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The signal detection system for the VIRGO interferometer

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Abstract

Several interferometers devoted to the detection of gravitational waves are currently being built in Europe and in the USA. The detection of the tiny mirror displacements (10^{-18}–10^{-19} m) induced by a gravitational wave requires to measure fringe variations between 10^{-10} and 10^{-11} fringes. The solutions adopted for the VIRGO interferometer are described. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

VIRGO [1,2] is a gravitational wave detector based on a Michelson interferometer with 3 km long arms (see Fig. 1). The detector is currently being built near Pisa (Italy) by a French–Italian collaboration supported by INFN (Italy) and CNRS (France). The aim of the project is the first direct detection of gravitational waves generated by astrophysical processes in the 10 Hz to a few kHz frequency band.

As a gravity wave crosses the interferometer plane, one arms gets longer while the other gets shorter. Gravitational waves having an amplitude $h = 3 10^{-22}$ will produce a change in length of the order of 10^{-18} m. The VIRGO interferometer will use a 3 km long Fabry–Perot cavity in each arm (as shown in Fig. 1) to increase the light phase shift due to a mirror displacement. The signal detection system will have to measure light phase shifts of the order of 10^{-10} rad.

2. Interferometer signal detection

The phase sensitivity of a Michelson interferometer is maximum when the interferometer is 'operated at the dark fringe', i.e. when the light reflected by the two arms of the interferometer interfere in a way that no light is transmitted towards the photo-detectors.

In this condition the interferometer phase sensitivity is theoretically limited by photon shot-noise [3]. According to this limit, the minimum detectable light phase difference is equal to $1/\sqrt{\eta N_\gamma}$ where N_γ is the number of photons impinging on the beam-splitter per second and η is the photo-detector quantum efficiency. A light power of 1 kW at the splitter will be achieved in VIRGO using high power Nd:YAG laser [4] and the so-called recycling technique [5]. High quantum efficiency at the laser wavelength (1.06 μm) is thus required in order to attain a good sensitivity.

Technical limits like laser power noise may spoil the interferometer sensitivity. To reduce the effect

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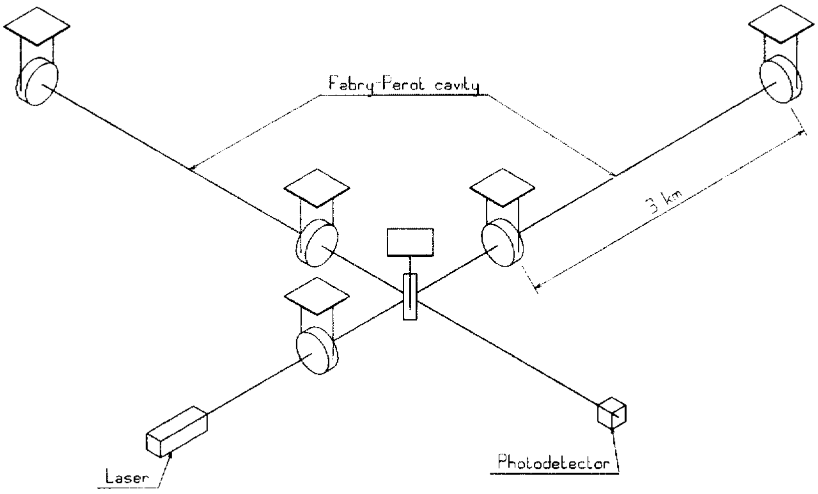

Fig. 1. Sketch of the VIRGO interferometer.

of this noise the light is phase modulated at high frequency (~ 10 MHz) and the signal is detected at this same frequency.

3. Photo-detectors selection

One of the task of the signal detection system is to collect and detect the light at the interferometer output port. InGaAs photo-detectors have been chosen for the VIRGO interferometer since they have the best quantum efficiency at 1.06 μm. As the dimension of the detectors increases so does the capacitance and, as a consequence, the bandwidth decreases. On the other hand, larger detectors allow to deal with larger light powers and make the alignment easier. A good compromise is to use photo-detectors having a diameter of 3 mm.

