Digitally enhanced interferometry: principles and applications

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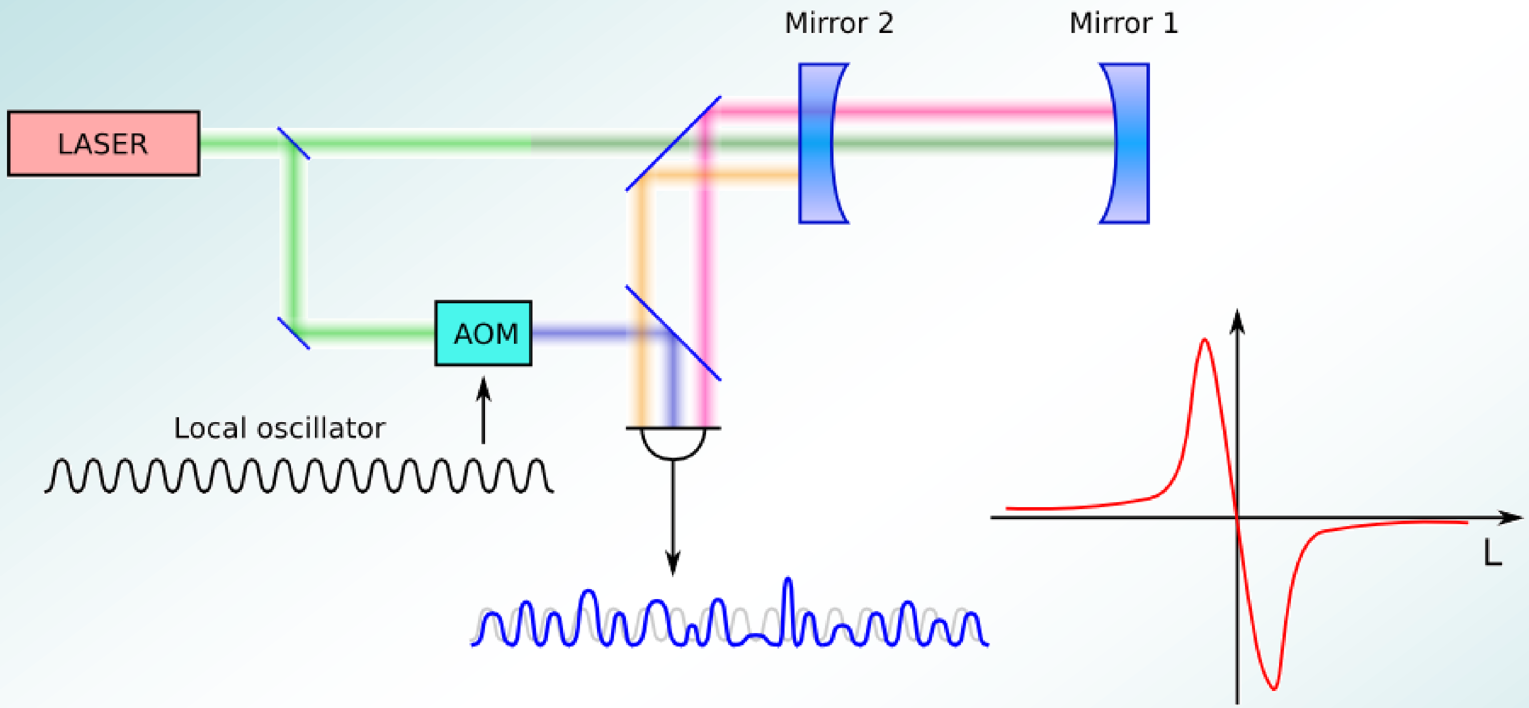
Outline

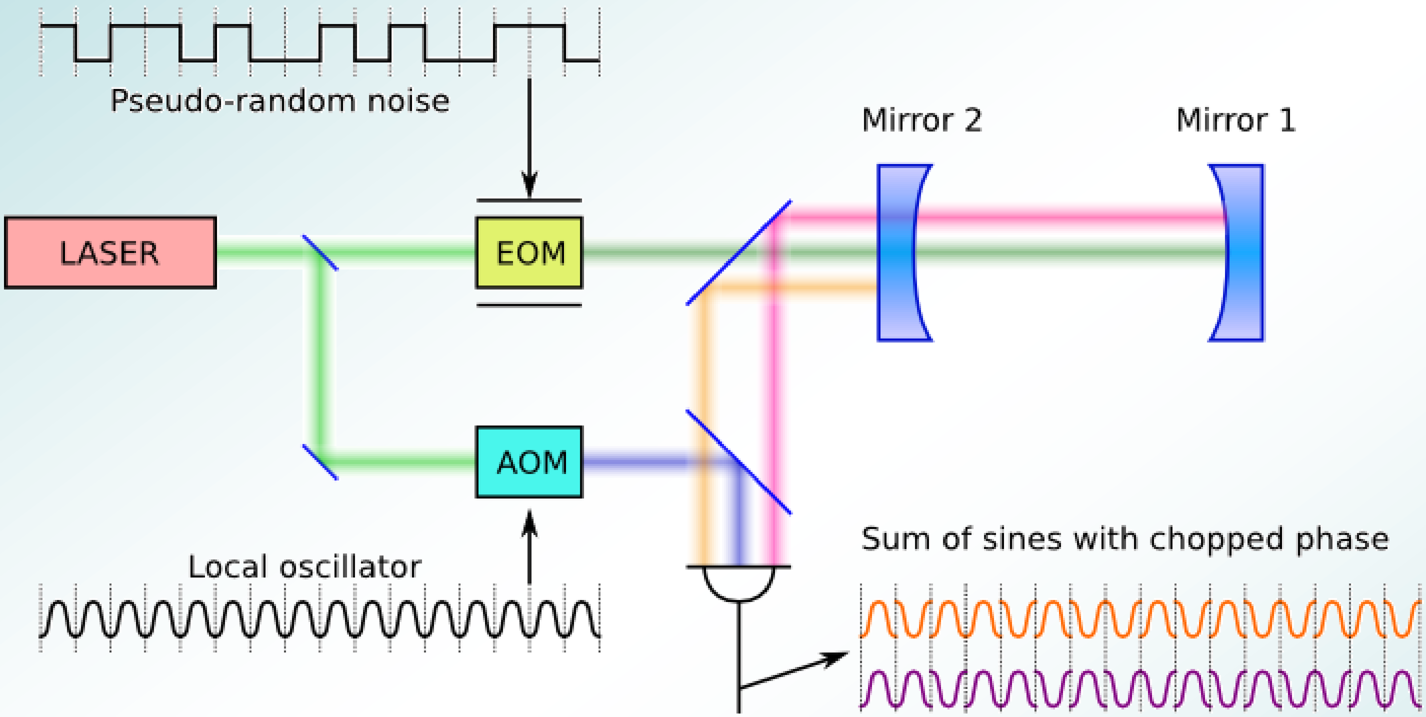
- What is Digitally Enhanced Interferometry (DI)?
- What is the current status of the technique?
- What are the foreseen evolutions?
- How can it be useful in ring laser systems?

