

An optical readout configuration for advanced massive GW detectors

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Optical readout of displacement

- Standard detection technique in interferometers
- Proposed in the 80's for bar detectors¹
- Recently applied to a room temperature detector²

[1] J.-P. Richard, J. Appl. Phys. **64**, 2202 (1988)

[2] L. Conti *et al.*, J. Appl. Phys. **93**, 3589 (2003)



Room temperature Weber bar with optical readout

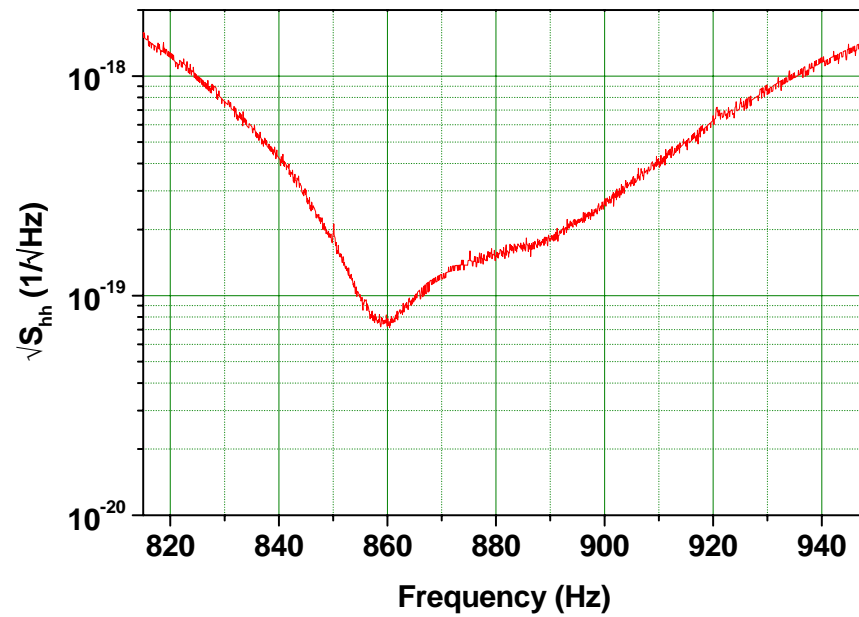
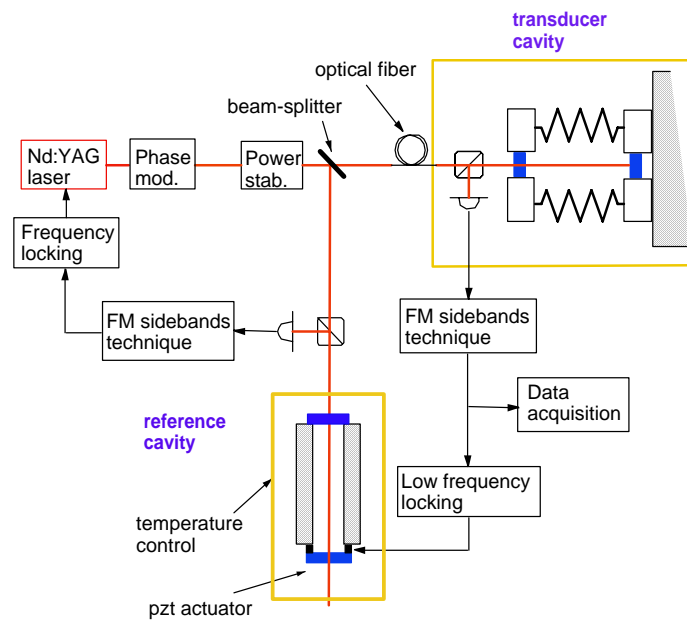
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Room temperature Weber bar with optical readout

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Room temperature Weber bar with optical readout

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Work in progress:

- Cleaner vacuum system
- New mechanical suspension
- Higher Finesse transducer cavity
- Cooling (at least 77K)



Brownian noise and radiation pressure (**back-action**) are the usual sensitivity limiting sources in a **few-modes** model, together with the displacement detection sensitivity (**displacement noise**)

In a real, massive system: **several modes**, with their thermal noise and back-action.

