Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Instruments and Methods in Physics Research A 518 (2004) 240–243
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

# Thermal noise reduction for present and future gravitational wave detectors

P. Amico[a,b], L. Bosi[a,b], L. Gammaitoni[a,b], G. Losurdo[c], F. Marchesoni[a,d], M. Mazzoni[c,e], M. Punturo[a,*], R. Stanga[c,e], A. Toncelli[f,g], M. Tonelli[f,g], F. Travasso[a,b], F. Vetrano[c,h], H. Vocca[a,b]

[a] Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Via Pascoli, Perugia, Italy
[b] Dipartimento di Fisica, Universitá di Perugia, Perugia, Italy
[c] Istituto Nazionale di Fisica Nucleare, Sezione di Firenze/Urbino, Firenze, Italy
[d] Dipartimento di Fisica, Universitá di Camerino, Camerino, Italy
[e] Dipartimento di Fisica, Universitá di Firenze, Firenze, Italy
[f] Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Pisa, Italy
[g] Dipartimento di Fisica, Universitá di Pisa, Pisa, Italy
[h] Istituto di Fisica, Universitá di Urbino, Urbino, Italy

**Abstract**

Thermal noise in mirror suspension is and will be the most severe fundamental limit to the low-frequency sensitivity of interferometric gravitational wave detectors currently under construction. The technical solutions, adopted in the Virgo detector, optimize the current suspension scheme, but new materials and new designs are needed to further reduce the suspension thermal noise. Silicon fibers are promising candidates both for room temperature advanced detectors and for future cryogenic interferometric detectors.


*PACS:* 43.40.Cw; 62.40.+i; 05.40.−a; 04.80.Nn

*Keywords:* Gravitational wave detectors; Thermal noise; Silicon

## 1. Introduction

The thermal noise sources in an interferometric gravitational waves (GW) detector are mainly two: the suspension wires fluctuation and the mirror internal vibration. Both the phenomena are described by the fluctuation–dissipation theorem [1], that relates the thermal fluctuation spectrum to the dissipation processes inside the observed system. A detailed description of the thermal noise due to suspension wires in a GW detector can be found in Ref. [2]. The horizontal displacement power spectrum $|X_{\rm h}(\omega)|^2$, neglecting any horizontal to vertical coupling in the suspension, is given by

$$|X_{\rm h}(\omega)|^2 \simeq \frac{4k_{\rm B}T}{\omega^5}\, g\, \frac{1}{L_{\rm w}^2}\sqrt{\frac{Eg}{4\pi nm}}\left\{\frac{\phi(\omega)}{C_{\rm s}T_{\rm B}}\right\} \tag{1}$$

where $L_{\rm w}$ is the suspension wire length, $E$ is the Young's modulus of the wire material, $n$ is the

*Corresponding author. Fax: +39-075-584-72-96.
*E-mail address:* michele.punturo@pg.infn.it (M. Punturo).

0168-9002/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2003.10.071

number of suspension wires (in Virgo $n = 4$) for each mirror of mass $m$ and $C_s$ is the percentage of tensile breaking stress $T_B$ at which the wire is loaded. The loss angle $\phi(\omega)$ represents the sum of all the dissipative processes that occur in the suspension wire: $\phi(\omega) = \phi_w + \phi_e + \phi_{th}(\omega)$, where $\phi_w$ is the loss angle due to the wire material itself, $\phi_e$ is the excess loss angle due to parasitic dissipation processes, like the residual clamping losses [3] and $\phi_{th}(\omega)$ is the (linear) thermoelastic contribution:

$$\phi_{th}(\omega) = \Delta \frac{\omega\tau}{1 + (\omega\tau)^2},$$

$$\Delta = \frac{E\alpha^2 T}{c_v}, \quad \tau = \frac{c_v d_w^2}{2.16\, 2\pi\, \kappa} \tag{2}$$

where $c_v$ is the specific heat per volume unit, $\alpha$ the linear expansion coefficient and $\kappa$ is the thermal conductivity of the wire material. In Virgo, thanks to the very efficient seismic noise filtering system [4], the thermal noise given by Eq. (1) dominates from about 4 up to 500 Hz.

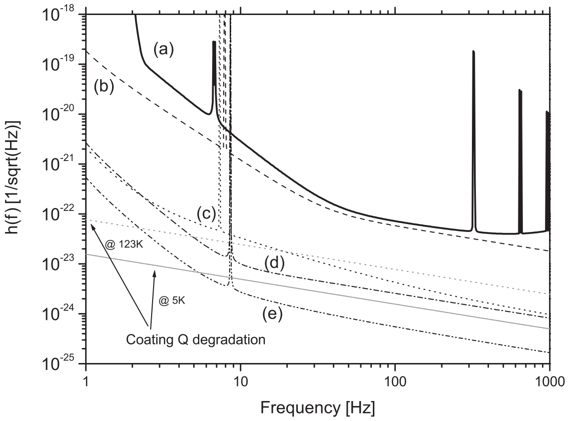


Fig. 1. Virgo sensitivity curves: (a) the expected current Virgo sensitivity; (b) the thermal noise contribution (pendulum and mirror) for an upgraded version of Virgo, using monolithic fused silica suspension. The other curves represent the thermal noise contribution in an advanced cryogenic GW detector using (c) silicon suspension fibers and calcium fluoride substrates at 5 K; (d) Si suspension fibers and substrates at 123 K; (e) Si suspension fibers and substrates at 5 K. In the cryogenic detector simulation a $Q = 10^8$ has been used as mechanical quality factor for the mirror, neglecting the coating dissipation; the mirror thermal noise increase, due to a 6 μm thick $Ta_2O_5$ coating, is reported in the figure.

