Title

July 1, 2014

Introductive note for this preliminary draft

This document is only a preliminary draft of the TDR chapter about the OPO pump beam. Of some sections there are only the title and few indicative rows or are not complete. Some figures too are not the definitive or the right one, and in this case are set only to give a sketch.
The part in text that are presented in red color, like some values - results of measurement or calculation - indicate that at the moment is a reasonable value but that must be verified, like, for example, the closed loop frequency of the pump power stabilization system. Moreover, since at this time really a lot of decisions had not been done about about the set-up, and in particularly about the pump beam, like

- the pump beam source (commercial doubled laser or home made SHG);
- use of the green mode cleaner

the relative section are presented how possibilities, that once the decision will be taken, could be suppressed or maintained.

The text in green are sentence on which in particulary I would like to have feedback and on which I would focus the attention in the next discussion (Martina's note).

Contents

Chapter 1

OPO Pump Beam

1.1 Pump beam source: home made SHG vs commercial doubled laser

1.2 Pump beam source by commercial doubled laser

1.3 Homemade SHG

Our aim is to realize a squeezed light source similar to the two constructed at AEI-GEO600 and at ANU-LIGO. Both this two had inside an homemade second harmonic generator (SHG). We started a nearly identical SHG, including in the design some improovements, coming from the knowledge of some problems that affected the SHG installed at GEO600.

1.3.1 SHG optical design

- NLC

- SHG cavity (optical and geometrical parameters; optical simulation)

- expected threshold and temperature phase matching condition

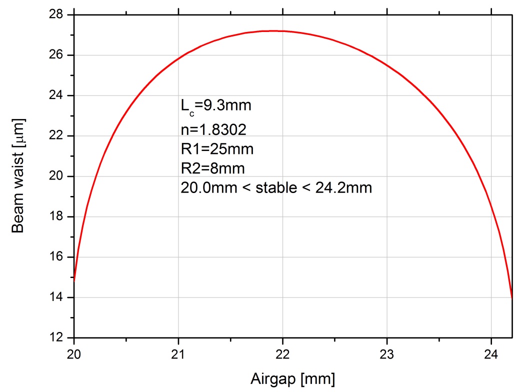

Figure 1.1. Optical simulation performed with Finesse of the stability region of the SHG as a function of the distance between the incoupling meniscous and the NLC.

1.3.2 Temperature control

The temperature control is performed using a PID.

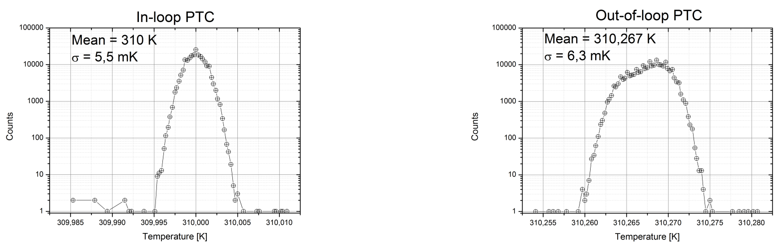

Figure 1.2. In loop and out of loop termistor histogram.

1.3.3 Mechanics

The mechanical design was thought to have the highest stability in term of vibration. Since the SHG is a Fabry-Perot cavity with a non linear medium (NLM) inside, a mechanical motion of a part of the cavity will translate in a phase noise of the producted green. Even if the highest stability is obtained with a monolithic cavity (i.e. the single NLC with both the facet coated with HR coatings), we decided to go for an hemilitic cavity where there is an incoupling mirror and the NLC with a facet with AR coating and the rear facet HR coated and curved.

