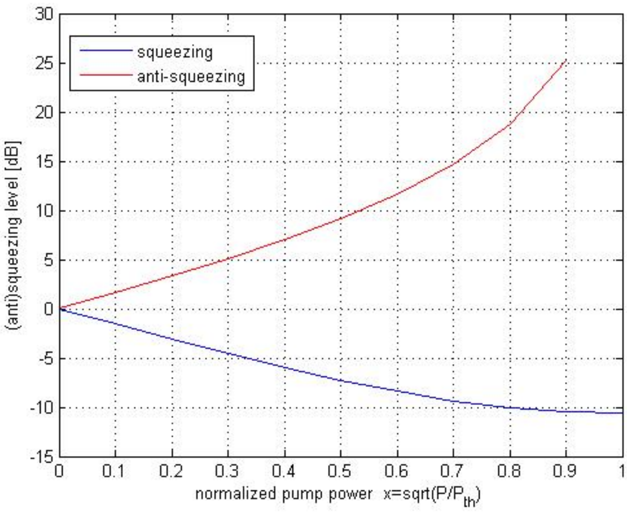

Figure 1.2. Taking into account the estimated value of losses, for $x = 0.8$, 10 dB is the maximum achievable level of squeezing.

1.4 Temperature Control

To reach the phase matching condition, the crystal temperature must be kept constant, at a value of about 35° C. Also in this case, the desired temperature is maintained by an active control loop, using a sensor and an actuator. In the control scheme used for the OPO, two NTC thermistors (*Conrad Elektronik, Type: NTC-SEMI833, Part number: 188506*) and a peltier element (*Laird Technologies CP1.4.17-045L*), that is driven by an external DC power supply, are used.
One of the two thermistors (In-Loop) is part of the control system and the other thermistor (Out-of-Loop) is used to measure the temperature independently of the control loop.
The first one is inserted in an analog circuit (Wheatstone bridge) whose output voltage (related to the NTC resistance, and then to the measured temperature) is used for a PID control loop, running under LabView. Since the two thermistors have the same behavior with respect to the the output of the bridge, for its calibration the out of loop resistance value was used.
The Out-Of-Loop temperature stability measurement was performed using a high precision digital multimeter[1].
The control loop make possible to reach a temperature stability of less than a mK for the Out-of-Loop measurement and of about 2 mK with the In-Loop thermistor.

[1] Keithley 3706 multi-switch/multimeter

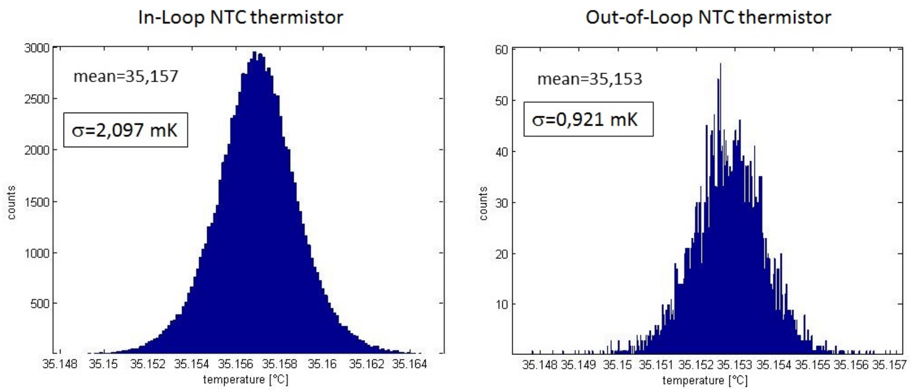

Figure 1.3. Temperature stability obtained by a PID control loop. The measurement was performed for a period of roughly 60 hours.

1.5 Mechanical Design

Both the optical components (crystal and mirrors) and the elements used for the temperature control (temperature sensors and actuator) are embedded in a case composed by an aluminium base and by a piece of peek to ensure thermal isolation and protection of the cavity from air flow perturbation.

The crystal stand on a copper L shaped element, under which a Peltier element was placed. In this copper element two NTC thermistors are placed with a completely dry assembly, this to avoid the introduction of impurities due to the use of conductive pasta. Two grooves, with the same radius of the thermistors, are drilled in this copper plate. The two NTC thermistors enter in each of these grooves and they were fixed by a copper spring and two little screws. Another L shaped element of peek is placed on the crystal, and whole this stack is fixed by a screw. To lock the cavity, the outcoupler mirror position is changed by a ring piezo-electric-transducer (PZT) placed in a brass piece. This mirror is placed in an aluminium mount and it is protected by a peek disc. In figure 1.4 (left part) we can see an exploded CAD drawing of our cavity. The distance from the center of the case, that corresponds to the height of the beam is equal to 61 mm (see right part of figure 1.4) and the width of the aluminium base is equal to 70 mm. This compact system ensures a very good mechanical stability.