Standard heterodyne metrology



- Very sensitive to cavity length displacement
- Interference destroys single mirror motion information
- Error signal is linear for a small fraction of possible positions

Digitally enhanced interferometry

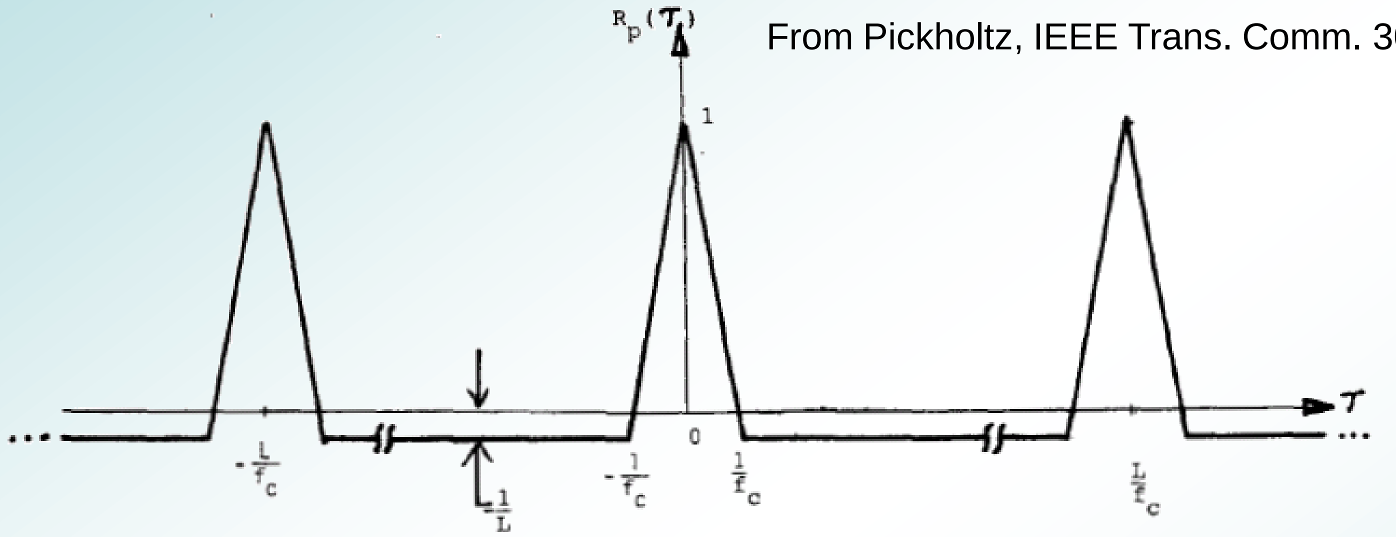


- Add a phase modulation driven by a digital code, with 0 or 180 degrees steps

D.A.Shaddock, Opt. Lett. 32, 3355 (2007)

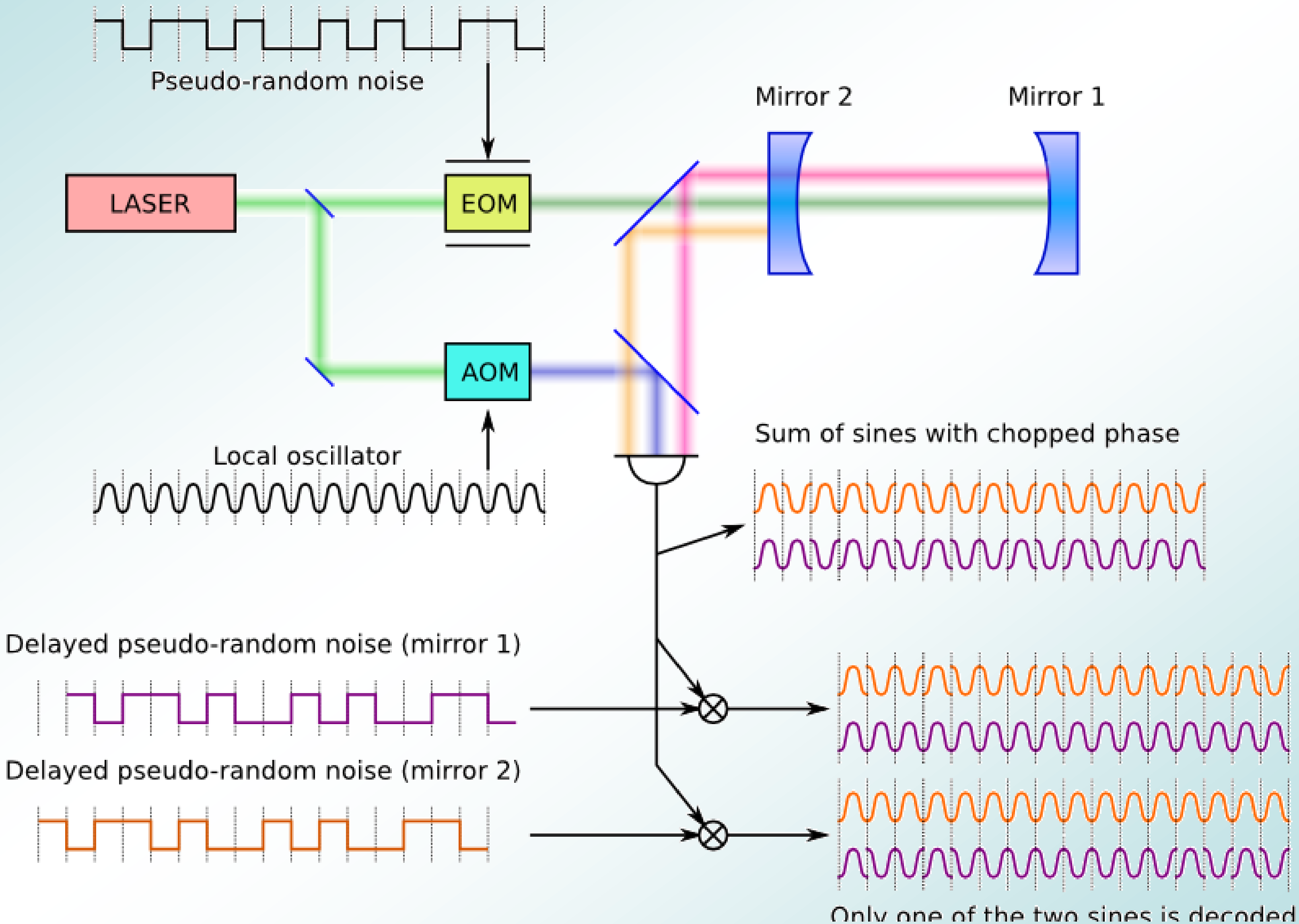
Pseudo-random code

From Pickholtz, IEEE Trans. Comm. 30, 862 (1982)



- Use a Maximal Length Sequence pseudo-random noise with length of P samples
- Autocorrelation is 1/P for any time delay larger than one sample
- Easy to generate with shift register of length about log2(P)

