INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **21** (2004) S1009–S1013 PII: S0264-9381(04)68258-X

Monocrystalline fibres for low thermal noise suspension in advanced gravitational wave detectors

P Amico[1,2], **L Bosi**[1,2], **L Gammaitoni**[1,2], **G Losurdo**[3], **F Marchesoni**[1,4], **M Mazzoni**[3,5], **D Parisi**[7], **M Punturo**[1], **R Stanga**[3,5], **A Toncelli**[6,7], **M Tonelli**[6,7], **F Travasso**[1,2], **F Vetrano**[3,8] **and H Vocca**[1,2]

[1] Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Virgo Project, I-06100 Perugia, Italy
[2] Dipartimento di Fisica, Università di Perugia, I-06100 Perugia, Italy
[3] Istituto Nazionale di Fisica Nucleare, Sezione di Firenze/Urbino, Firenze, Italy
[4] Dipartimento di Fisica, Università di Camerino, Camerino, Italy
[5] Dipartimento di Fisica, Università di Firenze, Firenze, Italy
[6] Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Pisa, Italy
[7] NEST—Dipartimento di Fisica, Università di Pisa, Pisa, Italy
[8] Istituto di Fisica, Università di Urbino, Urbino, Italy

E-mail: tonelli@df.unipi.it

Received 29 August 2003
Published 12 February 2004
Online at stacks.iop.org/CQG/21/S1009 (DOI: 10.1088/0264-9381/21/5/094)

Abstract

Thermal noise in mirror suspension will be the most severe fundamental limit to the low-frequency sensitivity of future interferometric gravitational wave detectors. We propose a new type of materials to realize low thermal noise suspension in such detectors. Monocrystalline suspension fibres are good candidates both for cryogenic and for ambient temperature interferometers. Material characteristics and a production facility are described in this paper.

PACS number: 43.40.Cw

1. Introduction

The suspension wire fluctuation and the mirror internal vibration are the two main thermal noise sources in an interferometric gravitational wave (GW) detector. Both phenomena are described by the fluctuation–dissipation theorem [1], which 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 [2]. The horizontal displacement power spectrum $|X_h(\omega)|^2$, neglegting any horizontal-to-vertical coupling in the suspension, is given by

$$|X_h(\omega)|^2 \simeq \frac{4k_BT}{\omega^5} g \frac{1}{L_w^2} \sqrt{\frac{Eg}{4\pi nm}} \left\{ \frac{\phi(\omega)}{C_s T_B} \right\} \tag{1}$$

where L_w is the suspension wire length, E is the Young modulus of the wire material, n is the number of suspension wires 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: $\phi(\omega) = \phi_w + \phi_e + \phi_{\mathrm{th}}(\omega)$, where ϕ_w is the loss angle due to the wire material itself, ϕ_e is the excess loss angle due to parasitic dissipation processes, such as the residual clamping losses [3] and $\phi_{\mathrm{th}}(\omega)$ is the (linear) thermoelastic contribution:

$$\phi_{\mathrm{th}}(\omega) = \Delta\frac{\omega\tau}{1+(\omega\tau)^2}, \qquad \Delta = \frac{E\alpha^2 T}{c_v}, \qquad \tau = \frac{c_v d_w^2}{2\times 16\times 2\pi\times k} \tag{2}$$

where c_v is the specific heat per unit volume, α the linear expansion coefficient and k is the thermal conductivity of the wire material.

2. Selection of the suspension fibre material

It is well known that, using fused silica (FS) fibres to suspend the mirrors, it is possible to strongly reduce the thermal noise on the pendulum oscillation mode [3–6]: the GEO600 GW detector already uses a monolithic FS design [7]. FS fibres show an intrinsic loss angle of more than two orders of magnitude lower than metallic wires [8]. The thermo-elastic dissipation in FS fibres is suppressed by the fact that the thermal expansion coefficient α is about $0.5\times 10^{-6}\,\mathrm{K}^{-1}$ at room temperature and the tensile strength is about $T_b \simeq 4\,\mathrm{GPa}$ [2]. In spite of these positive characteristics, FS presents some drawbacks: the tensile strength (and, partially, the dissipation) is dominated by the cracks and defects present in the fibre surface (low C_s); FS presents a sort of ageing due to ambient moisture; the dissipation angle shows a peak at low temperature [9, 10] and the low thermal conducibility of FS reduces the extraction of the heat deposited by the laser in the mirror in a future high circulating power interferometer. Other materials must be investigated. In addition to the constraints imposed by equation (1) (low loss angle ϕ, 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. Several materials have been investigated, modelling, for a cylindrical fibre of 200 μm of diameter, their linear thermoelastic noise at room temperature (see figure 1, material properties extracted by [11]). Crystalline silicon is a good candidate thanks to its high thermal conductivity ($k(300\,\mathrm{K}) = 1.48\times 10^2\,\mathrm{W\,m^{-1}\,K^{-1}}$) [12] that pushes the thermoelastic peak at higher frequency, where the pendulum thermal noise is not more dominant [13]. Silicon becomes a perfect candidate when it is studied for a cryogenic interferometer; the large thermal conductivity (figure 2) at low temperature permits us to extract a large fraction of energy from the interferometer mirror. The expansion coefficient α is null (figure 2) at about 17 K and 123 K; under 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 $\phi(4.2\,\mathrm{K}) \simeq 6\times 10^{-10}$) [14] and the breaking strength of a Si fibre is larger than that of 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 [15–18].

