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Istituto Nazionale di Ottica

In collaborazione

lens European Laboratory for Non-Linear Spectroscopy

INAF-OAA

15 febbraio 2013

Titolo:

Metrologia ottica con i comb per l'astronomia

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Outline

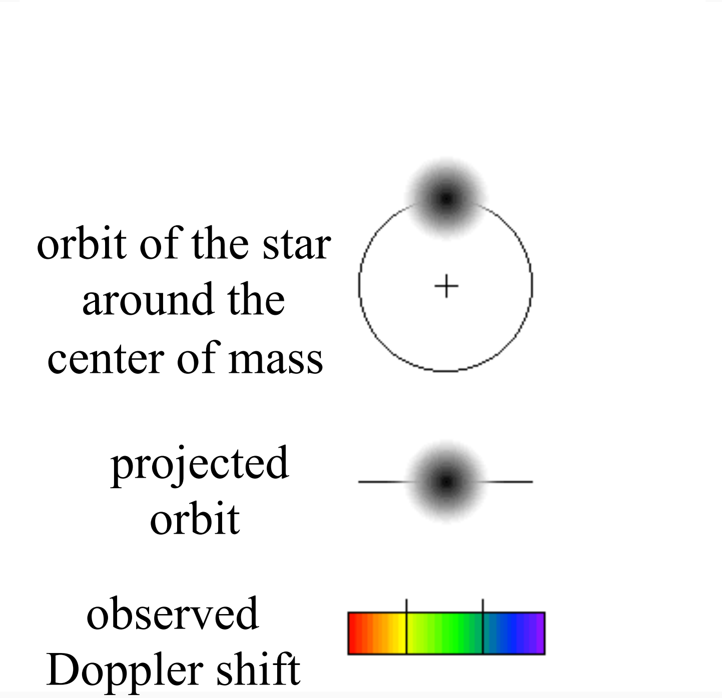
- Astronomical motivations
- The ideal calibration source of wide bandwidth astronomical spectrographs
- The optical frequency comb (OFC) as calibration source
- Interferential optical filtering of an OFC
- Design and development of a filtering system
  - Filtering with Fabry-Perot cavities with dielectric coated mirrors
  - Filtering with Fabry-Perot cavities with metallic coated mirror
- Conclusions and perspectives with different approaches

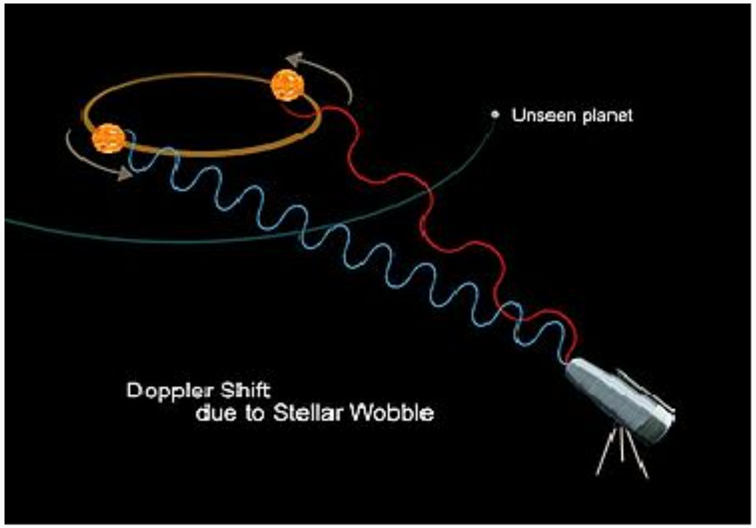
Astronomical motivations

- Search for extra-solar planets via indirect methods: Radial Velocity Method

$$v_r \propto \left(\frac{M_1}{P}\right)^{1/3} \frac{q}{(1-q)^{2/3}} \sin i$$

P: orbital period
M_1, M_2: mass of star, planet
$q = M_2 / M_1$
i: inclination of orbital axis





Astronomical motivations

•Search for extra-solar planets: measuring velocity wobble with precisions ranging from cm/s to m/s

•Determination of the universe's expansion history: measuring the evolution of the cosmological red-shift of distant objects with a precision of 1 $cms^{-1}yr^{-1}$

•Measurement of the variability of fundamental constants: comparing laboratory and distant objects spectra

↓

Possible by using a very large number of absorption lines of the astronomical object and statistical analysis by cross-correlation technique

↑

High resolution astronomical spectrometers, operating in a wide spectral region and **calibrated with high precision and in real-time**

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Astronomical motivations

•Search for extra-solar planets:

Sun-like start → **Jupiter:** $v_r \sim 10 \text{ m/s}$

Earth: $v_r \sim \mathbf{10\ cm/s}$

Earth-like planet around M-type dwarf starts:

- easier to detect;
- most common stars (80% in our galaxy).

→ $v_r \sim \mathbf{1\ m/s}$

The GIANO spectrograph at TNG: Near-IR (0.95 – 2.5 μm) echelle spectrograph

Resolving power → R = 50000 $\Delta\lambda_{max}$ = 2 × 10^{-5} λ → Δf_{max} = 4 GHz (at 1.5 μm).

Precision → $\dfrac{\Delta\lambda}{\lambda} = \dfrac{v_r}{c} \sim 3 \times 10^{-9}$

The ideal calibration source

The ideal calibration spectrum would comprise lines which:

(i) have known wavelengths ;

(ii) are individually unresolved;

(iii) are resolved from each other;

(iv) have uniform spacing;

(v) cover the whole range of operation;

(vi) have nearly uniform intensity;

(vii) are stable over long-time scales;

(viii) don't reduce S/N of observed object.

moreover:

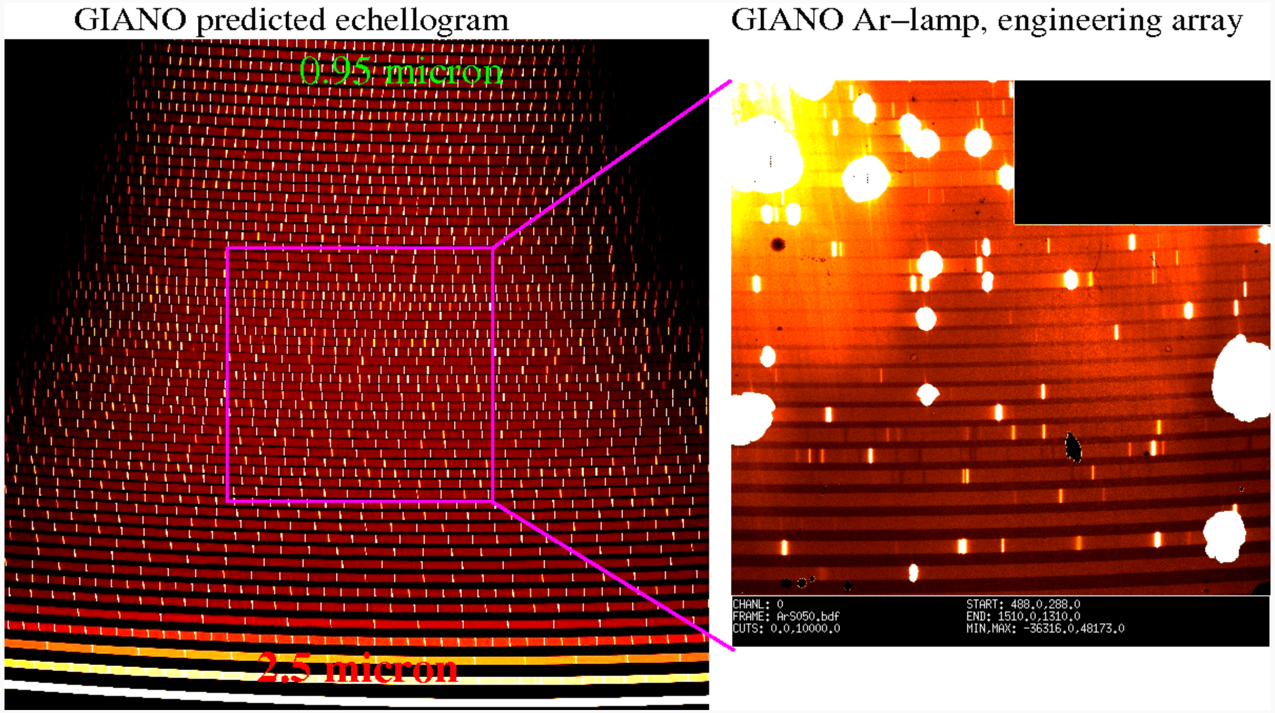
(ix) exchangeable (2 independent sources produce the same spectrum);
(x) easy to use (nearly turn-key);
(xi) reasonably low costing.

The ideal calibration source

Limitations of the current standard calibration source in the near-IR:

Th-Ar discharge lamp

comparison with the ideal calibration spectrum:



The nearly-ideal calibration source has been identified as the Optical Frequency Comb

(Murphy et al. 2007, MNRAS 380, 839; Osterman et al. 2007, SPIE 6693, 66931G1)

The optical frequency comb (OFC)

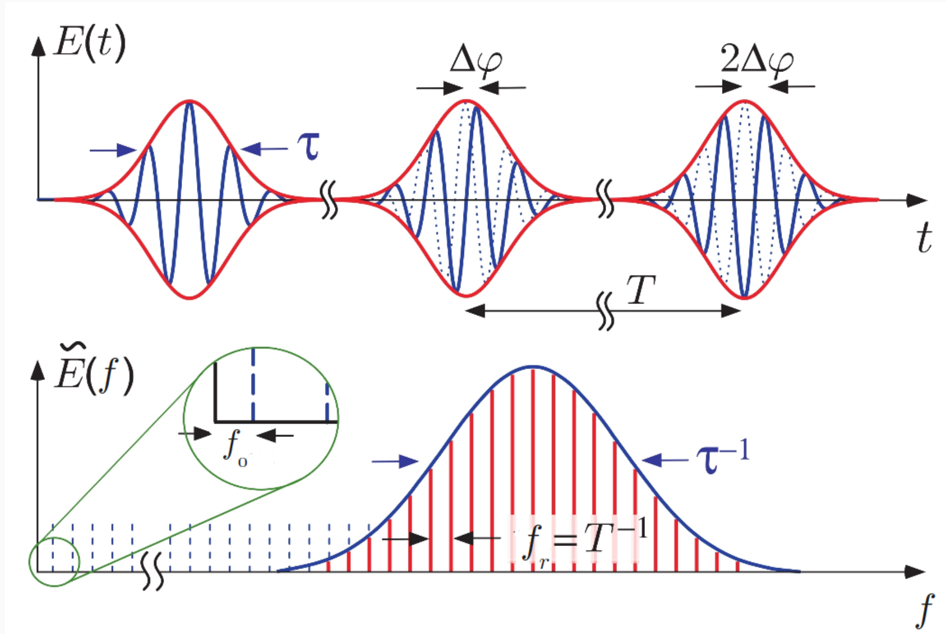
Principles of operation

Mode-locked pulsed laser: store a single pulse (~ tens fs) and maintain it on a repetitive path, emitting a copy of the pulse after each round-trip, resulting in an train of pulses

Time domain

Fourier transform

Frequency domain



$$f_n = n f_r + f_0$$

n integer and f_o, f_r radio-frequencies controllable against atomic clocks (< 250MHz for commercial near-IR combs)

$$\Rightarrow \frac{\Delta f_n}{f_n} \leq 10^{-12}$$

$$\Delta f \propto \tau^{-1} \Rightarrow \textit{tens nm}$$

Easily broadened to one octave in the near-IR by non-linear effects in optical fibers

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The optical frequency comb (OFC)

A quasi-ideal calibration spectrum:

(i) have known wavelengths ;

(ii) are individually unresolved;

(iii) are resolved from each other;

(iv) have uniform spacing;

(v) cover the whole range of operation;

(vi) have nearly uniform intensity;

(vii) are stable over long-time scales;

(viii) don't reduce S/N of observed object.