Multiplexing capabilities



Multiplexing capabilities

- The key is to be able to separate the time of flight of the beam coming from different optical elements
- Coding frequency fc must be high enough:

  fc > c/2L

  where L is the minimum distance between optical elements (L = 10 m fc > 15 MHz,
  L = 1 m fc > 150 MHz
  L = 1 cm fc > 15 GHz)
- A heterodyne signal is recovered separately for each mirror
- Cross talks are reduced to **1/P**

Cross-talk rejection

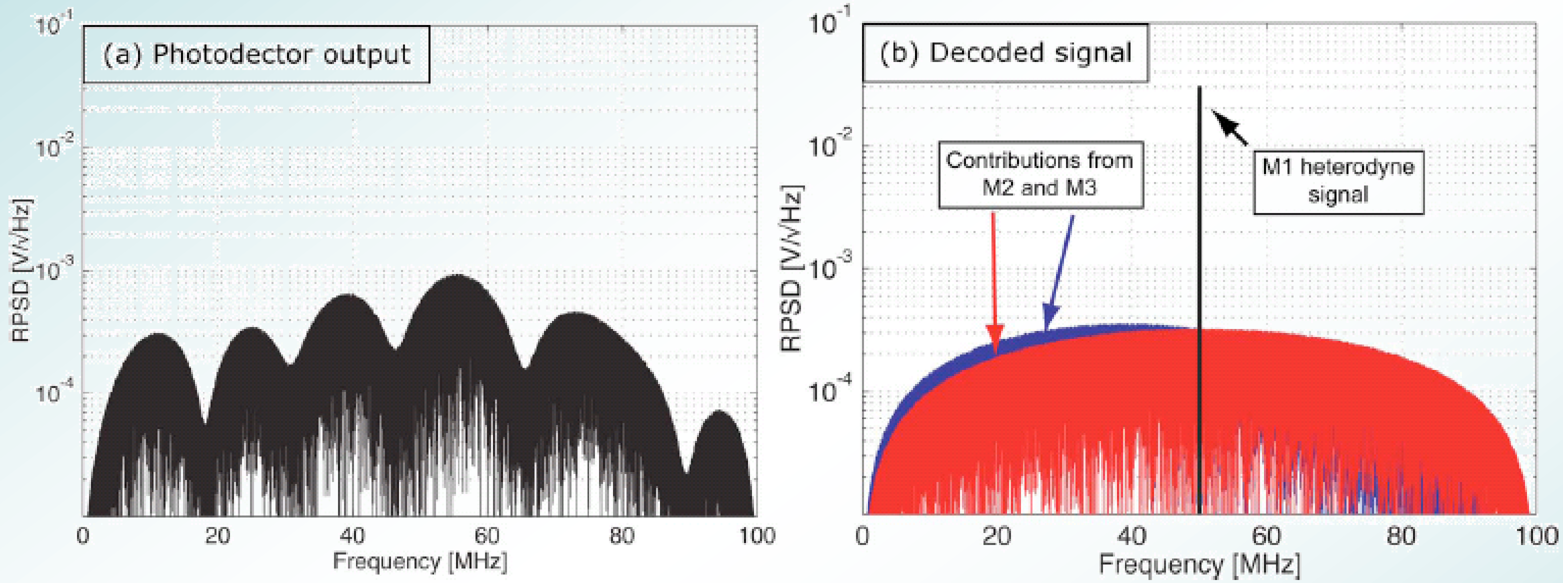


Fig. 2. (Color online) Simulated root power spectral densities of the configuration depicted in Fig. 1 for (a) the photodetector output and (b) contributions of each reflection to the $c(t-\tau_1)$ decoded output, V_{M1}.

From D.A.Shaddock, Opt. Lett. 32, 3355 (2007)

Some experimental results

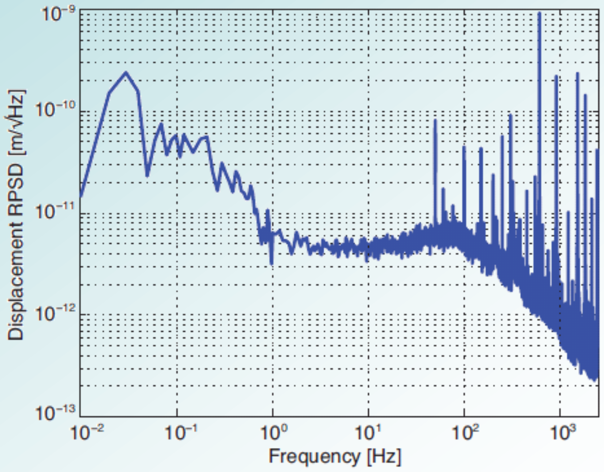


Fig. 3. Spectral density of the DI measurement of cavity displacement when the cavity is locked using PDH locking. Spectral density averaged for clarity (3x for $0.1 > f > 1$ Hz, and 10x for $f > 1$ Hz). note: The roll-off above 100 Hz is due to the transfer function of the phasemeter.

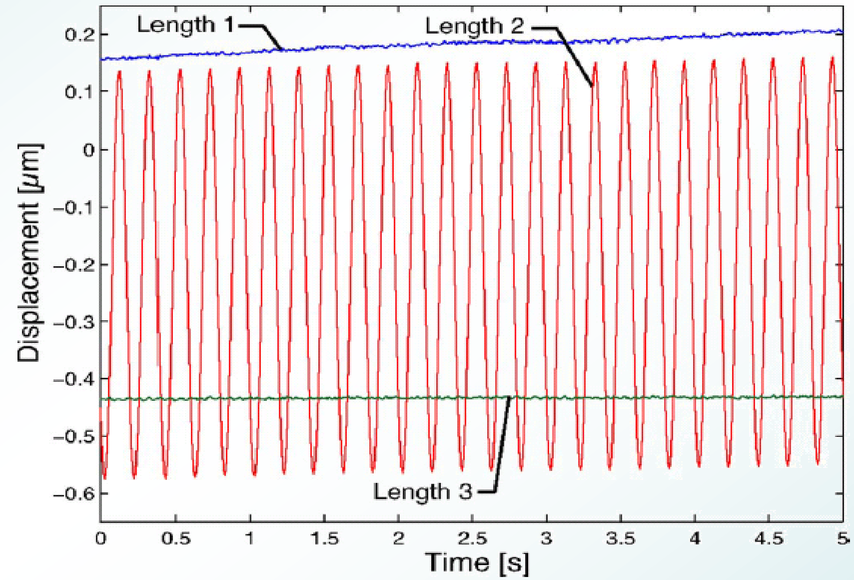


Fig. 3. (Color online) Time domain data showing low cross talk between signals when modulating L_2 with a 5 Hz sine wave.