## 2. Current solution

Almost all the GW interferometric detectors (LIGO, TAMA and Virgo) are realized suspending the mirrors, composing the optical cavities of such interferometers, by metallic wires. In Virgo a specific kind of steel (C85) has been choosen that optimizes [5] the ratio between brackets in Eq. (1). In this configuration the main effort, in terms of thermal noise reduction, is devoted to the minimization of the excess losses, using a low dissipation clamping system [3] and inserting fused silica spacers in the wire-to-mirror contact points [6]. The mirror thermal noise is optimized reducing the excess dissipation introduced by the control components (camera targets, magnets and spacers), attaching them through the *silicate bonding* [2] technology. With these solutions a pendulum quality factor $Q$ and mirror $Q$ of about $10^6$ has been obtained, reaching the expected sensitivity curve (curve (a)) reported in Fig. 1.

## 3. Future developments

### 3.1. Fused silica fibers

It is well known that, using fused silica (FS) fibers to suspend the mirrors, it is possible to strongly reduce the thermal noise on the pendulum oscillation mode; the GEO600 GW detector already uses a monolithic design, but, because of several technical issues, with different and more relaxed specifications with respect to the Virgo requirements. FS fibers show an intrinsic loss angle of about two orders of magnitude lower than metallic wires [5]. The thermo-elastic dissipation in FS fibers is suppressed by the fact that the thermal expansion coefficient $\alpha$ is about $0.5 \times 10^{-6}\ K^{-1}$ at room temperature. The tensile strength of a FS fiber is about $T_b \simeq 4$ GPa [2], dominated by the cracks and defects present in the fiber surface (low $C_s$). In the Perugia labs, the development of a FS suspension for Virgo has successfully completed the research phase and, now, it is in the engineering phase. A full scale prototype will be soon realized in the Virgo site. The main difficulties in the realization of this suspension are due to the fact that Virgo has the largest and heaviest mirrors available in the current GW detectors and the seismic attenuation system is currently the most complex one realized for a GW detector. The sensitivity of Virgo, with monolithic FS suspension should improve as reported in Fig. 1 (curve (b)).

### 3.2. Crystalline fibers

FS fibers are not a good candidate to realize a cryogenic suspension for a future interferometer; in fact, the dissipation angle of FS shows a (Debye) peak at low temperature and the low thermal conducibility of FS reduces the extraction of the heat deposited by the laser in the mirror. Other materials must be investigated. In addition to the constraints imposed by Eq. (1) (low loss angle $\phi$, high tensile strength $T_B$ and high reliability $C_s$), a material, good to realize the suspension of an advanced cryogenic interferometer, must show a high thermal conductivity and, possibly, a low thermal expansion coefficient. The latter characteristics reduce also the thermoelastic contribution (see Eq. (2)) to the thermal noise. Several materials have been investigated, modeling their linear thermoelastic noise at room temperature (see Fig. 2). Crystalline silicon is a good candidate thanks to its high thermal conductivity ($\kappa(300\ \mathrm{K}) = 1.48 \times 10^2\ \mathrm{W\ m^{-1}\ K^{-1}}$) that pushes the thermoelastic peak at higher frequency, where the pendulum thermal noise is not dominant. Silicon becomes a perfect candidate when it is studied for a cryogenic interferometer; the large thermal conductivity (Fig. 3) at low temperature permits to extract a large fraction of energy from the interferometer mirror. The expansion coefficient $\alpha$ is null (Fig. 3) at about 17 and 123 K; in these conditions the contribution to the thermal noise due to the linear thermoelastic effect is null. Furthermore, the intrinsic loss angle of Silicon is expected to be very good ($\phi(300\ \mathrm{K}) \simeq 2.8 \times 10^{-8}$, $\phi(77\ \mathrm{K}) \simeq 5 \times 10^{-9}$ and $\phi(4.2\ \mathrm{K}) \simeq 6 \times 10^{-10}$) [8] and the breaking strength of a Si fiber is larger than steel (about 7 GPa, but still dominated by surface effects that decrease that value down to about 1 GPa). For all these reasons crystalline silicon is a very good candidate to realize the suspensions of a future cryogenic interferometer. A fiber production facility, using the $\mu$Pull-Down technique, is under development, in the Pisa labs, to realize crystalline fibers to be tested in a cryogenic environment. If a new generation of lasers at wavelength longer than 1.3 μm, with characteristics compatible with the requirements of a GW detector, will be developed, crystalline silicon it is also interesting to realize the substrates of a cryogenic interferometric GW detector. In fact, the low thermal expansion coefficient, at cryogenic temperature, reduces the thermodynamical noise [9], that is the main substrate thermal