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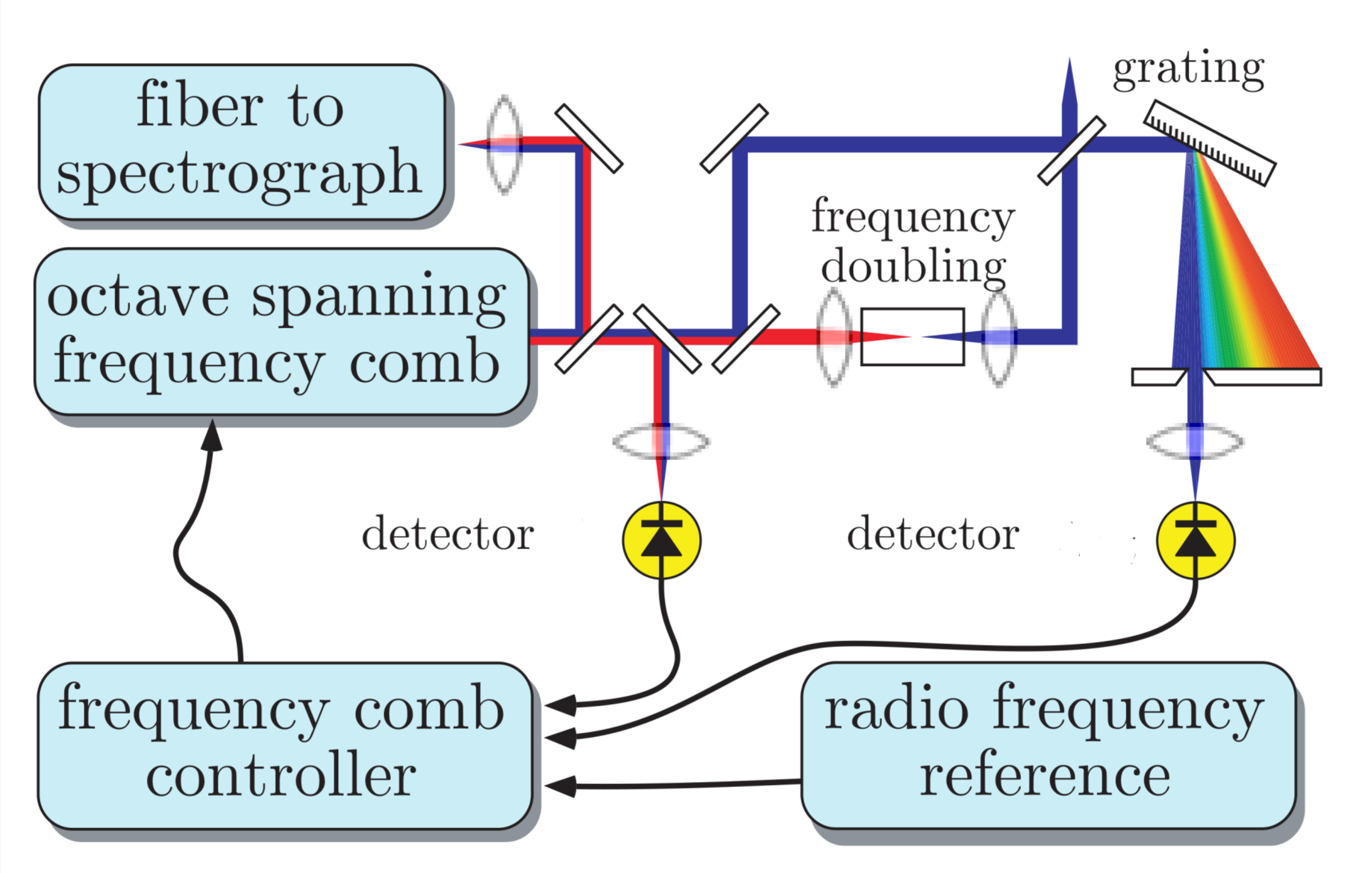
The optical frequency comb (OFC)

The Astro-comb set-up



G. Schettino *et al., Astro-comb project. Proc. SPIE 7808, 78081Q (2010)*

The optical frequency comb (OFC)

Not-resolved comb spacing problem

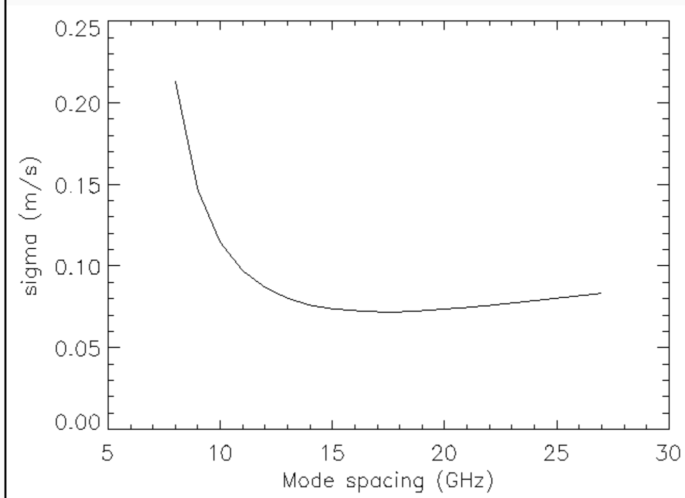
FC1500 Er-doped fiber OFC
(MenloSystems GmbH):

f_r = 100-250 MHz

Spectral coverage: 1 – 2 μm

GIANO:

optimum line spacing:
16 GHz



Possible solution: Interferential optical filtering

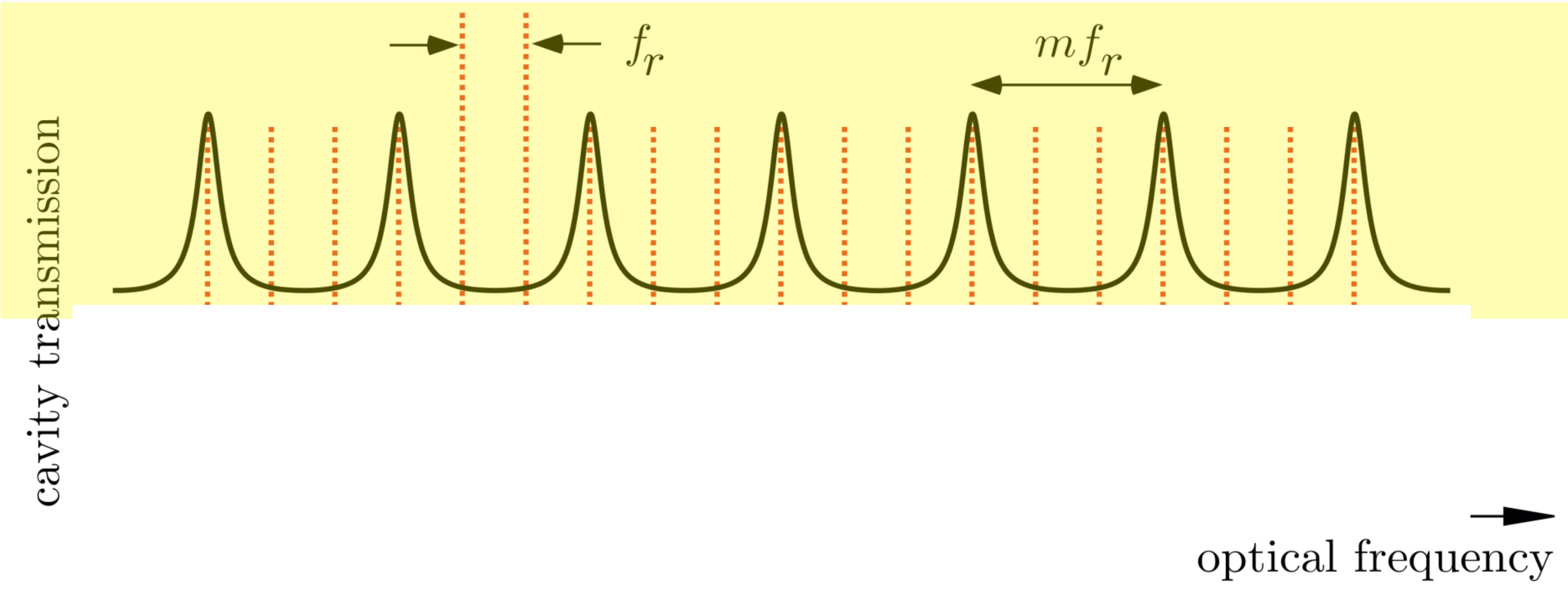
Interferential optical filtering

Filter out the unwanted modes with an external Fabry-Perot (F-P) cavity

Filtering order $m = FSR / f_r$ (160 for GIANO)