From De Vine et al, Opt. Expr. 17, 829 (2009)

From Wuchenich et al, Opt. Expr. 36, 672 (2011)

- Reached a noise level of 5 pm/rHz above 1 Hz and a resolution of 200 pm
- Cross talks reduced below 40 db

Present limitations

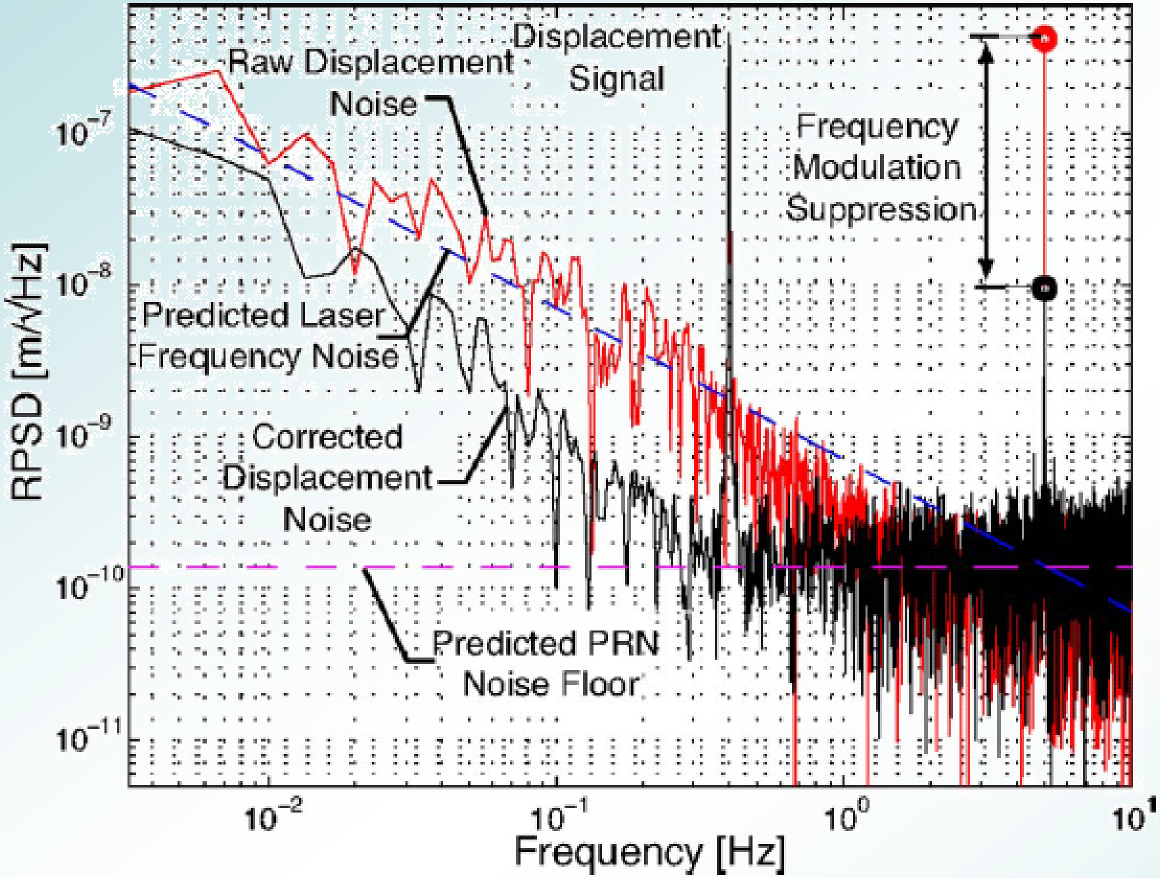
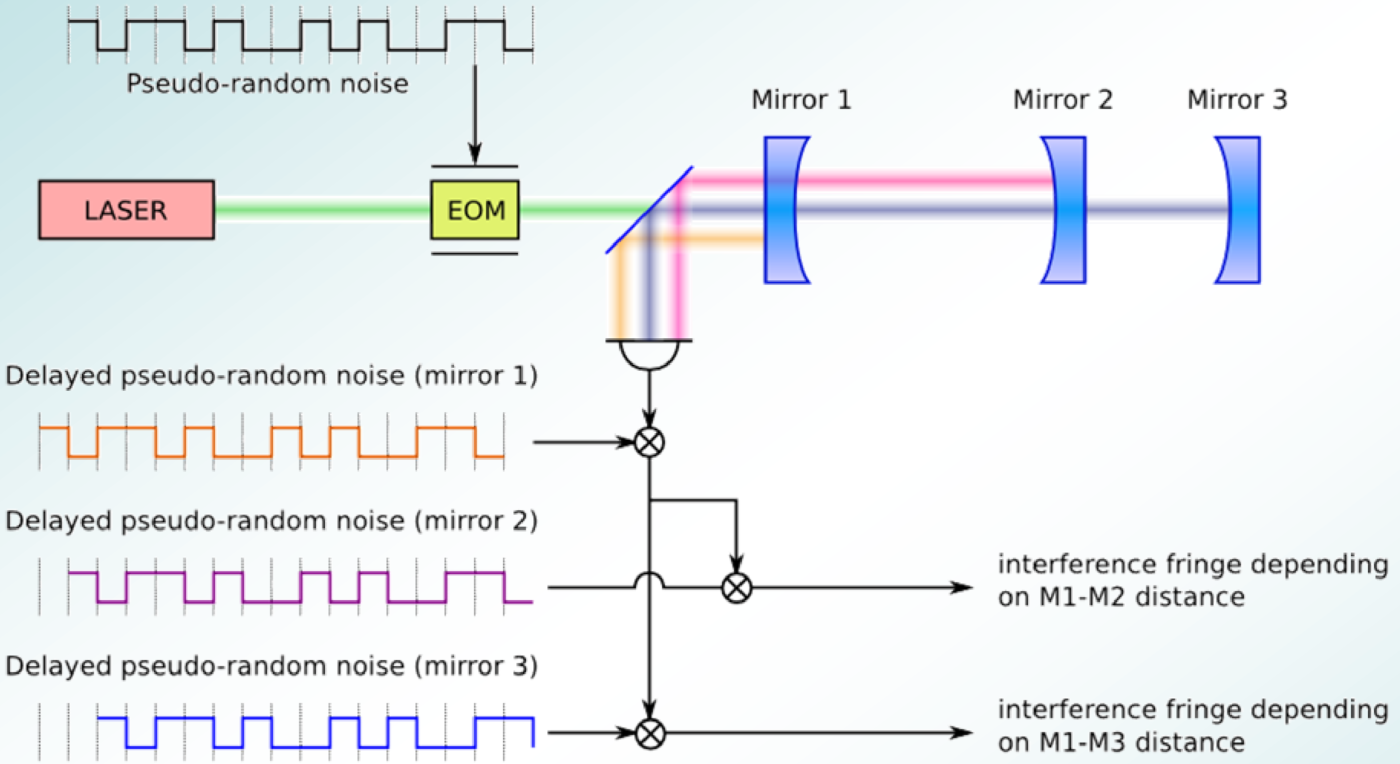


Fig. 5. (Color online) RPSDs of δL_2 and $\delta L_2 - \frac{L_2}{L_1}\delta L_1$. Frequency noise can be suppressed by correlating two displacement measurements with an appropriate scaling factor.