3. Fibre production facility

The international state of the art of growing crystalline fibres is still rather embryonic and rapidly expanding [19]. To the best of the author's knowledge silicon crystal fibres have been

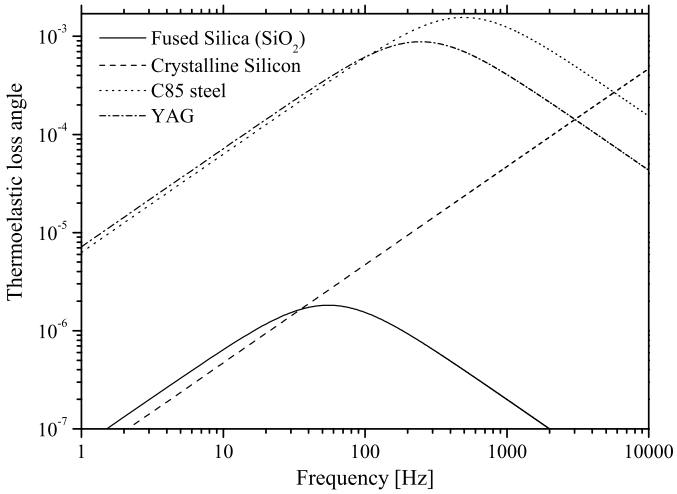

Figure 1. Thermoelastic loss angles, for a cylindrical fibre of 200 μm of diameter, computed for different materials at room temperature. Fused silica: continuous line, crystalline silicon: dashed line, C85 steel: dotted line, YAG: dash–dotted line.

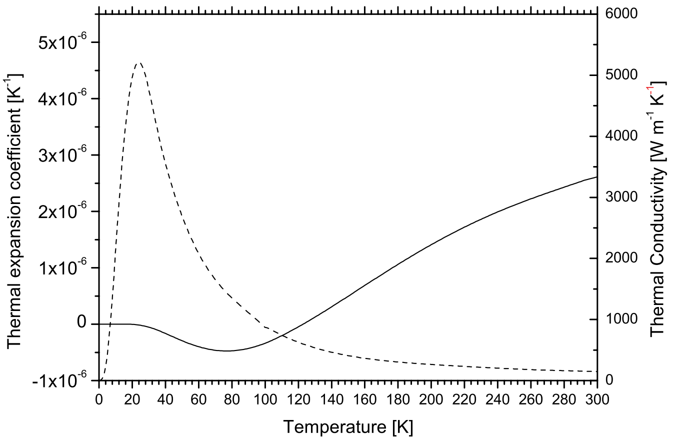

Figure 2. Thermal properties of silicon [12]: expansion coefficient (continuous line), conductivity (dashed line).

grown only once [20] with good results as regards the diameter control and the crystal quality of the fibres, even if evidence of some dislocations and other crystal defects was found in the grown samples. Nevertheless, the authors state that it should be possible to grow defect-free high strength Si crystal fibres.

For the production of crystal fibres one of the main methods developed is *micro pulling-down* (μ-PD) [21]. In this method the base material is fused in a small crucible and flows through a capillary hole (0.1–1 mm) in the bottom of the crucible; the fibre is pulled downwards by means of a rod that carries a seed. This system is derived from the Czochralski technique for the growth of bulk crystals. The interest of this method comes from the small volume of the melt (from a few cm^3 to some tens of cm^3), the fast growing speed (0.2–20 mm min^{-1}) which allows an uniform axial distribution of the components and the low cost. With the μ-PD method, it is possible to obtain monocrystal fibres of semiconductor and insulating crystals

Figure 3. Picture of the first LiF fibre grown in our μ-PD furnace.