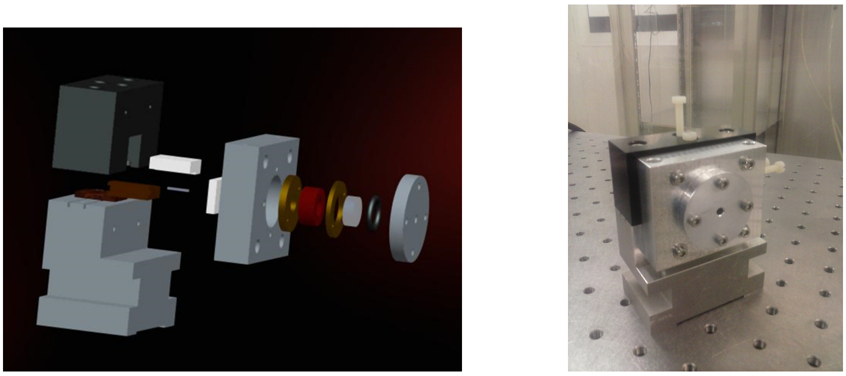

Figure 1.3. Exploded view of the SHG and image of a prototype.

From the GEO600 experience [], we know that vacuum grease and conductive grease (?) could lead to a degradation of the SHG via some photochemical reaction that damages the coatings. Therefore, our temperature control scheme does not involve any grease or grease and is effectivly a dry assembly.

In Fig.1.4 there is shown how the two termistor of the temperature control loop are mechanically attached to the copper L that stands below the NLC.

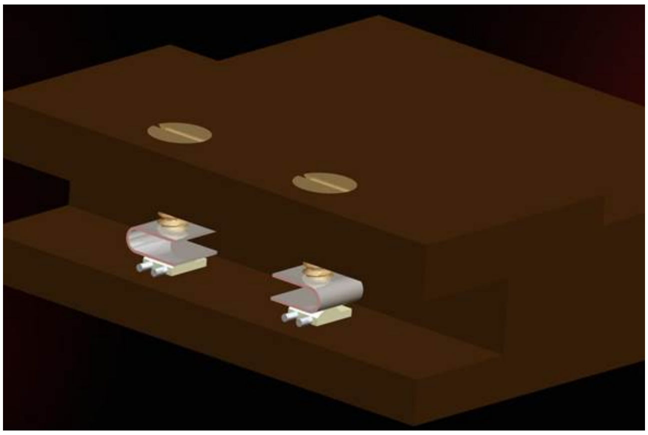

Figure 1.4. Dry assembly of the two termistor needed for the temperature control.

1.3.4 DPH locking system for the SHG

1.3.5 IR to GREEN convertion

1.4 Pump Beam Power Stabilization

Long-term squeezer operations requires the implementation of a pump power stabilization [5, 1]. The pump fluctuations cause a variation of the green light absorption in the OPO crystal and thus temperature fluctuations. The latest affect directly the squeezing degree by means of the non linear gain fluctuation but even the squeezing angle and the homodyne angle stability [4] by means of the cavity detuning that. Nevertheless the gain fluctuations due to the pump fluctuations results in a very weak squeezing value fluctuations, as shown in [4], where, considering realistic values for the OPO and of the homodyne detector parameters (i.e of the total intra-cavity losses, the escape efficiency, the propagation losses, the homodyne fringe visibility and efficiency) such that 9 dB of detected squeezing can be predicted, the estimate fluctuations due to a ± 10 % pump fluctuations are about ± 0.13 dB. More incisive are the effects of the detuning induced by the temperature fluctuations inside the non linear crystal. These lead to a refractive index change and thus to a loss of the phase matching conditions, since while DPH loop on the OPO assures the resonance of the beam used for the length stabilization (both if the OPO length is controlled in polarizations degeneracy conditions - i.e. by means of a beam with same frequency of the fundamental but orthogonal polarization - and if the length is stabilized on the pump resonance, like in the case of a doubly resonant OPO) the temperature change leads to a detuning of the fundamental beam inside the OPO. This detuning affects the coherent control scheme of the squeezing angle and the homodyne angle stabilization control too, so that it must be compensated by means of a fine, calibrated temperature control. Even if this is in principle realizable, the pump power stabilization results to be simpler and more precise, as experimentally observed in the LIGO-GEO experience [5, 1].

A theoretical stability requirement can be easily calculated by means of the simple model presented in [4], taking into account all the above-mentioned effects and the attended parameters of our set-up. It results to be a 0.1 deviation of the pump beam power, since within this value the squeezing degree and angle does not significantly change.

