

# Auxiliary lasers for Advanced Virgo Gravitational Wave detector using single pass Second Harmonic Generation in Periodically Poled Lithium Niobate crystal

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**Abstract.** The Advanced Virgo (AdV) detector is composed of different degrees of freedom (DOFs) i.e. Michelson interferometer, two Fabry-Perot arm cavities, signal recycling cavity, and power recycling cavity. These DOFs need to be locked to precise accuracy with robust, fast and reliable control systems. The control signals used to lock all the DOFs are mildly decoupled in frequency and the optical response of the DOFs are nonlinear, where the linear range of operation is just some percentage of the fringe for each DOF, thus posing difficulty in resonance lock at input laser wavelength for all the cavities. In particular, the control status of the arm cavities can alter the state of the detector's operational configuration. Using Auxiliary Lasers to lock the arm cavities at different wavelength offers flexible and robust lock of the detector and more spatial margin on the control signals. Second harmonic generation offers the most direct way to have laser beam with different wavelength and phase locked to the AdV input laser beam. We generated upto 97 mW of SH beam in single configuration at 532 nm using fibered amplified laser source at 1064 nm in a 10 mm long Poled Lithium Niobate crystal.

## 1. Introduction

Albert Einstein predicted the existence of Gravitational Waves (GWs) in 1916 thanks to his formulation of the field equations of General Relativity (GR). The experimental efforts in terms of laser interferometry based GW detectors around the globe like LIGO [1] in USA, Virgo [2] in Italy and GEO600 in Germany [3] use laser light to sense the test masses displacement in response to GW strain  $h(t)$ . Over the years, these detectors have improved the desired strain sensitivity while forming network of detectors to provide accuracy and source localization of GW events. With the first ever direct detection of GWs [4] in September 2015 by the twin LIGO detectors, GW astronomy has emerged as a new window on astronomy, that deals with the observation of GWs from astrophysical sources such as binary systems of neutron stars, black holes, astrophysical events such as supernovae and might also give information about the early



universe formation.

Advanced Virgo GW detector is a dual recycled Michelson interferometer (at present, the signal recycling cavity is not yet installed), with Fabry-Perot cavity in each arm. Other cavities, input and output mode cleaners, are used for spatial filtering of the input and output laser beams. Due to this complex structure DOFs need to be locked to precise accuracy with robust, fast and reliable control. The control signals used to lock these DOFs are mildly decoupled in frequency from each other, which poses difficulty in reaching the optimum working point of the detector i.e. to keep all the cavities on resonance simultaneously for the IR laser light at 1064 nm. In particular, the control status of the arm cavities can alter the state of the detector's operational configuration i.e. 25 W power recycled interferometer, 25 W dual recycled interferometer and 125 W dual recycled interferometer. Moreover, the optical response of the DOFs are nonlinear, where the linear range of operation is just some percentage of the fringe for each DOF. Keeping in mind these stringent conditions, resonance lock for all the DOFs is required, that makes it a challenging task.

The idea of using auxiliary lasers to lock the arm cavities with a different wavelength allows ease in achieving flexible and robust lock and offers more spatial margin on the control signals. The auxiliary lasers are used in the lock acquisition process, where auxiliary laser beam is resonant on the arm cavities and AdV input laser beam at 1064 nm is off resonance. Meanwhile, the central interferometer is locked with the AdV input laser beam. In the steady state, the arm cavities are brought back to resonance on the AdV input laser beam.

We are using the second harmonic generation (SHG) process to generate auxiliary laser beam, which is the most direct and less bulky way of producing different wavelength that is phase locked to AdV input laser beam.

## 2. The AdV control subsystem

One of the important consideration in the development of the GW detector is the control systems for locking the optical cavities. In AdV, the Interferometer Sensing and Control (ISC) subsystem is responsible for implementing the control system both in the lock acquisition and the steady state operation of the detector [5].

### 2.1. Degrees of freedom of AdV

The DOFs of AdV to be controlled are categorized into longitudinal and angular, and are operated with two different control systems. The longitudinal DOFs have to be dealt both in steady state and lock acquisition operation, while the controls related to angular DOFs have to be activated only in the final stage of the lock sequence. The longitudinal DOFs are described in the following section and are of more concern as they have to be dealt in both steady state and lock acquisition. In dual recycled configuration, the AdV is comprised of five longitudinal degrees of freedom (DOFs) i.e. differential arm cavity length (DARM), common arm cavity length (CARM), Michelson (MICH), power recycling length (PRCL) and signal recycling length (SRCL) as shown in Fig. 1. The scheme shows relevant physical distances between mirrors in dual recycled configuration.