- Frequency noise is the limiting factor in the sensitivity of these measurements
- PRN modulation non linearities are limiting the cross talk rejection

From Wuchenich et al, Opt. Expr. 36, 672 (2011)

Future evolutions



- Homodyne detection
  - Simpler optical system
  - Direct relative measurement

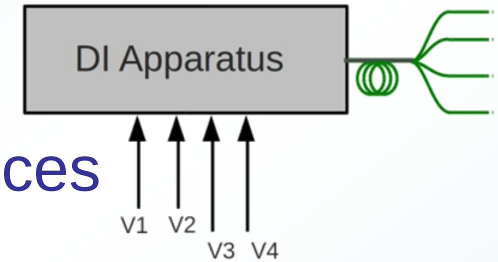
Summary of DI

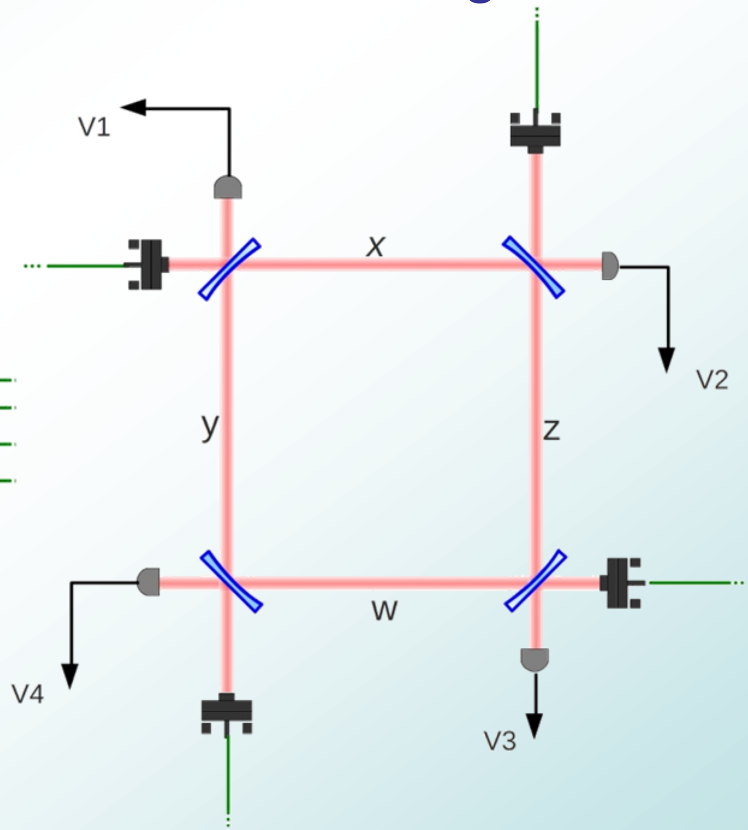
- An extension of standard interferometric metrology
- Allows separate measurement of single optical element displacements, provided the separation is large enough
- Retain the intrinsic precision of standard interferometry
  - Demonstrated sensitivity of the order of 5 pm/rHz above 1 Hz and accuracy of 100-200 pm

D.A.Shaddock, Opt. Lett. 32, 3355 (2007)
Lay et al, Opt. Lett. 32, 2933 (2007)
De Vine at al, Opt. Expr. 17, 828 (2009)
Wuchenich et al., Opt. Lett. 36, 672 (2011)

Applications to ring lasers - 1

- The goal is to measure the length of each side
- Four DI sources injected from each corner, sharing the same code
- Four detector, one at each corner all separately decoded
- There are 12 d.o.f.s: 4 side lengths, 4 distances from source to corner, 4 distances from corner to detector





- One can extract at least 16 signals

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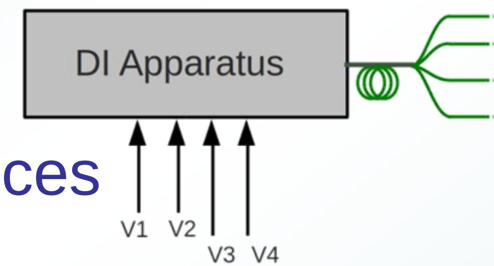

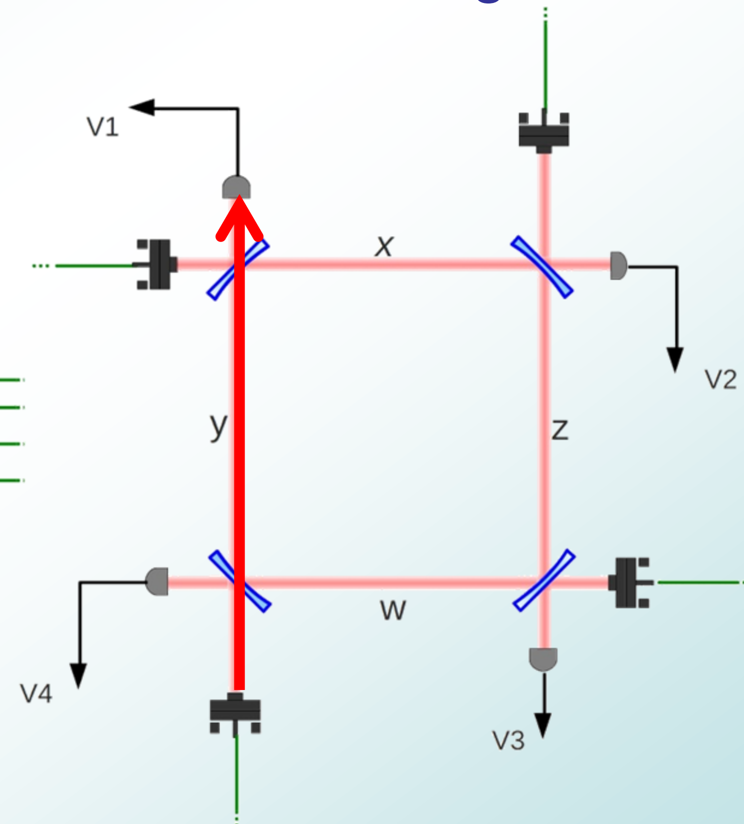

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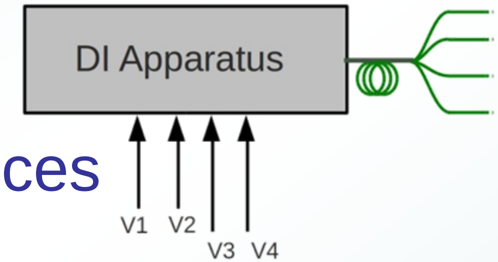