1.4.1 System description

Following the GEO-LIGO experience, we realize a pump power stabilization system that does not rely on non-linear effect, based on a simple unbalanced Mach-Zehnder interferometer [4, 2, 8]. It results to be more efficient, simple and precise respect to the common noise eater based on the Pockels cells, since the absence of the non linear medium avoids the thermal effects that could cause aging and disease on the long period.

A simple sketch of the system principle of operation is shown in figure 1.5. The transmitted power tuning in the unbalanced Mach-Zehnder is provided by means of piezoelectric element (PZT) on one of the interferometer mirrors by changing the relative arms length. The monitoring and control of the squeezer pump power is made by extracting a small fraction of the 532 nm light close to the OPO input port by means of a photodetector. The detector signal is then compared with a reference voltage that sets the working point. The system allows to remove the long-term power pump fluctuations and to make possible a

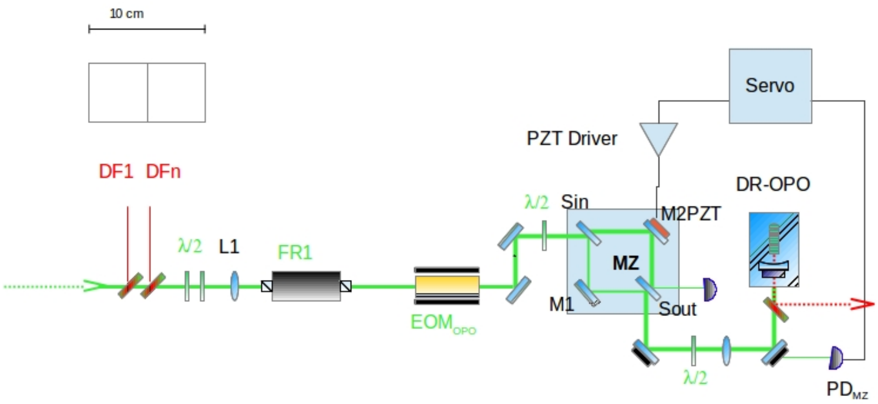

Figure 1.5. Sketch of the optical set-up and of the control loop for the OPO pump stabilization system based on a Mach-Zehnder.

squeezing degree and squeezing angle stability. Moreover the possibility to tune the power provides adjustment after the first calibration of the squeezing values.

Our unbalanced interferometer has equal arms length and unbalanced beams power along each arm, so that the mean power outgoing from the two out-port is different. It is made of two UV fused silica beam samplers ($S_o ut$ and $S_o ut$ in the sketch of figure 1.5) with a transmittivity at 45° of 10 % for the *p-polarization* and of 1 % for the *s-polarization*. In these conditions the mean transmitted power at the two out-put ports of the interferometer are $P_{ort}^{mean} = 0.98$ and $P_{par}^{mean} = 0.02$ with a dynamic range of ± 0.02 for the *p-polarization* and $P_{ort}^{mean} = 0.82$ and $P_{par}^{mean} = 0.18$ with a dynamic range of ± 0.2 for the *s-polarization*. The other two mirrors along the interferometer arms, M_1 and M_2, are HR mirrors with a reflectivity $R > 0.9999$ and a super-polished reflective surface with rms surface roughness ~ 0.5 Å and a scratch/dig of 10/5. A $\lambda/2$ waveplate before the interferometer input port allows the polarization adjustment and thus the tuning of the mean transmitted power. The waveplate at the output along the pump beam path, re-adjusts the polarization. A first, rough alignment of the system can be done by means of an input beam steering. The piezoelectric, PZT on the mirror M_2 (see figure 1.5) is a compact, high-speed multi-axis tip/tilt and z-positioners, the PI S-310, that has a resonant frequency of 6.1 ± 1.2 kHz with a 1 inch fused silica mirrors. It allows the fine interferometer alignment, while the rough alignment can be performed by means of the precision adjustment screws on the M_1 mirror holder.
The unity gain frequency of the closed loop system is 1 kHz.
The results of a preliminary prototype are already compliant with the specifications, as can be seen in the graphics of figure 1.6.