These DOFs have to be controlled and locked to an accuracy as shown in Tab. 1 for the optimum operation of the detector with a robust, stable and fast control system. The control mechanism for each DOF is implemented by using their corresponding error signals, allowing the related DOF to operate at the target point. The error signals are generated for these DOFs using a standard Pound Drever Hall (PDH) technique [6] that contains the information about the current position of the DOF and the distance between the current and the operating points. This information is used to drive the actuator to bring the suspended masses to the desired working points. All the beams related to these DOFs are sensed at appropriate positions with suitable photodiodes for monitoring and quadrant photodiodes for control purpose. The detection (DET)

**Table 1.** Lock accuracy required for DOFs [5].

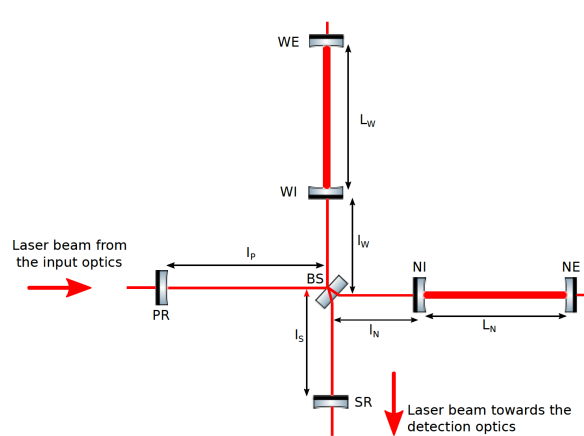
DOF	Power recycled 25W	Dual recycled 25W	Dual recycled 125W
DARM	$6 \times 10^{-16}m$	$2 \times 10^{-15}m$	$1 \times 10^{-15}m$
Frequency		7 mHz	
CARM		$4 \times 10^{-13}m$	
MICH	$2 \times 10^{-13}m$	$6 \times 10^{-13}m$	$3 \times 10^{-13}m$
PRCL		$2 \times 10^{-11}m$	
SRCL			$3 \times 10^{-13}m$

subsystem sets the limit on the amount of power to be sensed on the photodiodes (100 mW) and the quadrant photodiodes (25 mW) with the exception of the quadrant photodiode at the dark port, where the power is reduced to 2.5 mW per quadrant.

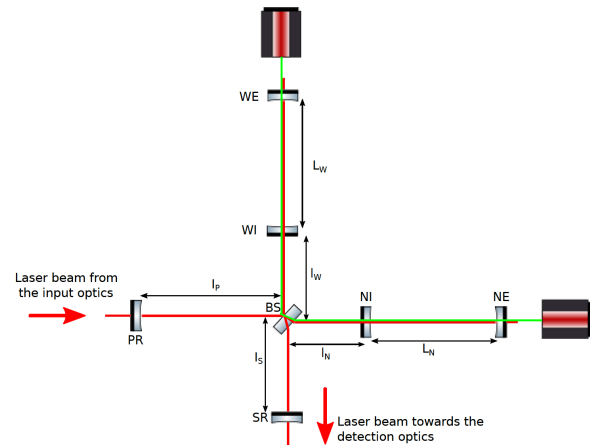
The control signals related to these DOFs are strongly coupled i.e. separated mildly in frequency, so it poses difficulty in locking the interferometer with all the cavities on resonance, particularly in the presence of signal recycling cavity, which will add more complexity to the AdV lock.

In particular, the arm cavities control status can strongly change the state of the dual recycled operation of the interferometer. The related DOF i.e. DARM, which is used for the detection of GWs, needs to be dealt with more care, as the error signal of DARM may get influenced by higher order modes (HOMs) interaction. The very high Finesse arm cavities will need lock mechanism based on a wavelength which is different than the main laser beam, the reason being that the Finesse can be chosen independently as seen by the Virgo main laser. Along with all these challenges, a simultaneous resonance lock on all cavities need to be achieved.

Using auxiliary lasers, the arm cavities are dealt separately in the lock sequence process, allowing for ease in lock acquisition process using a different wavelength and switching to the AdV main laser to perform the full lock of the detector in steady lock state. The AdV lock mechanism with auxiliary lasers is shown in Fig. 2. The auxiliary lasers will be injected through the two end test masses of AdV.