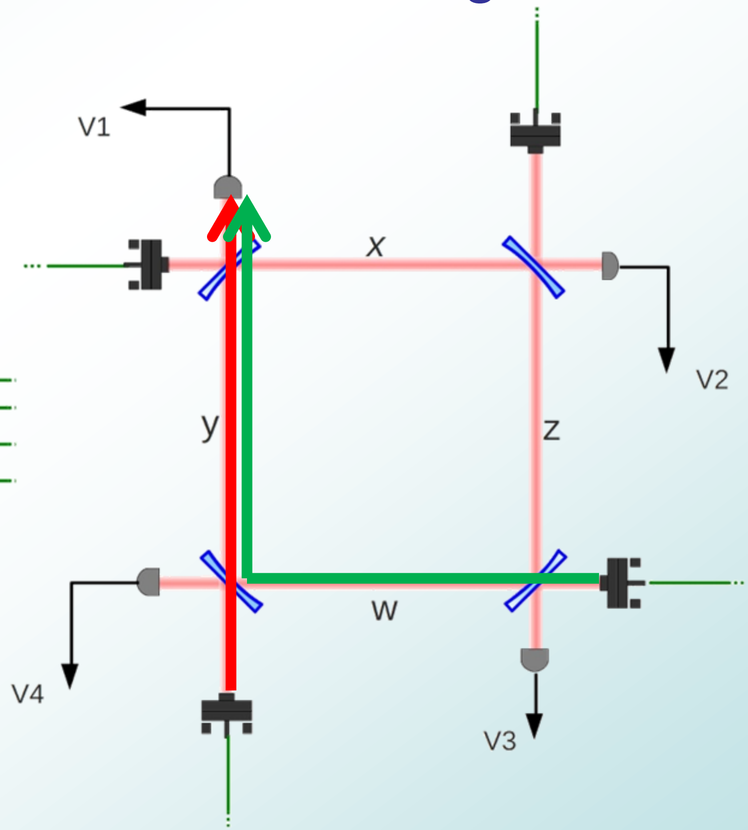

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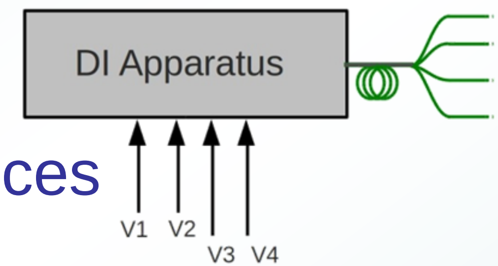

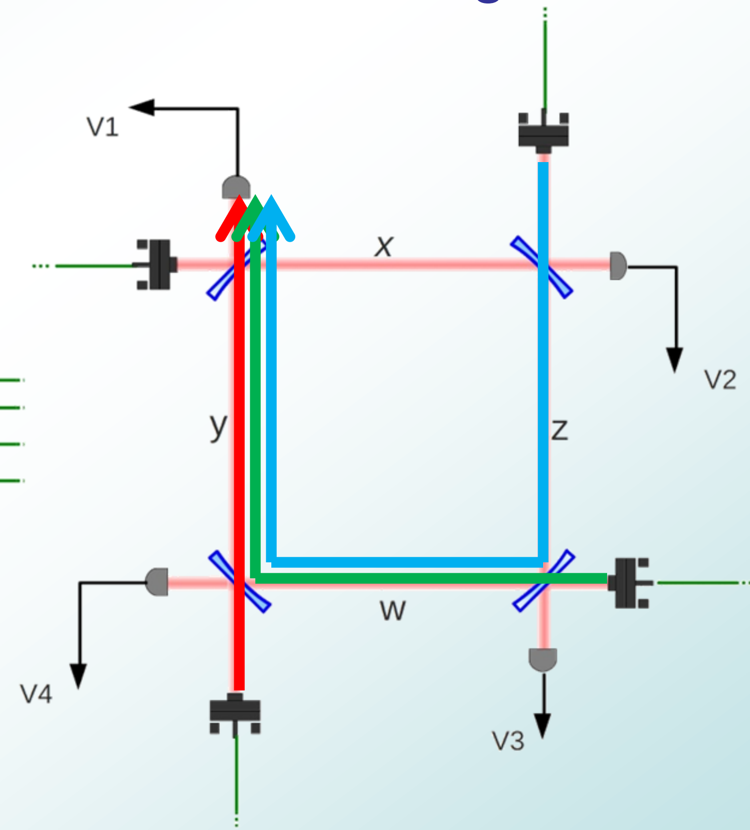

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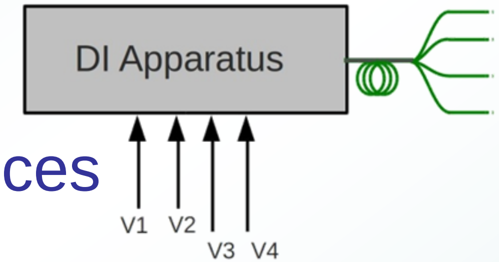