➡ **Small interrogation region means large fluctuations**

One must average over high order modes:

➡ **needs large interrogation region**



We must consider 'local' effects:

- **Thermal noise**
 - photothermal
 - thermodynamic
 - Brownian

Depends on material parameters

- At cryo-T:
- best material is sapphire
 - predominant Brownian

- **Radiation pressure**



Brownian noise:

$$S_{\text{Br}}(\omega) = \frac{4 k_{\text{B}} T}{\omega} \text{Im} [\chi(\omega)]$$

Radiation pressure effect:

$$S_{\text{rp}}(\omega) = |\chi(\omega)|^2 \left(\frac{2}{c}\right)^2 S_{\text{cav}}$$

intracavity radiation noise spectral power:

$$S_{\text{cav}} = 2 h \nu \left(\frac{F}{\pi}\right)^2 P_{\text{in}}$$



Gaussian spot on a half-infinite mirror:

$$\text{Im} [\chi(\omega)] \simeq \phi |\chi(\omega)|$$

$$|\chi^{\text{single}}| = \frac{1}{\pi^{1/2}} \frac{1 - \sigma^2}{\omega Y}$$

Single-spot noise:

$$S_{\text{Br}}^{\text{single}}(\omega) = \frac{4 k_{\text{B}} T}{\pi^{1/2}} \frac{\phi}{\omega} \frac{1 - \sigma^2}{\omega Y}$$

$$S_{\text{rp}}^{\text{single}} = \left(\frac{2(1 - \sigma^2)F}{\pi^{3/2} c Y \omega} \right)^2 2 h \nu P_{\text{in}}$$



Main figures

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Sapphire (1 K):

Young modulus $Y = 4 \cdot 10^{11}$ Pa

Poisson coefficient $\sigma = 0.25$

Loss angle $\phi = 3 \cdot 10^9$

Cavity Finesse: $F = 10^6$

Displacement sensitivity

with 1 W: $7 \cdot 10^{-45}$ m²/Hz

with 10 W: $7 \cdot 10^{-46}$ m²/Hz



Target (Ex.: dual sphere *)

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- Best stiffness: for laser power = 7 W
- Thermal noise negligible for $Q/T > 2 \cdot 10^8$

$$S_{xx} = 10^{-45} \text{ m}^2/\text{Hz}$$

... *but*

With a waist of $w = 1 \text{ mm}$:

$$S_{Br} = 5 \cdot 10^{-44} \text{ m}^2/\text{Hz}$$

$$S_{rp} = 8 \cdot 10^{-41} \text{ m}^2/\text{Hz}$$



We need a waist of

$w > 20 \text{ cm} \text{ !!!!}$

* M. Cerdonio *et al.*, Phys. Rev. Lett. **87**, 031101 (2001)



Possible solutions?

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Concave - Convex cavity :

$$(-R_2) = R_1 + r$$

Stable if $d > r$

If $(d - r) \ll d \ll R_1, R_2$:

$$W^2 \cong \frac{\lambda R}{\pi} \sqrt{\frac{d}{d-r}}$$

Plano-concave
Cavity:

$$W^2 \cong \frac{\lambda}{\pi} \sqrt{Rd}$$

Ex. : $R = 10 \text{ m}$
 $r = 10 \text{ mm}$
 $d - r = 0.1 \text{ mm}$
 $\lambda = 1.064 \mu\text{m}$



$W = 5.8 \text{ mm}$

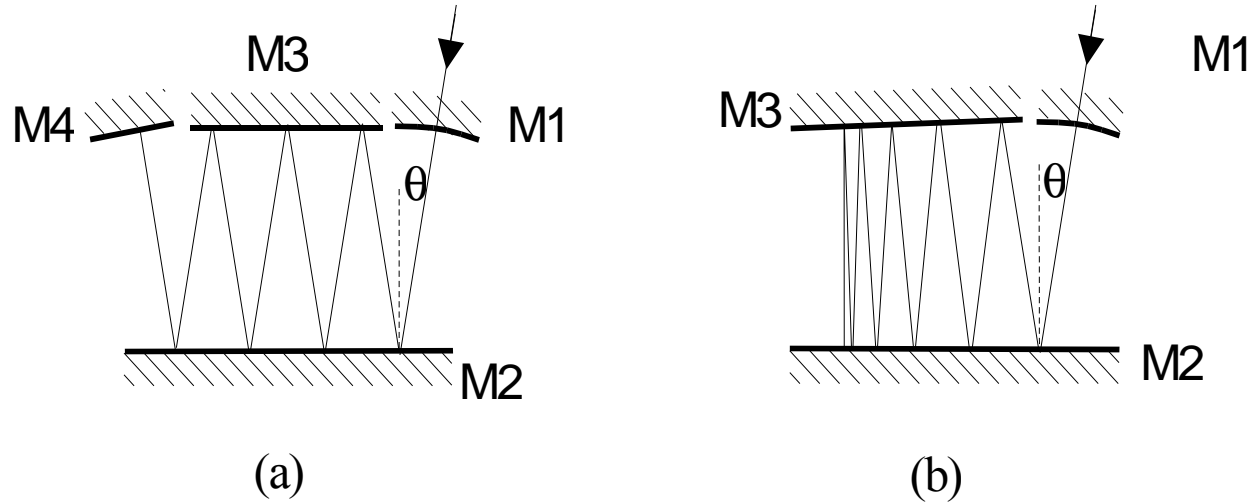
Delay line :