**Figure 1.** Degrees of freedom of the AdV detector.



**Figure 2.** Auxiliary Lasers mechanism in AdV locking.

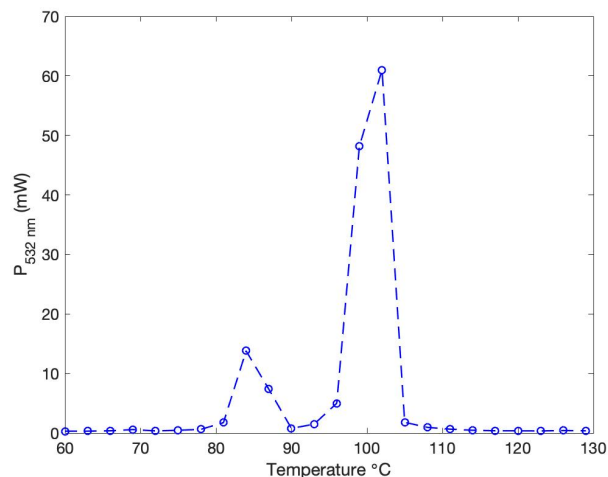


compact design and stable homogeneous temperature distribution across the crystal length. The oven is mounted on a translational stage, that allows two DOFs i.e. the vertical and the perpendicular degrees of freedom with respect to the fundamental laser beam propagation axis. There exist another DOF along the laser beam propagation direction by using the translation stage of lens f2. All these DOFs allow optimum focusing of the fundamental laser beam at the centre of the crystal. We performed the single pass SHG measurement with measured beam waist of  $w_0 = 20 \mu\text{m}$  inside the crystal. The measured data is compared with theoretically expected single pass SHG with effective nonlinear coefficient for PPLN crystal to be  $d_{eff} = 16 \text{ pm/V}$ .

In order to make the optical system free of stray light, acoustic noise, and to avoid the contamination of the optical components on the bench, an enclosure is placed, that also makes the system portable. Our optical system is plug and play, where the fiber collimators are used to input the 1064 nm laser beam to the system and another to take out the 532 nm laser beam.

#### 3.4. Phase match temperature characterization

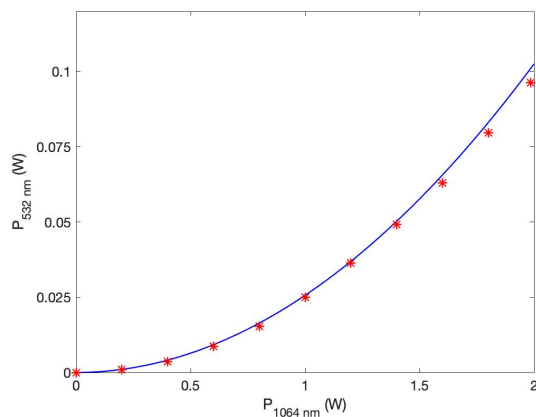
In order to find the optimum phase matching temperature, we used Covision OC2 Temperature Controller to vary the temperature across the crystal placed in Covision PPLN oven for fundamental laser beam power of 1.5 W. OC2 temperature controller offers long term stable temperature maintenance with set point stability and resolution up to  $\pm 0.01 \text{ }^\circ\text{C}$  and maximum set temperature up to  $200 \text{ }^\circ\text{C}$  for optimized conversion efficiency. The temperature across PPLN crystal is varied from  $60 \text{ }^\circ\text{C}$  up to  $129 \text{ }^\circ\text{C}$  and the measured optimum phase matching temperature is  $101.5 \text{ }^\circ\text{C}$ . Phase match temperature characterization is shown in Fig. 4.



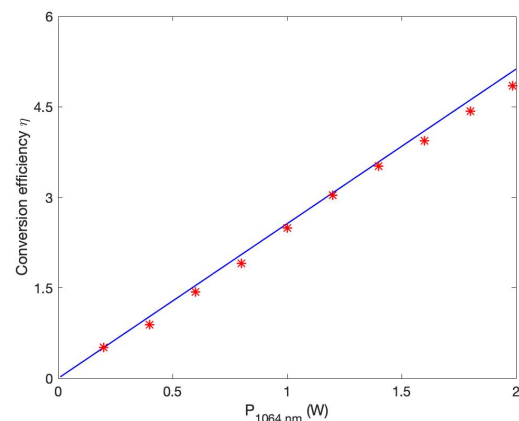
**Figure 4.** Phase matching temperature for optimum conversion efficiency of SHG interaction in PPLN crystal.

#### 3.5. Measured single pass SHG versus theoretically expected SHG in PPLN crystal

Fig. 5 represents the generated SH laser beam power for range of fundamental laser beam power from 200 mW to 1980 mW at beam waist of  $w_0 = 20 \mu\text{m}$ . The solid line represents the theoretical expected SHG, and the circles represent the measured SHG data. Conversion efficiency calculated in single pass SHG at focused fundamental laser beam of waist size  $w_0 = 20 \mu\text{m}$  is shown in Fig. 6. In this experimental activity we generated upto 97 mW of SH laser beam at 532 nm with conversion efficiency of  $\eta = 4.85$  at fundamental laser power of



**Figure 5.** Single pass SHG at different optical powers of fundamental laser beam of waist size  $w_0 = 20 \mu\text{m}$  in PPLN crystal.



**Figure 6.** Single pass SH conversion efficiency versus fundamental laser beam in PPLN crystal.

1980 mW. To conclude, coherent and stable frequency doubled laser beam at 532 nm provides simple, robust and economical solution towards the implementation of auxiliary lasers for AdV GW detector. This experimental study provides the laboratory demonstration of single pass SHG in PPLN crystal as an alternate to employing dedicated solid state laser units as auxiliary lasers using a small pickoff beam from the AdV main laser, and thus also eliminating the need of additional phase lock loops between auxiliary lasers and AdV input laser.

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