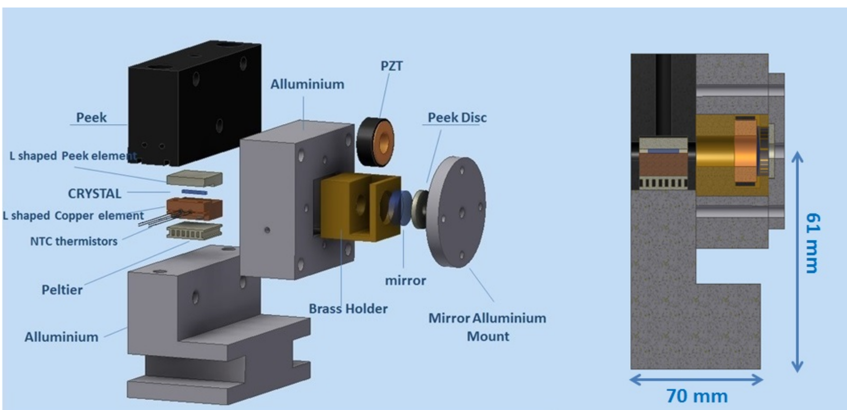

Figure 1.4. Left part: exploded CAD drawing of the protype cavity. Right part: cavity dimensions.

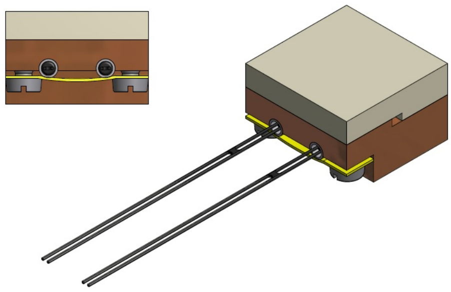

Figure 1.5. NTC thermistors dry assembly

1.6 Alignment and cavity length control

To align the cavity a bright beam at the same wavelength of the squeezed beam (1064 nm) (*bright alignment beam*, BAB), is used. Since this beam is also used to align the homodyne detector, it must have the same polarization (s-polarization) of the produced squeezed light exiting the cavity and of the homodyne local oscillator. The BAB is injected through the HR curved face of the crystal (the rear mirror of the cavity).

In order to avoid the spatial overlap between the squeezing cavity eigenmode and the input green light, matching lenses are used (see section **??**). This because the interaction of the pump beam with the higher mode of the infrared light represents an additional noise and then a squeezing level degradation source. Once the cavity and the homodyne are aligned, the BAB must be switched off.

The OPO cavity length control, like that for the other cavities (SHG and MCs), was performed using the Pound Drever Hall technique.

Since the cavity is singly resonant (not resonant on the pump beam) the cavity locking is performed my means of a beam at frequency equal to $\omega_0 + \Omega_{LC}$, where, we remember, ω_0 is the frequency of the MAIN Laser, while Ω_{LC} is a suitable frequency shift (see in the next).

This locking beam has a polarization orthogonal with respect to that of the squeezed signal, i.e it is p-polarized. The use of the orthogonal polarization avoid the OPO seeding, since, due to the crystal birefringence, the non linear gain for this polarization is negligible. Moreover it does not interfere with the squeezed signal. The beam used for this purpose is provided by an auxiliary infrared laser (*Mephisto S200*) phase locked to the main laser. We refer to this laser as AUXLC (*AUXialiary Laser for the LoCking*), and to the beam as LCB (*LoCking Beam*). The simultaneous resonance of both the polarization is reached by acting on the frequency of the AUXLC through the PLL control loop, thus by determining the suitable frequency Ω_{LC}. This allows to not act on the crystal temperature to compensate the dispersion between the resonance of the two orthogonal polarizations, and thus to not perturb the OPO phase matching condition. The procedure to determine the needed frequency shift (Ω_{LC}) between the OPO s-polarization and the p-polarization, once that the temperature phase-matching is reached, is to inject both the s-polarized BAB and the p-polarized LBB simultaneously in the OPO and scanning its cavity by means of a linear ramp on the OPO coupling mirror PZT. By recording the two signal with an oscilloscope, it possible to determine the needed frequency shift and thus to set the PLL reference to have the desired frequency for the AUXLC output.

The LCB is injected in the OPO through the rear port (HR face of the crystal) and transmitted by the cavity through the its coupling mirror. It is then separated by the squeezed light by a polarizing beam splitter and then detected by a photodiode.