Requirements:

•High side-mode suppression ρ



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Interferential optical filtering

•Side-mode suppression

$$\rho = T(f_r, R, L) \quad \text{with} \quad T(f,R,L) = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(2\pi f L/c)}$$

R: mirror reflectivity
L: cavity length

Spectral shift for remaining side modes:

$$\Delta f = \frac{0 + \rho f_r}{1+\rho} \simeq \rho f_r \;\Rightarrow\; \rho \simeq \frac{\Delta f}{f}\frac{f}{f_r}$$

GIANO's request: $\Delta f / f = v/c = 3 \times 10^{-10}$ ⇒ *f=200THz*, *f_r=100MHz* ⇒ **ρ = -32 dB → Finesse** $F \approx \frac{\pi}{1-R}$

F **~ 3000 (R = 99.9%)**

•Cavity-mirrors dispersion

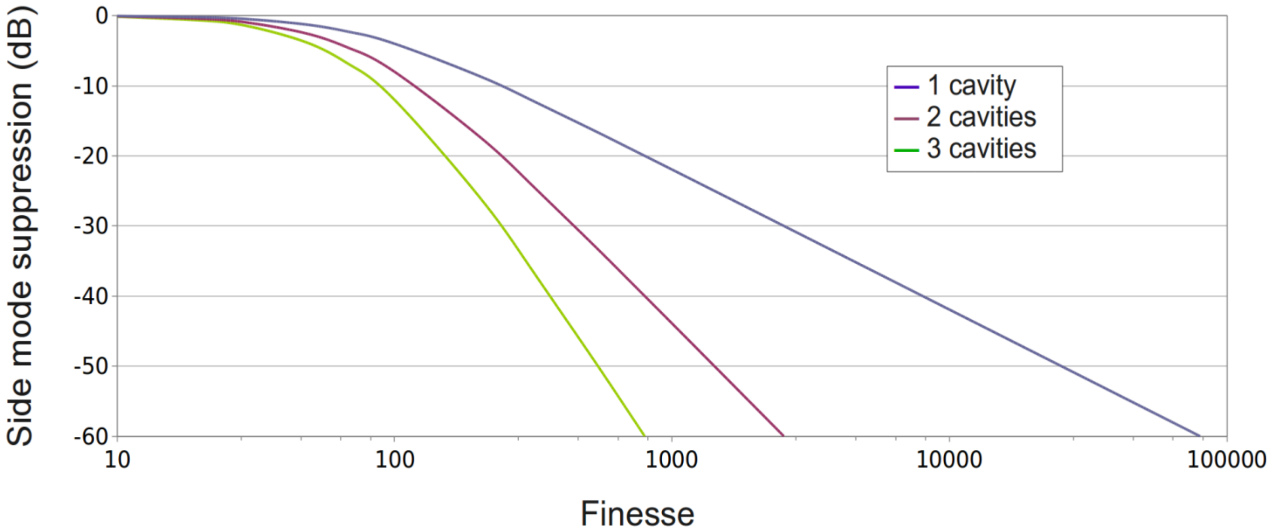
$$FSR(f) = \frac{c}{2L + (c/\pi)\partial\phi/\partial f}$$

$\delta\phi/\delta f$: round-trip phase shift due to mirror reflections ⇒ **> Finesse → > dispersion**

Conflicting requirements: high finesse for good side-mode suppression, low finesse to reduce mismatches.

Interferential optical filtering

<u>Solution</u>: more than one F-P cavity in series



Case ρ = -32 dB

- 1 cavity: F = 3000 (R = 99.9%)
- 2 cavities: F = 500 (R = 99.4%)
- 3 cavities: F = 250 (R = 98.7%)

Cavity-mirrors dispersion: Group Delay Dispersion (GDD)

$$GDD(f) = \frac{d}{df}\frac{1}{FSR(f)}[fs^2]$$

GIANO's request:

FSR=16GHz
f_r = 100MHz
0.1% *FSR* change between 1-2 μm

→ GDD < 150 fs^2

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Design of a filtering system

Feasibility of a 16GHz OFC calibrator in the 1-2 μm operation range with ρ<32dB and GDD <100fs^2

1st approach:

2 cavities (FSR_1=1.6 GHz and FSR_2=16GHz) in series made of **dielectric** coated mirrors (F=320 and GDD <100 fs^2) in the range 1500 – 1650 nm

\+

spectral broadening in a highly non-linear fiber (HNLF).

2nd approach:

3 cavities (FSR_1=1.6 GHz FSR_2=8GHz and FSR_3=16GHz) in series made of **metallic** coated mirrors (F=100 and GDD = 0 fs^2) in the range 1000 – 2000 nm.

Design of a filtering system

Additional constraints

- Transversal high order modes

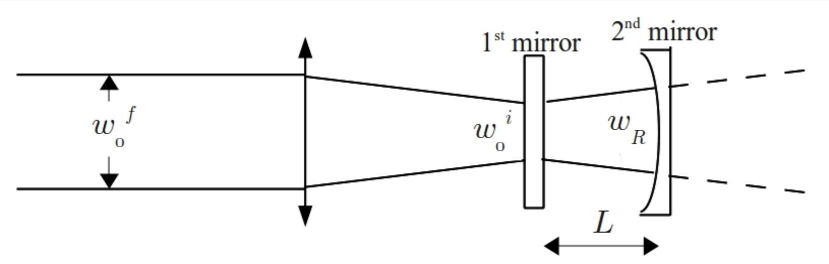
$$f_{qmn} = \frac{c}{2L}\left[q + (n+m+1)\frac{\arccos(\sqrt{g_1 g_2})}{\pi}\right]$$

→ Define optical configuration of the F-P's

hemifocal cavities (R_2= 100 mm)

spot size at 1st mirror:

$$w_0^i = \left[(R-L)\frac{\lambda^2}{\pi^2}L\right]^{1/4}$$



- Final power / comb mode

Defined by the spectrograph sensitivity → For GIANO:

total power 16 – 165 pW in the 1-2 μm range

- Air dispersion inside the F-P's → Cavities under vacuum

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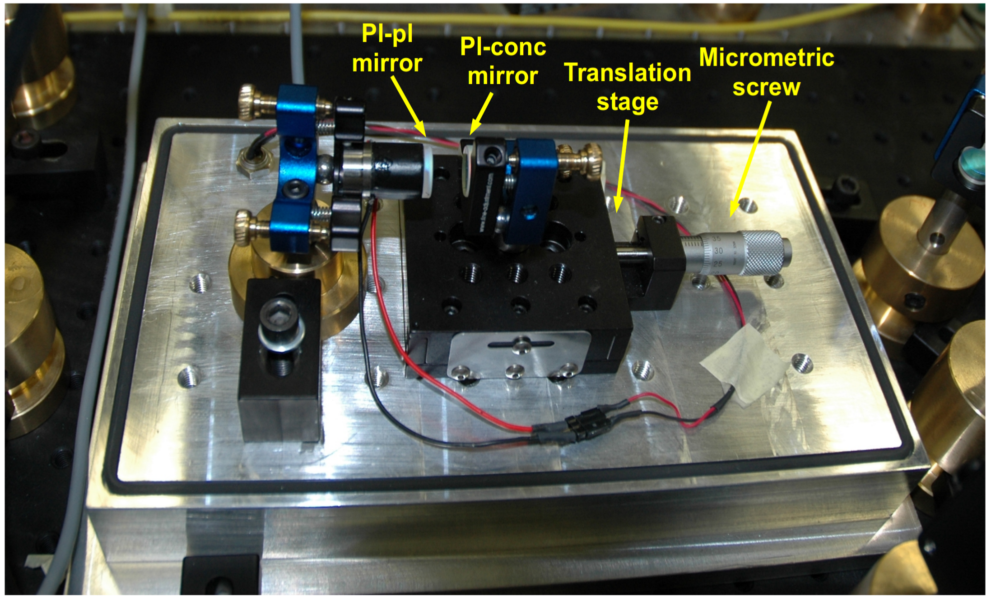
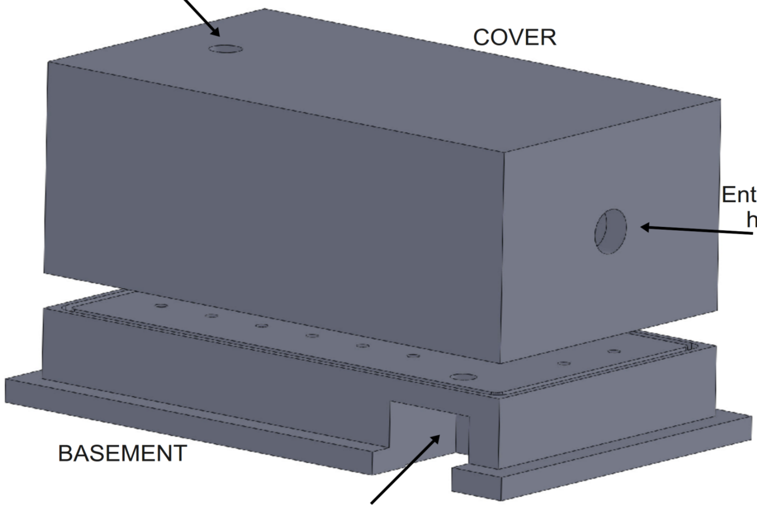
F-P cavity