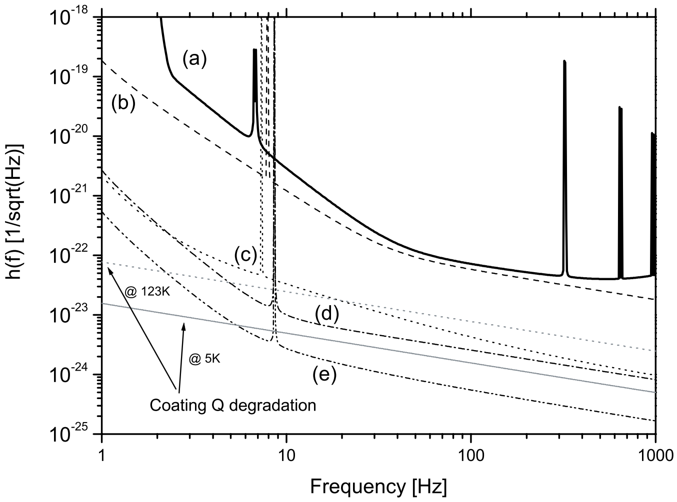

Figure 4. Virgo sensitivity curves: (*a*) the expected current Virgo sensitivity; (*b*) the thermal noise contribution (pendulum and mirror) for an upgraded version of Virgo, using monolithic fused silica suspension. The other curves represent the thermal noise contribution in an advanced cryogenic GW detector using (*c*) silicon suspension fibres and calcium fluoride substrates at 5 K; (*d*) Si suspension fibres and substrates at 123 K; (*e*) Si suspension fibres 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 tick Ta_2O_5/SiO_2 alternate layer coating, is reported in the figure.

with diameter 100–2000 μm and up to several tens of centimetres long. A μ-PD furnace devoted to the growth of insulating crystals has just set up at the University of Pisa. With that furnace and without any active diameter control system some fibres have already been grown with good results. In figure 3 we show a LiF fibre. To the best of the authors' knowledge, it is the first time this crystal has been grown in the shape of a fibre. During the growth process the temperature was kept constant at about 775 °C, and the pull rate was 0.5 mm min^{-1}. The fibre is about 12 cm long with a diameter of about 0.5 mm. In the same apparatus a 14 cm long $LiNbO_3$ fibre has also been grown.

With a similar apparatus and with a diameter control system, we will be able to grow monocrystal silicon fibres to be tested as possible materials for the suspension of the mirrors in GW detectors.

4. Conclusion

Monocrystalline materials are a possible candidate to realize the suspension fibres of the optics of a future interferometric GW detector. In particular, silicon fibres result to be an interesting alternative to fused silica fibres both at room temperature and for cryogenic interferometers. Silicon fibres will be produced using a μ-PD facility under development. The expected sensitivity of a future detector with silicon suspension fibres and substrates is reported in figure 4 (curves (*c*), (*d*) and (*e*)).

Acknowledgment

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

References

[1] Callen H B and Welton T A 1951 *Phys. Rev.* **83** 34

[2] Amico P *et al* 2002 *Rev. Sci. Instrum.* **73** 3318

[3] Cagnoli G *et al* 1996 *Phys. Lett.* A **213** 245

[4] Cagnoli G *et al* 2000 *Phys. Rev. Lett.* **85** 2442

[5] Braginksy V B *et al* 1996 *Phys. Lett.* A **218** 164

[6] Rowan S *et al* 1997 *Phys. Lett.* A **233** 303

[7] Rowan S *et al* 1999 *Proc. of 2nd TAMA Workshop* p 203

[8] Cagnoli G *et al* 1999 *Phys. Lett.* A **255** 230

[9] Fine M E *et al* 1954 *J. Appl. Phys.* **25** 402

[10] Kobayashi H *et al* 1994 *J. Non-Crystalline Solids* **179** 324

[11] Material Properties Database (MPDB), http://www.jahm.com

[12] Swenson C A 1983 *J. Phys. Chem. Ref. Data* **12** 179

[13] Punturo M 2003 *The VIRGO sensitivity curve*, VIR-NOT-PER-1390-51, Virgo Internal Note and http://www.virgo.infn.it/senscurve

[14] Ferreirinho J 1991 *The Detection of Gravitational Waves* ed David G Blair (Cambridge: Cambridge University Press)

[15] Rowan S 2000 *LIGO internal note:* LIGO-G000069-00

[16] Amico P *et al* 2001 *Virgo internal note:* VIR-NOT-PER-1390-202

[17] Amico P *et al* 2004 *Proc. Conf. Front. Detectors for Front. Phys.* (*Nucl. Instrum. Methods* in press)

[18] Rowan *et al* 2003 *Proc. SPIE* vol 4586 *GW Detection* ed M Cruise and P Saulson p 292

[19] Rudolph P and Fukuda T 1999 *Cryst. Res. Technol.* **34** 3

[20] Shimamura K *et al* 1996 *Japan. J. Appl. Phys.* **35** L793

[21] Yoon D H and Fukuda T 1994 *J. Cryst. Growth* **144** 201