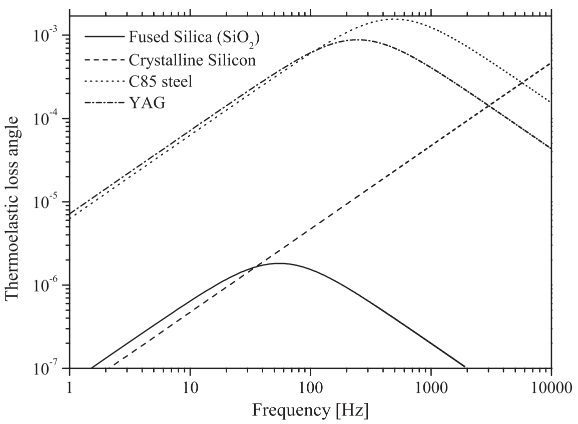


Fig. 2. Thermoelastic loss angles computed for different materials at room temperature.

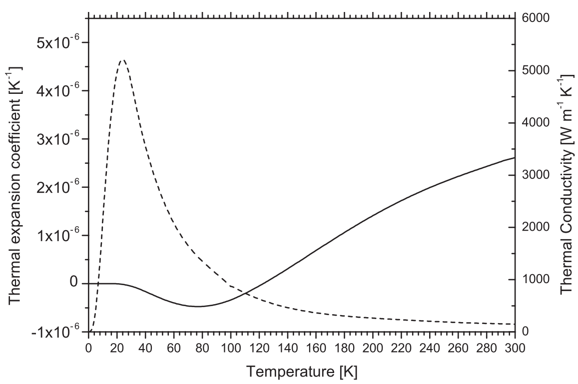


Fig. 3. Thermal properties of silicon [7]: expansion coefficient (continuous line), conductivity (dashed line).

noise source in other material candidates (sapphire, calcium fluoride) for cryogenic GW interferometer. The expected sensitivity of a future detector with silicon suspension fibers and substrates is reported in Fig. 1 (curves (c), (d) and (e)).

### *3.2.1. Optical cooling*

In the thermoelastic dissipation formula (2), the parameter $T$ is the temperature of the flexural point of the suspension wire. To reduce this noise contribution, it is enough to cool down only a limited region around these flexural points. It is under investigation the possibility to cool down a limited section of a crystalline fiber through a technology based on the anti-Stokes luminescence [10]. In a rare-earth-doped fiber, the fundamental and first excited energy atomic levels are split in multiplets by Stark effect. The Stark splitting is typically small ($E_S \simeq 0.02$ eV), while the energy gap between the fundamental and excited levels is about 1.2 eV ($\lambda_g \simeq 1$ μm). An incident laser (optical pump) of wavelength $\lambda_g$ can excite the ions by absorption; by interacting with the phonon energy, the emission can occur at a slight higher energy ($\Delta E \simeq E_S$). Hence, this process can be used to cool down a small sample. In effect, the energy extraction with this technology shows a low efficiency (few percent), ulteriorly decreasing with the overall temperature [10]. The cooling efficiency can be increased by multiple interaction of the incident laser light with the crystalline medium. In a fiber this could be implemented thanks to the cylindrical geometry of the sample. The possibility to work with cryogenic GW interferometers at intermediate temperature, as suggested in the silicon fiber case, permits to use this optical cooling technique to cool down or to control the temperature of the suspension fibers or, maybe, mirrors.

## Acknowledgements

This work has been supported by the Istituto Nazionale di Fisica Nucleare, under the Virgo project.

## References

[1] H.B. Callen, T.A. Welton, Phys. Rev. 83 (1951) 34; H.B. Callen, R.F. Greene, Phys. Rev. 86 (1952) 702.
[2] P. Amico, et al., Rev. Sci. Instrum. 73 (2002) 3318.
[3] G. Cagnoli, et al., Phys. Lett. A 213 (1996) 245.
[4] G. Ballardin, et al., Rev. Sci. Instrum. 72 (2001) 3643.
[5] G. Cagnoli, et al., Phys. Lett. A 255 (1999) 230.
[6] G. Cagnoli, et al., Rev. Sci. Instrum. 71 (2000) 2206.
[7] C.A. Swenson, J. Phys. Chem. Ref. Data 12 (1983) 179.
[8] J. Ferreirinho, in: D.G. Blair (Ed.), The Detection of Gravitational Waves, Cambridge University Press, Cambridge, 1991.
[9] V.B. Braginsky, et al., Phys. Lett. A 264 (1999) 1.
[10] M.T Murtagh, et al., J. Non-Cryst. Solids 253 (1999) 50.