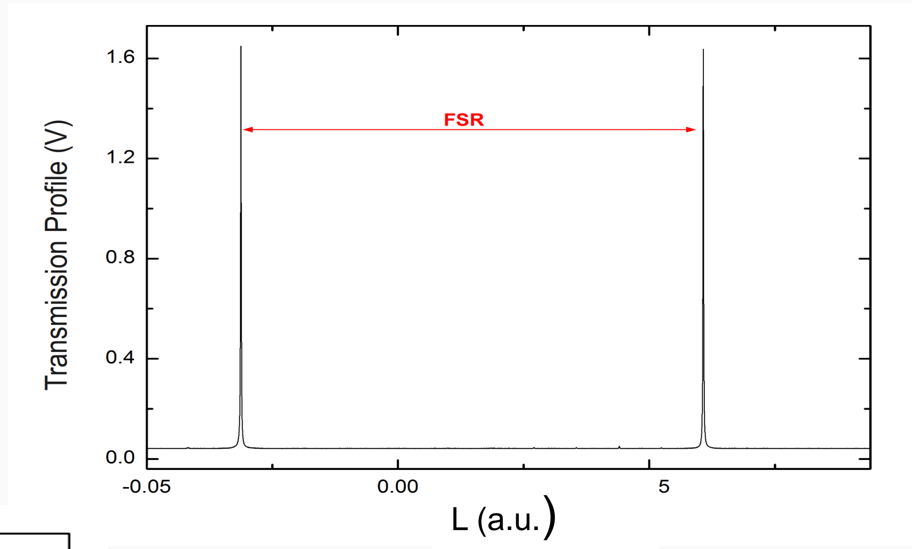


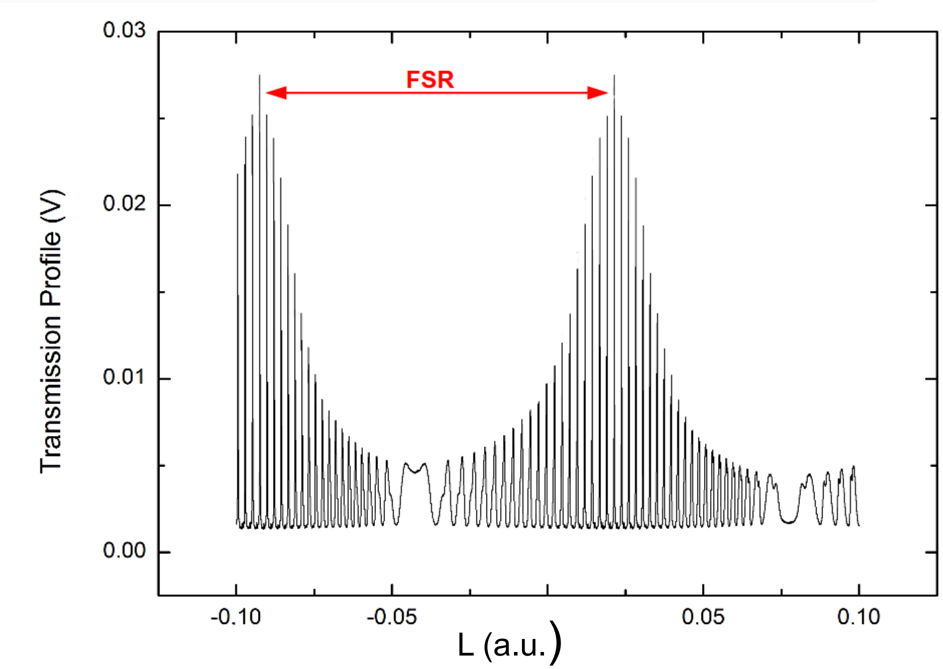


F-P cavity

Cavity alignment

Mirror alignment by using a cw laser at 1550 nm





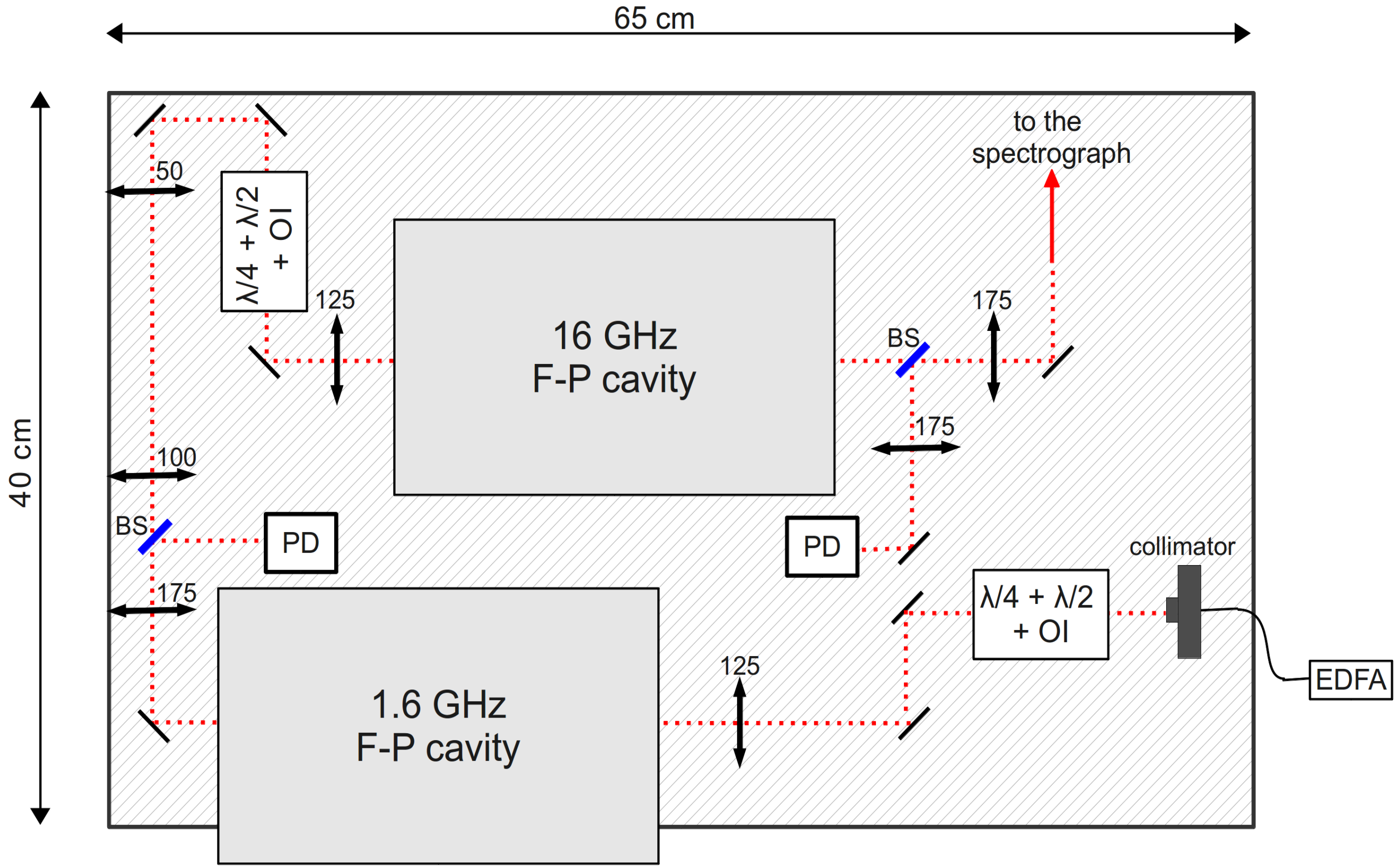
$$\frac{c}{2L} = m f_r$$

m integer only in perfect comb matching

F-P with dielectric coated mirrors

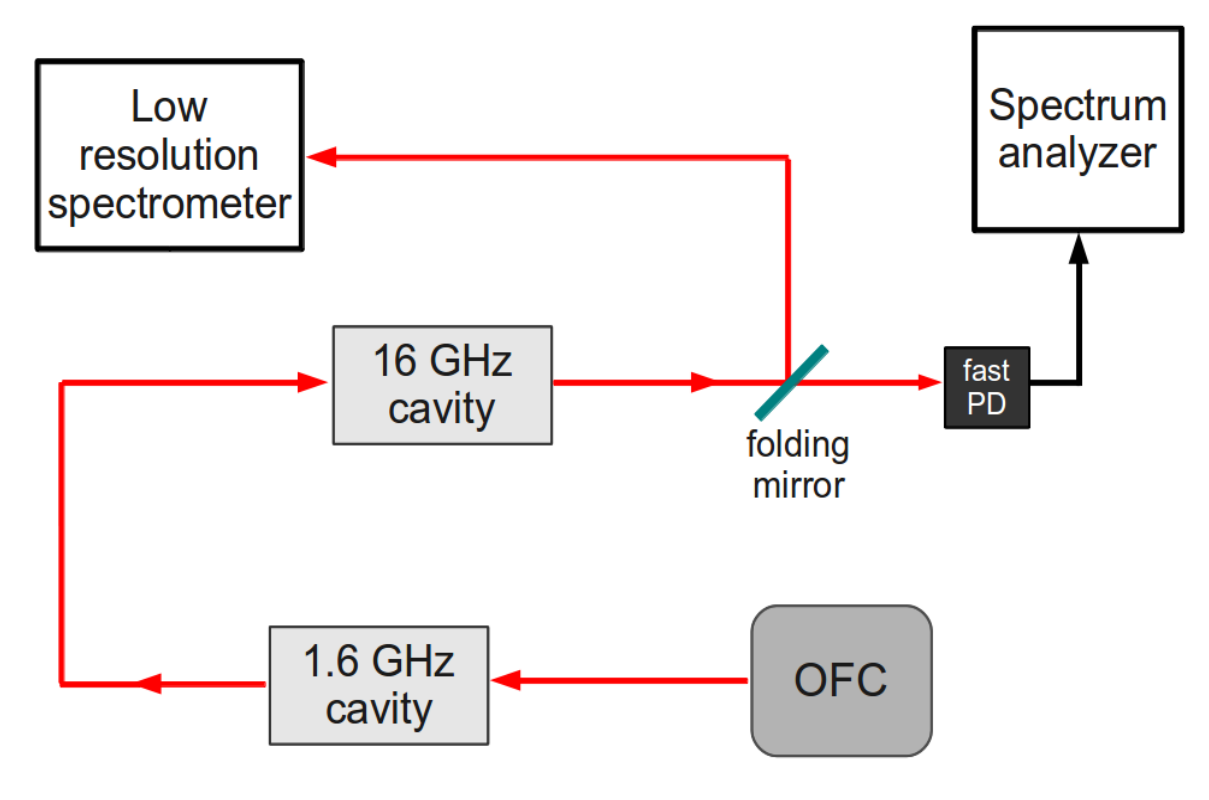
FSR_1 = 1.6 GHz → ρ = -32 dB with F = 320