Low equivalent Finesse



Folded Fabry-Perot (FFP)

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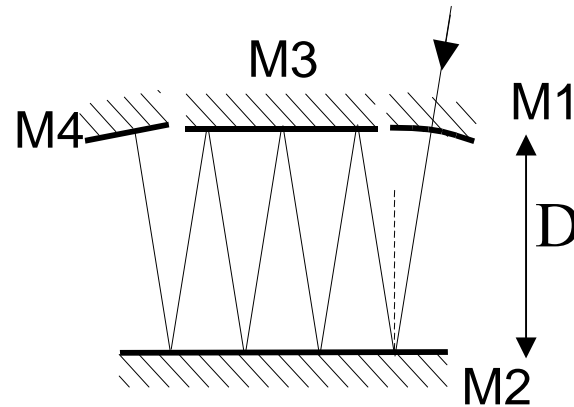


F. Marin, L. Conti, M. De Rosa: “A folded Fabry-Perot cavity for optical sensing in gravitational wave detectors”, Phys. Lett. A **309**, 15 (2003)



Folded Fabry-Perot (FFP)

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Signal: $\propto N$

Brownian noise: $\propto \sqrt{N}$

Radiation pressure: $\propto N \cdot F$ (constant)

Displacement noise: $\propto 1/F \propto N$

Linewidth (\rightarrow bandwidth): $\propto 1/(N \cdot F)$ (constant)



For non-correlated spot fluctuations

Brownian noise effect:

$$\frac{S_\nu}{\nu^2} = \frac{S_{\text{Br}}^{2L}}{(2L)^2} = \boxed{\frac{S_{\text{Br}}^{\text{single}}}{2D^2}} \frac{1}{N}$$

Radiation pressure effect:

$$\frac{S_\nu}{\nu^2} = \frac{S_{\text{rp}}^{2L}}{(2L)^2} = \boxed{\frac{S_{\text{rp}}^{\text{single}}}{4D^2}} \boxed{\frac{1}{N^2}}$$



Taking into account correlations

$$\chi_N = \chi^{\text{single}} \left\{ N+2 \sum_{n=2}^N \sum_{q=1}^{n-1} \exp\left(-\frac{|\mathbf{r}_n - \mathbf{r}_q|^2}{2w^2}\right) I_0\left(\frac{|\mathbf{r}_n - \mathbf{r}_q|^2}{2w^2}\right) \right\}$$

N Nakagawa *et al.*, Phys. Rev. D **65**, 082002 (2002)

Brownian noise effect:

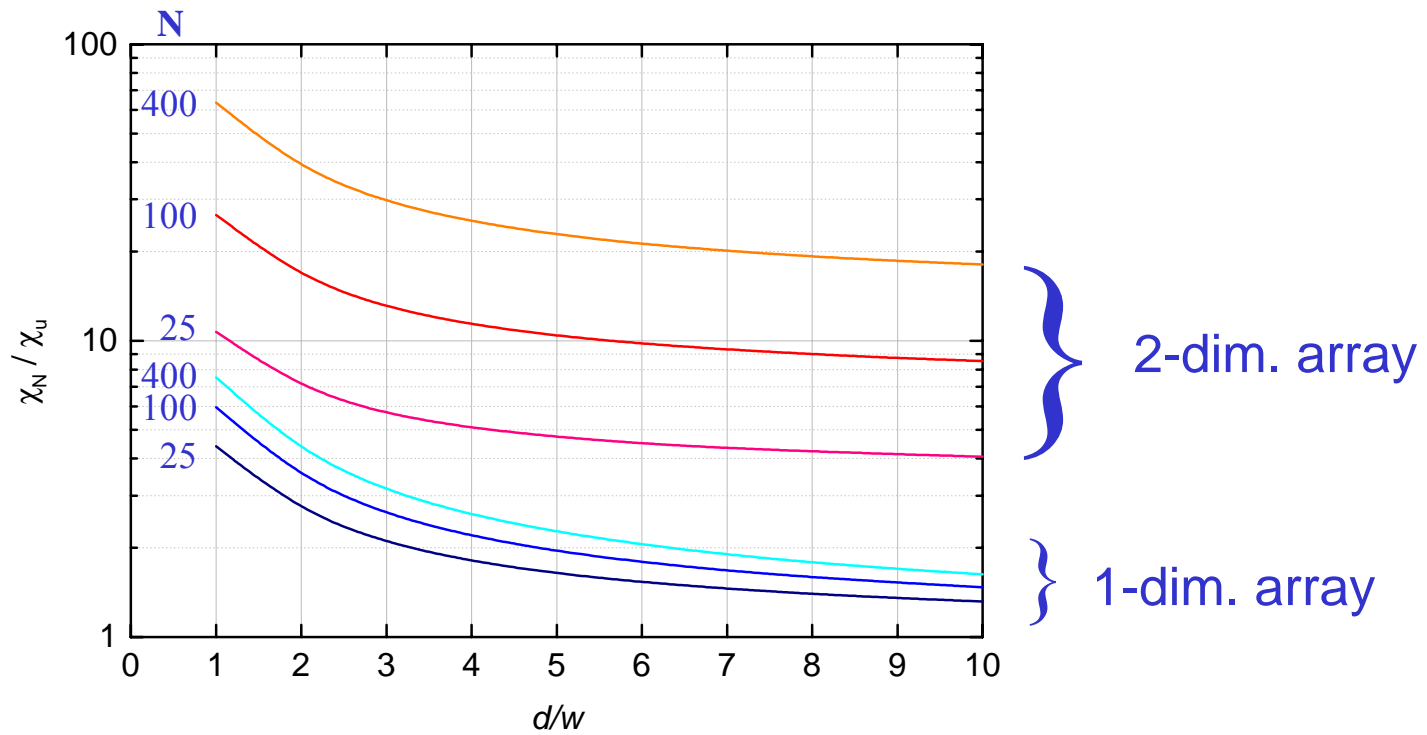
$$S_{\text{Br}}^{\text{FFP}}(\omega) = \frac{4 k_B T}{\omega} \phi (4\chi_N + 4\chi_{N'} + 2\chi^{\text{single}})$$

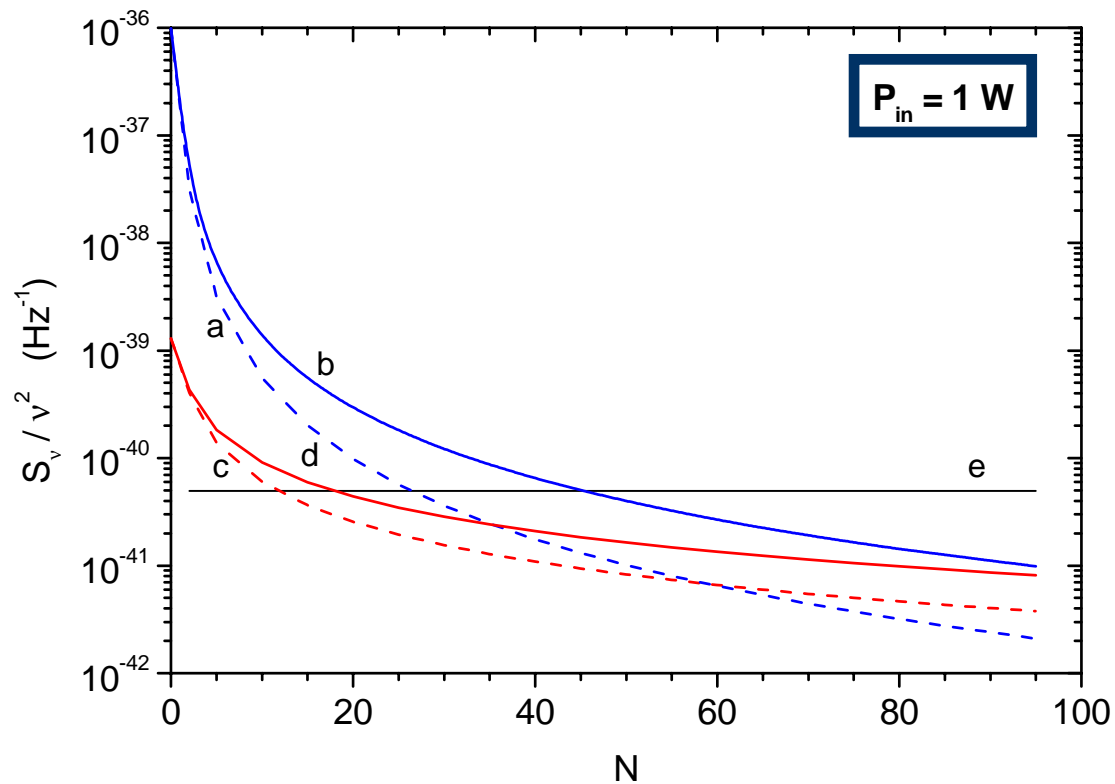
Radiation pressure effect:

$$S_{\text{rp}}^{\text{FFP}} = \left(\frac{2}{c}\right)^2 S_{\text{cav}} |2\chi_N + 2\chi_{N'} + 2\chi^{\text{single}}|^2$$



Correlation effect





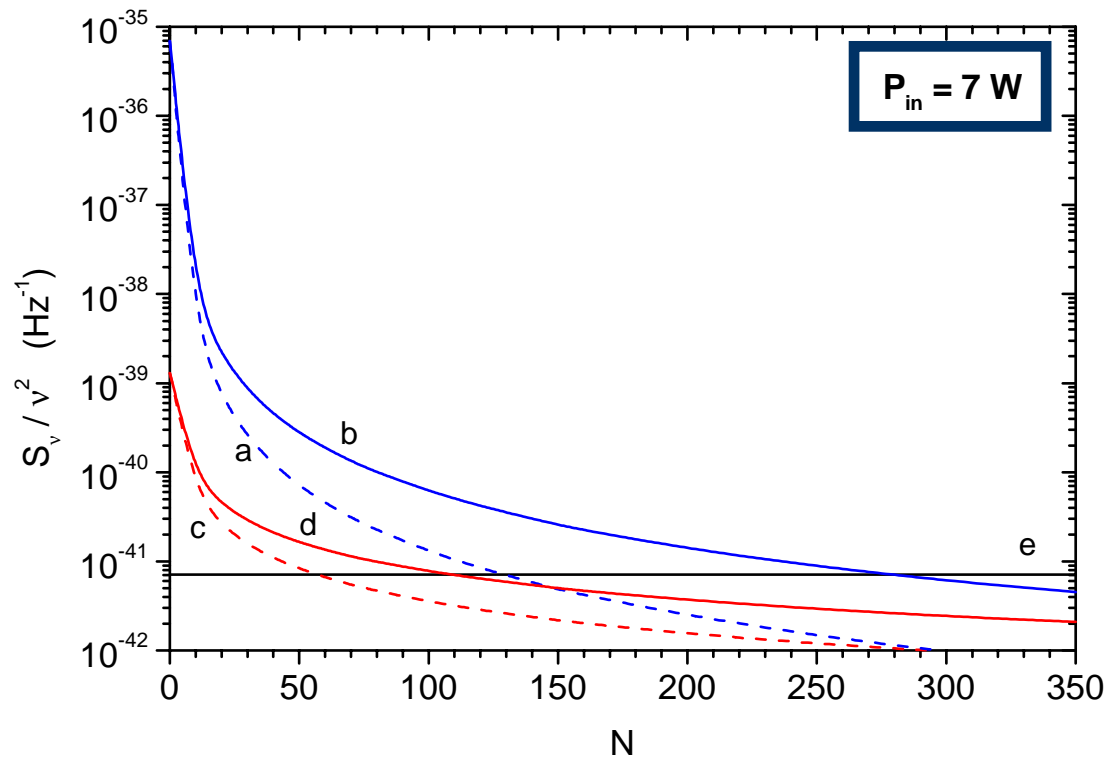
a: radiation pressure effect (no correlations)

b: radiation pressure effect (full)

c: Brownian noise @ 1.3 kHz (no correlations)

d: Brownian noise @ 1.3 kHz (full)

e: Shot-noise limited displacement sensitivity



D = 6 mm
R = - 10 m
d = 4 w

- a: radiation pressure effect (no correlations)
- b: radiation pressure effect (full)
- c: Brownian noise @ 1.3 kHz (no correlations)
- d: Brownian noise @ 1.3 kHz (full)
- e: Shot-noise limited displacement sensitivity

Power density:
≈ 10 kW/mm²



Conclusions

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The **FFP** allows to closely approach with the present technology the quantum-limited sensitivity and best stiffness calculated for the main modes of a high sensitivity, wide bandwidth dual detector



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