Several 3 mm diameter photo-detectors have been tested at LAPP [6]. The Hamamatsu company was able to provide photo-detectors with AR coating deposited on the detectors. The coating allows to reduce the retro-reflected light below 1% and to obtain a quantum efficiency of about 86%. The photo-diodes equivalent capacitance and series resistance have been measured to be low enough ($C = 300\,\mathrm{pF}$ and $R = 7\,\Omega$) to allow for a use of the detectors up to more than 10 MHz. The photo-diodes linearity at DC and at high-frequency (6–18 MHz) has also been measured. The result of the measurement at 6 MHz are shown in Fig. 2. The linearity is seen to be excellent. Similar results have been obtained at 12 and 18 MHz. These results led to the choice of such photo-diode for VIRGO. According to the measurements and tests performed at LAPP one single photo-detector can measure light levels up to more than 100 mW. Several photo-detectors in parallel will be used to deal with the higher power (1 W) expected for the VIRGO interferometer.

4. Interferometer output beam filtering

A bad interference contrast will reduce the sensitivity. As a matter of fact the light will travel back and forth in the arms many times (50) before recombining at the splitter and, due to the mirrors surface deformation, the wavefronts interference at the splitter will not be perfect. As a consequence some light is transmitted towards the interferometer output port even 'at the dark fringe'. The residual light thus impinging on the photo-detectors produces excess noise that limits the interferometer sensitivity.

The sensitivity may be improved by using an optical filter able to transmit the TEM00 mode component of the field and to filter out the higher-order modes due to the wavefronts deformation.

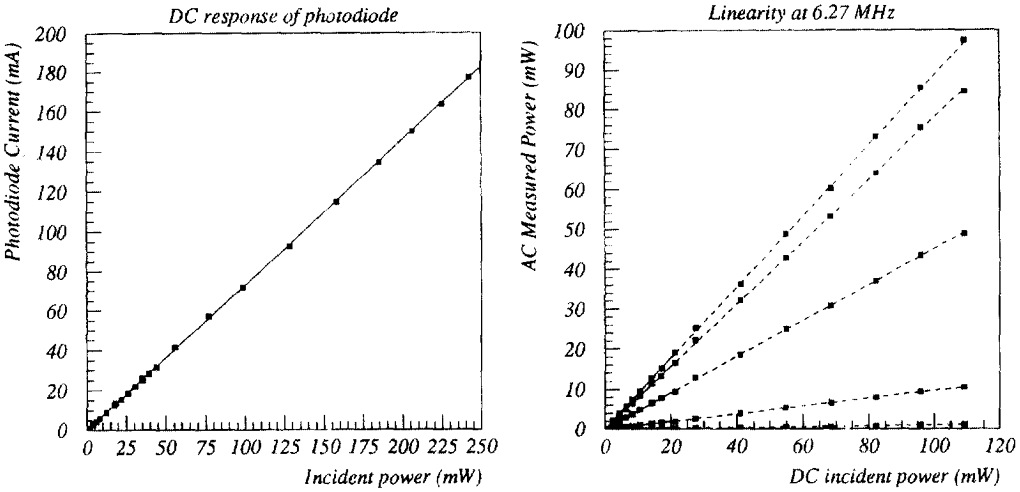

Fig. 2. Measured photo-diode linearity at DC (left) and at 6 MHz (right). The curves at 6 MHz correspond to different light modulation amplitudes.

Such a filtering can be achieved by passing the interferometer output beam through a resonant optical cavity placed in front of the photo-detectors. By adjusting the cavity length only the TEM00 mode will be completely transmitted while the other modes will be attenuated by a factor depending on the cavity finesse. In doing this one has to consider that any mechanical vibration of this cavity can simulate a gravitational wave signal. For this reason the solution of a compact monolithic cavity made by a small pieces of silica properly polished, has been adopted. The cavity is arranged in a triangular shape and is 2.5 cm long. The cavity optical length is controlled using a thermal feedback which changes the glass index of refraction. The experimental test done at LAPP shows that this control is able to maintain the cavity at resonance with a precision of the order of $\lambda/30\,000$ [7].

5. The design of the signal detection system

The signal detection system is the system devoted to the following functions: output beam filtering, light photo-detection and signal read-out. First the interferometer output beam is focused and filtered by the output optics. This optics is suspended to a seismic isolator and kept in vacuum (as well as most of the interferometer) in order to reduce the effect of seismic and acoustic noise. Once reduced in size and filtered, the interferometer output beam is sent outside the vacuum chamber towards the photo-detectors. The resulting high-frequency signal is demodulated and amplified. The largest low-frequency component (< 1 Hz) of the signal is attenuated in order to reduce the dynamic range and the filtered signal is then digitized using a 16 bits ADC for each photo-detector. The signal is then sent to the DAQ and to interferometer global control.

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