FSR_2 = 16 GHz → ρ = -44 dB and ρ1.6GHz= -32 dB with F = 320



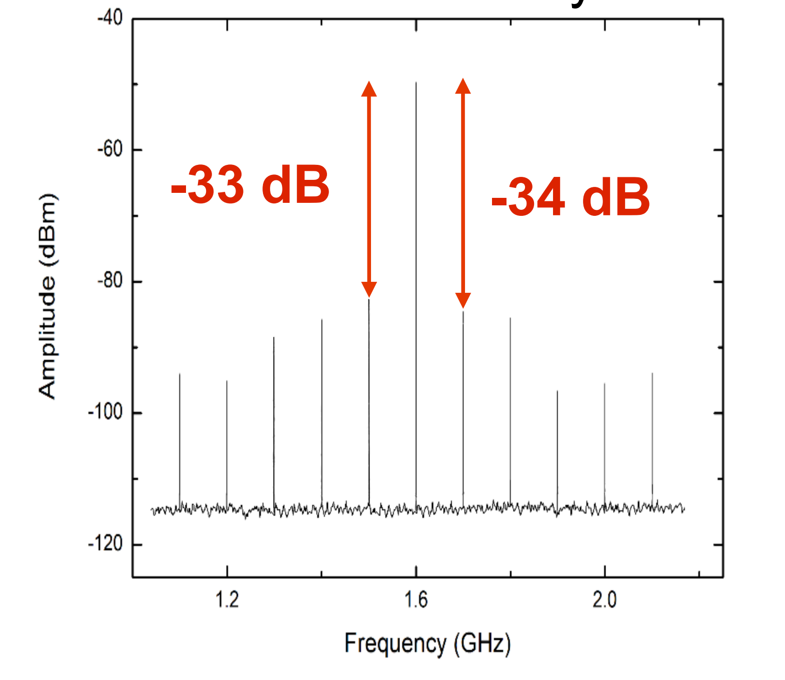
F-P with dielectric coated mirrors

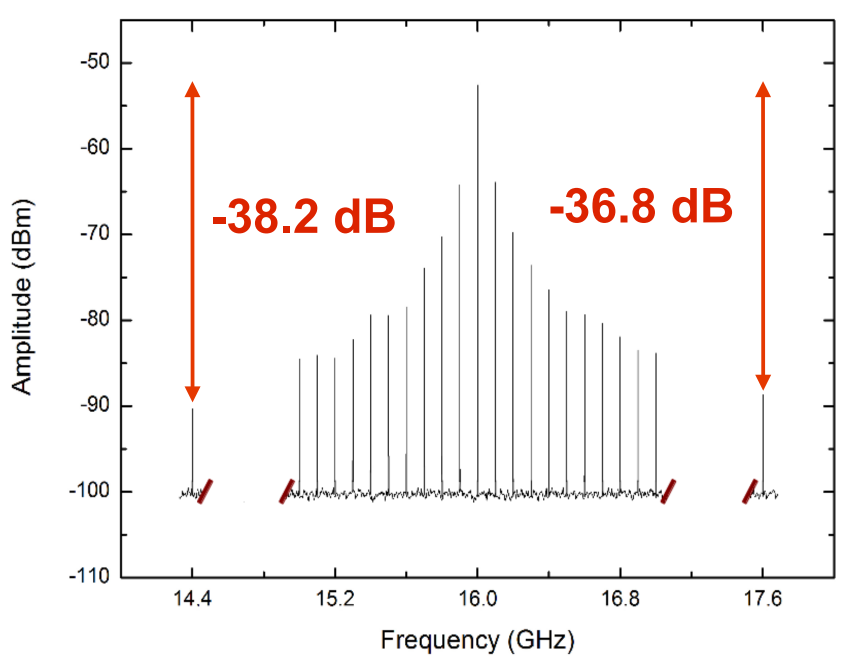
Filtering characterization



F-P with dielectric coated mirrors

The 100 MHz OFC coupled
in each cavity

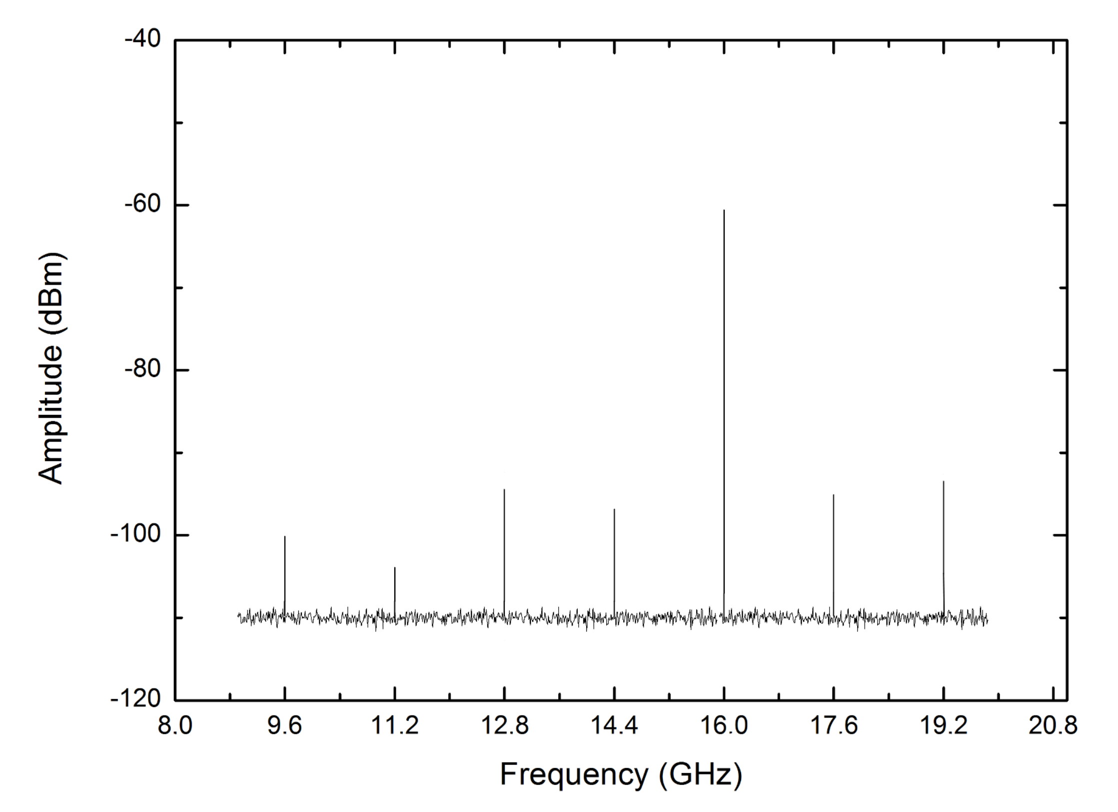




16 GHz Cavity

F-P with dielectric coated mirrors

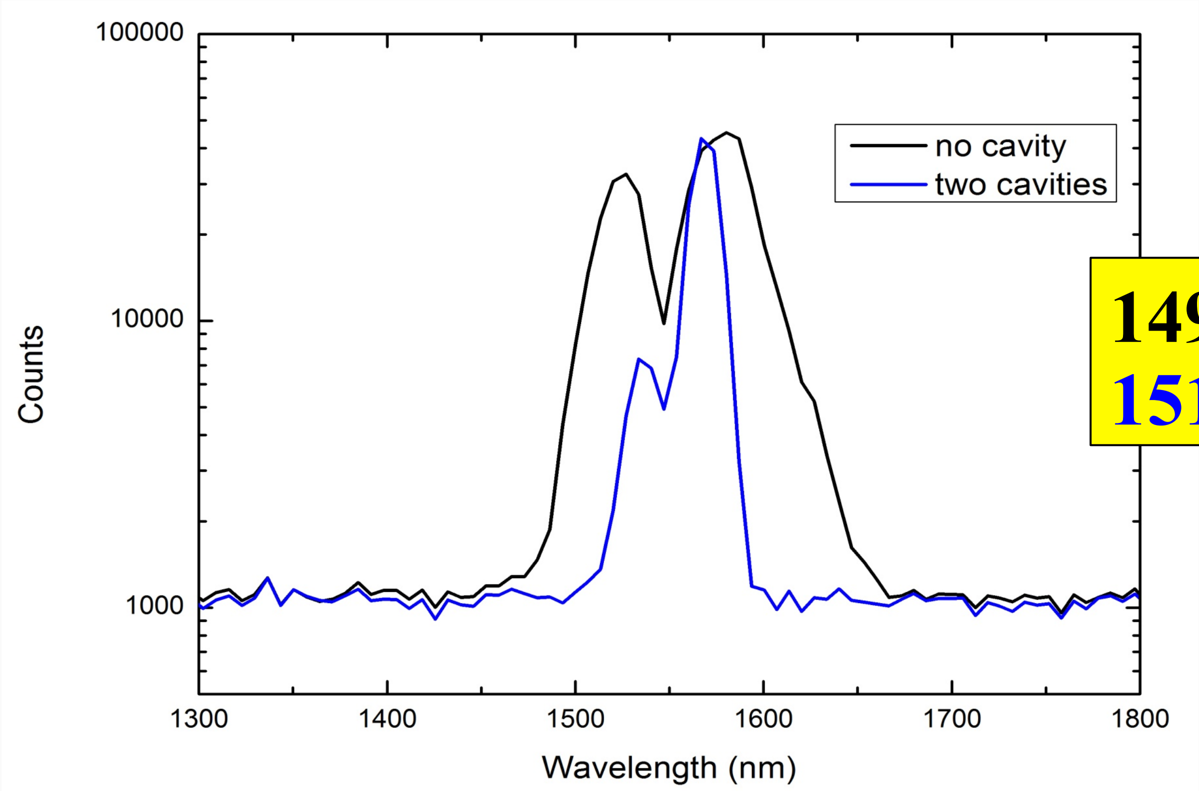
Two F-P in series



More than 35 dB suppression

F-P with dielectric coated mirrors