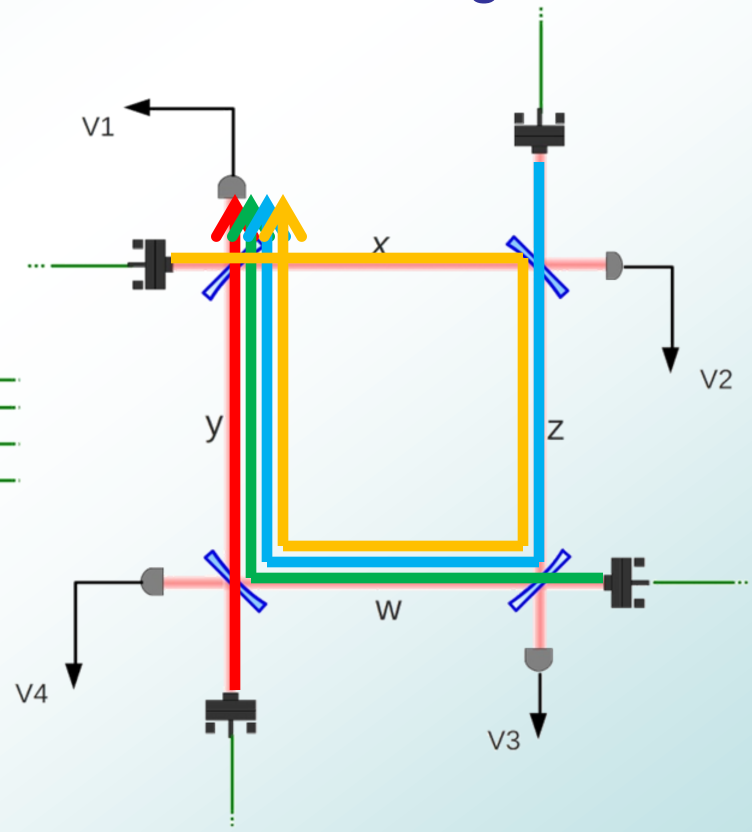

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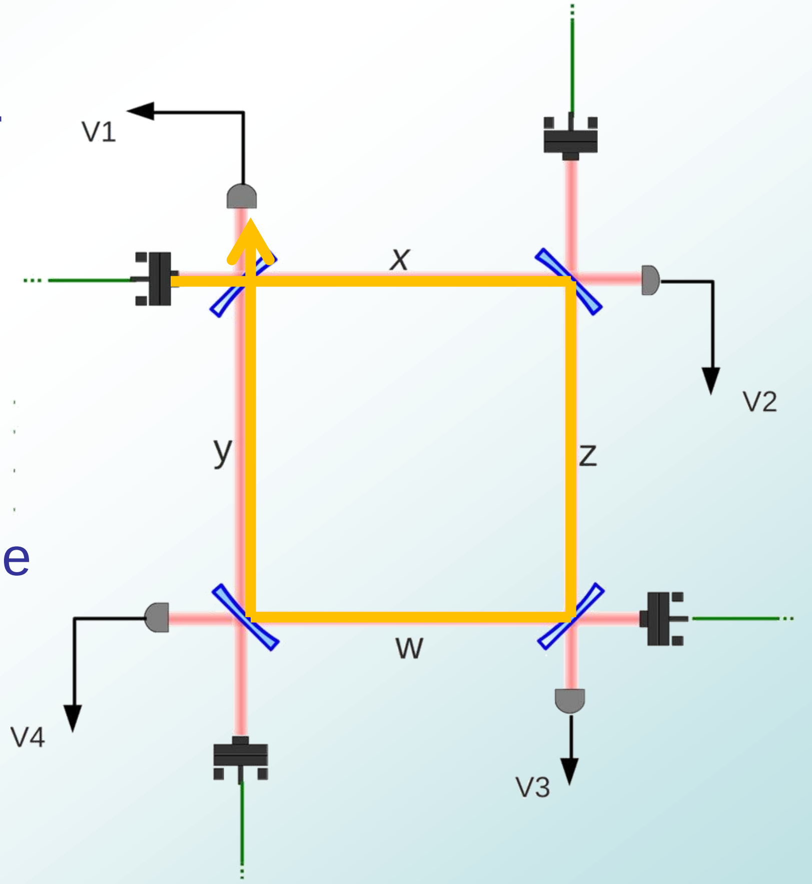
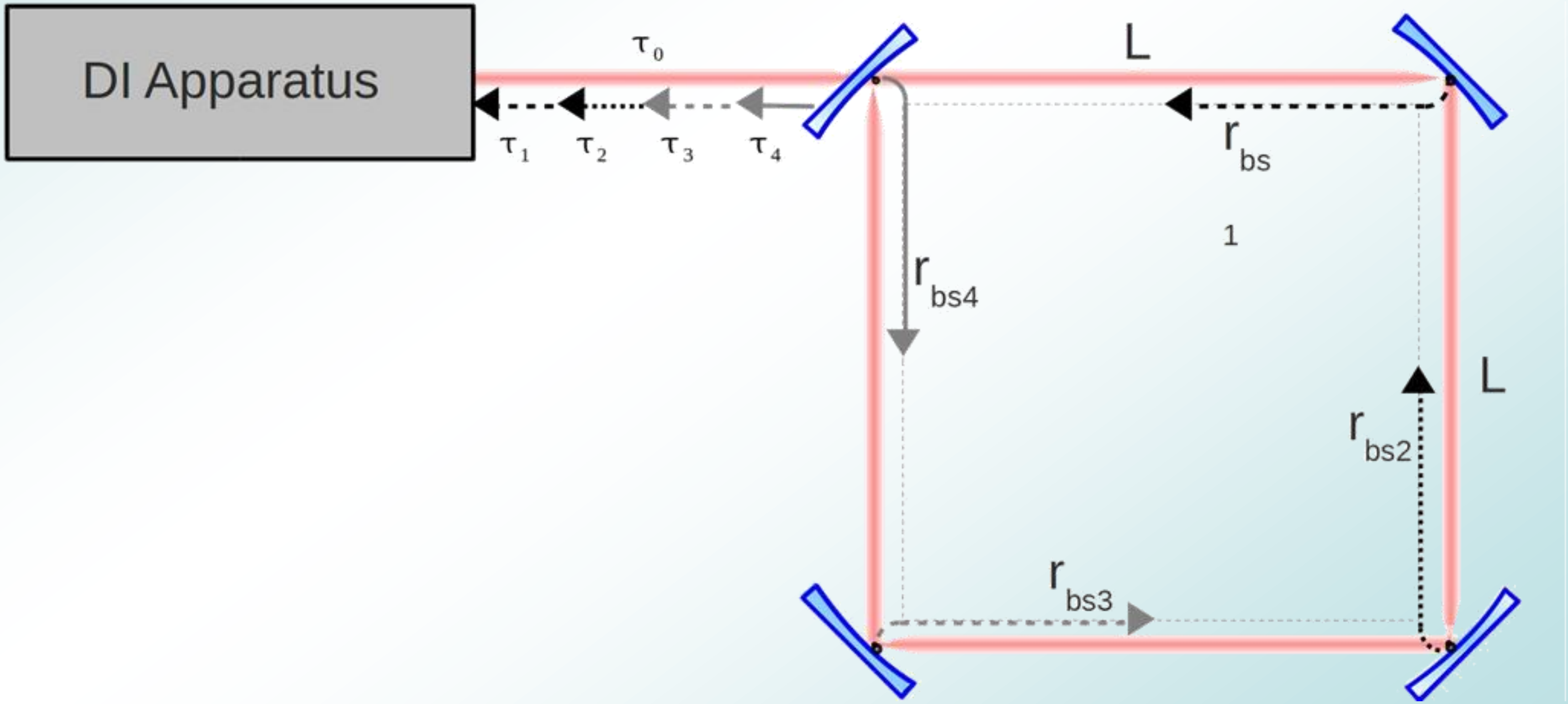
Application to ring lasers – freq. stab.

- The signals are enough to reconstruct all d.o.f.s
- The main limitation below 1 Hz is the DI laser source frequency noise
- DI measures also the perimeter
  - It is stabilized to an absolute reference with the main ring laser
  - Any signal measured by the DI is simply laser frequency noise
  - We can **use the ring laser itself as a transfer cavity** to stabilize the DI laser source to the same reference