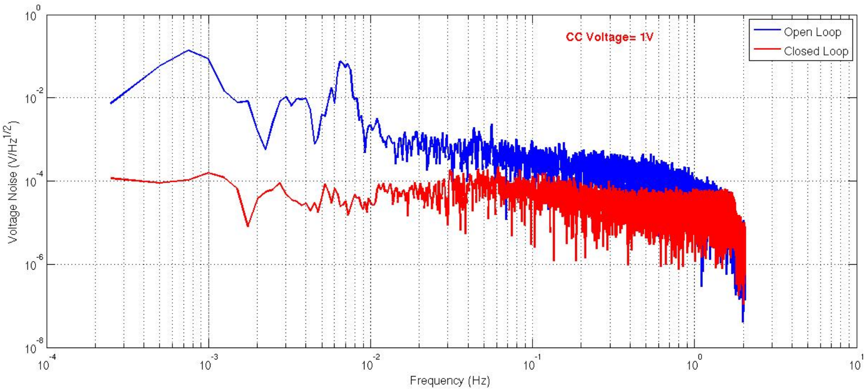

Figure 1.6. Spectrum of the detected output signal of the Mach-Zehnder power stabilization system. This preliminary test - done with a system prototype - shows a stability well below the required 1 %.

1.4.2 Mechanical design

The mechanical design of the Mach-Zehnder interferometer holder is shown in figure 1.7 The holders of the Mach-Zehnder mirrors are mounted on a square aluminum base with height 35.6 mm. The M_1 mirror holder is the Newport 9817-6 of the Stability$^{\mathrm{TM}}$ series. It is a clean and low-outgassing mirror mount with an optics center height equal to 25.4 mm. An adapter, suitably designed, allows the mounting of the M_2 mirror fixed on the PZT on the same kind of holder. The beam sampler are fixed at 45° on the base by means of a single thin aluminum plate that assures their relative position and a center height of 1 inch. The center of the optics is in this way fixed at 61 mm. The whole mechanical system is designed to be vacuum compatible.

1.4.3 Electronic control loop

Figure 1.7. Mechanical design of the Mach-Zehnder interferometer holder.

Figure 1.8. Transfer function of the closed loop system.

1.5 OPO pre-Mode Cleaner Cavity

The *mode-cleaner* cavities (MC) have a crucial role in quantum optics experiments based on OPO/OPA sources and in particularly in the squeezing experiments [10, 4, 9] thanks to their frequency and spatial filtering features. Spatially they reflect the mode higher than the TEM_{00} allowing the power concentration in the latest. In the frequency space they acts as low-pass filter for the laser amplitude and phase noise: outside the cavity linewidth, the amplitude noise of the injected laser field is attenuated with a single cavity-pole transfer function. In particular this feature has been demonstrated to be a crucial key to reach higher squeezing value since it filters the high frequency phase noise introduced by the Drever Pound Hall locking systems (DPH) by means of the RF modulation [9, 3, 7].

Even though when DR-OPO is used, in principle a pump pre-MC is not required, since the pump resonance assure the self mode cleaner, it could be useful to introduce a pre-MC cavity to further filter the OPO pump, since really both the SHG cavity and the OPO have a low finesse..... .... Furthemore a ring pre-MC acts as polarization filter [6].

Moreover it could provide the spatial mode for the homodyne detector, by designing a MC cavity for the homodyne LO equal to the OPO pre-MC and and by suitably matching the latest with the OPO cavity. In fact in this way the identical cavities geometry will determine the spatial mode of the two beams on the homodyne BS and this allows a easy way to maximize the homodyne efficiency, by maximizing its visibility with the best overlap of the two modes on the BS. (*will follow a dedicate note about*)

1.5.1 532MC optical parameters

The pre-MC is a triangular cavity ring resonators with two plane input/output coupler mirrors and the third one plane-concave with $RoC = 1$ m. It has been designed performing a trade-off between the minimization of the astigmatism and the minimization of the backscattering [6], so that the incidence input angle has been chosen $\alpha = 43.88$ °, resulting in a incidence angle on the concave mirror $\theta = 2.25$ °. The cavity length is $L_{MC532} = 582.29$ mm. In the table 1.1 the cavity geometrical parameters are reported, included the stability factor, g.