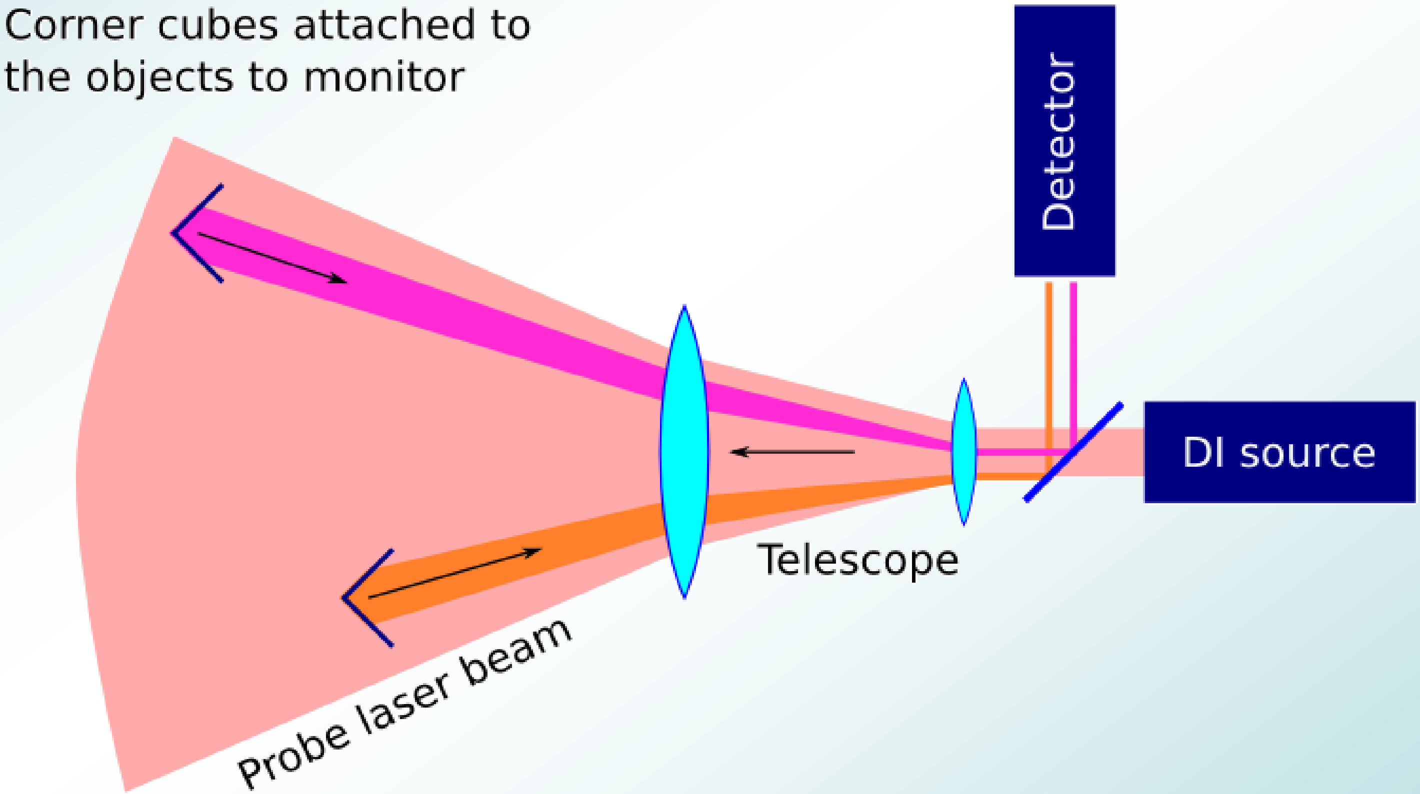
Application to ring lasers - 2

- Characterization of back-scattered amplitudes and phases
- If DI laser source is different from main one, mirrors can have low reflectivity. Ideal is 25% transmission to equalize amplitudes
- This approach allows measuring the lengths and the amplitude of the back-scattered light



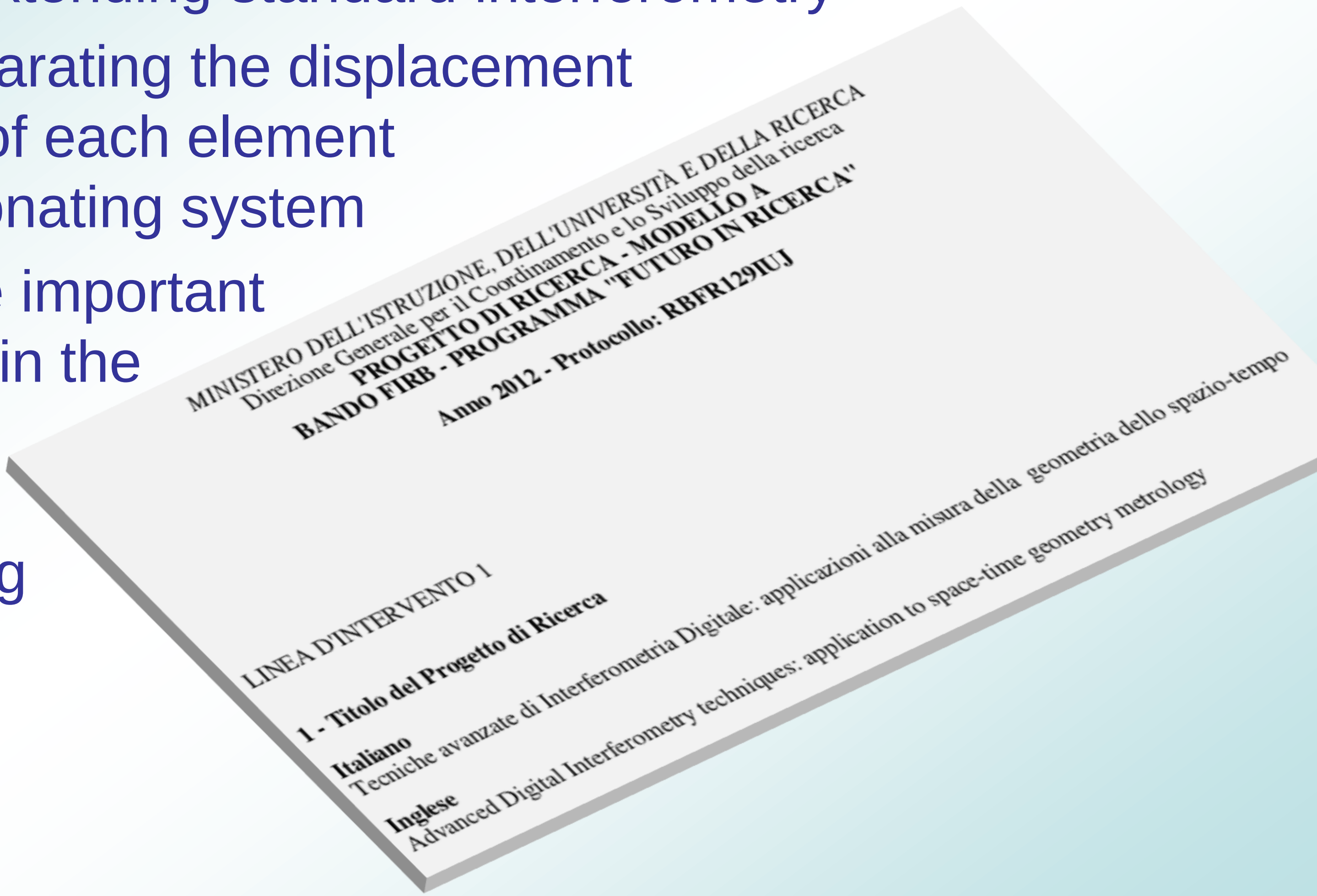
Positioning control

- A simple idea, using corner cubes attached to the objects to be monitored. Three sources will allow a 3-d tracking of the object positions with high accuracy



Conclusions

- Digitally Enhanced Interferometry is a rather new technique, extending standard interferometry
- It allows separating the displacement information of each element inside a resonating system
- It could have important applications in the field of geometrical control of ring lasers.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PROGETTO DI RICERCA - MODELLO A
BANDO FIRB - PROGRAMMA "FUTURO IN RICERCA"
Anno 2012 - Protocollo: RBFR129IUJ

LINEA D'INTERVENTO 1

1 - Titolo del Progetto di Ricerca

Italiano
Tecniche avanzate di Interferometria Digitale: applicazioni alla misura della geometria dello spazio-tempo

Inglese
Advanced Digital Interferometry techniques: application to space-time geometry metrology