– –	w_0 (µm)	w_{in} (µm)	w_{out} (µm)	w_{cc} (µm)	z_R (mm)	Gouy phase (π)	g
x	392.036	392.151	392.151	465.785	453.797	0.3625	0.6991
y	392.463	392.577	392.577	465.996	454.784	0.3631	0.7006

Table 1.1. Geometrical parameters od the 532MC. LEGENDA: w_0 beam waist size; w_{in} beam waist size on the input planar mirror; w_{out} beam waist size on the output planar mirror; w_{cc} beam waist size on the concave mirror; z_R Rayleigh parameter; g stability factor of the equivalent plane cavity.

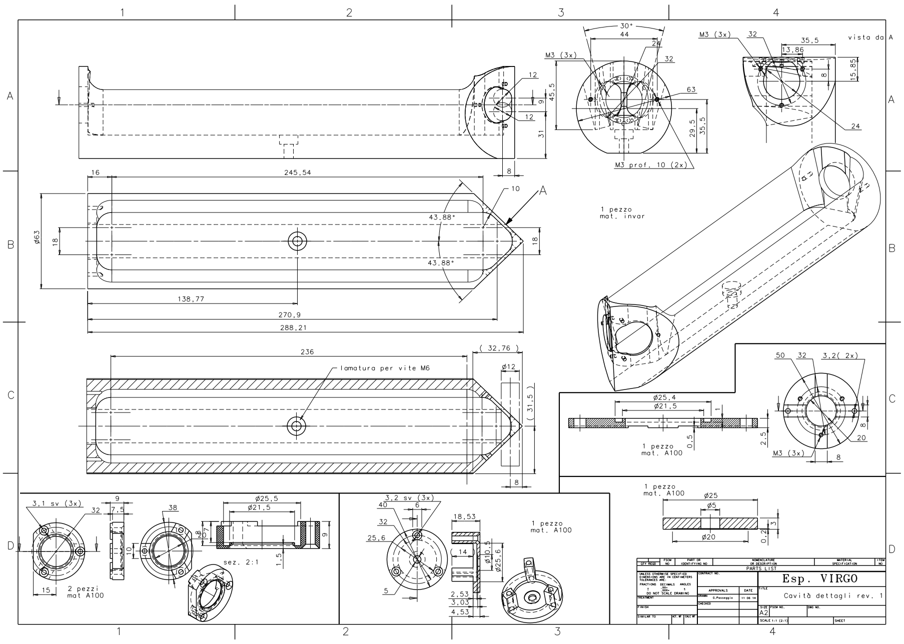

Figure 1.9. CAD design of the MC holder. N.B.: The concave mirror design is not the definitive.

All the mirrors will be super-polished and the reflectivity of the input and output coupler is $R = 0.995$, while the reflectivity of the rear concave mirror is $R = 0.9998$.
The resulting finesse is $\mathcal{F} = 614$, the linewidth $FWHM = 514.85$ MHz anf the free spectral range $FSR = 514.85$ MHz

1.5.2 532MC mechanical design

The holder of the pre-MC is made of an INVAR bar with the mirrors mechanically fixed to it by means of aluminum holder, in order to avoid the mirrors coating contamination by means of the glue (figure 1.9). The invar holder has wedge-shaped lateral walls at 15° to allow to the eventually scattered photons on them to fast leave the cavity. The concave mirror holder hostes the PZT of the DPH locking system. The system is a sandwich of PZT, a aluminum ring, the mirror and a elastic viton ring hosted in a suitably trilled holder that is fixed on the main invar body by means of screw. The aluminum ring between the PZT and the mirror assure that no deformation on the center of the mirror surface can happen. All the system is vacuum compatible, having suitable hair holes where necessary.

1.5.3 532MC DPH loocking system

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