Spectral coverage



1490 – 1630 nm
1510 – 1590 nm

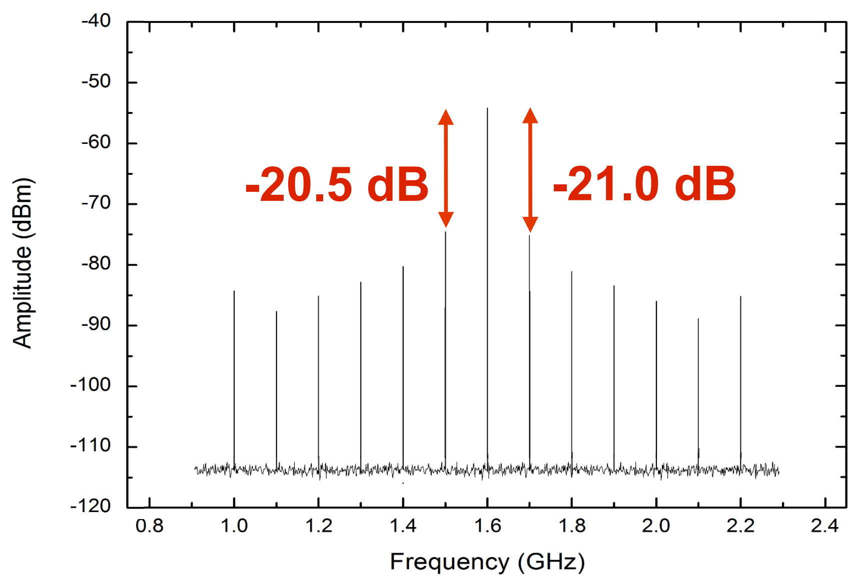
Final Power : 300 μW with a loss factor of 1500 → insufficient for spectral broadening

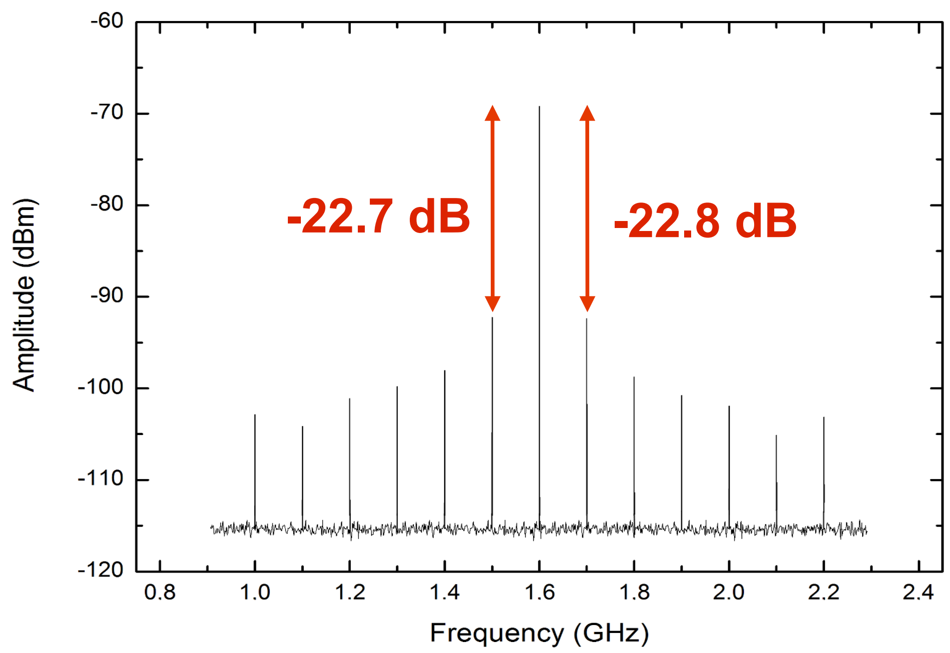
F-P with metallic coated mirrors

The 100 MHz OFC
coupled in 1.6 GHz Cavity

<u>Required suppression: </u>ρ = -20.8 dB

R= 97.5 %, T=0.4%





R= 98.5 %, T=0.2%

Higher suppression but 5 times higher power losses

$$R + T \neq 1 (A > T)$$

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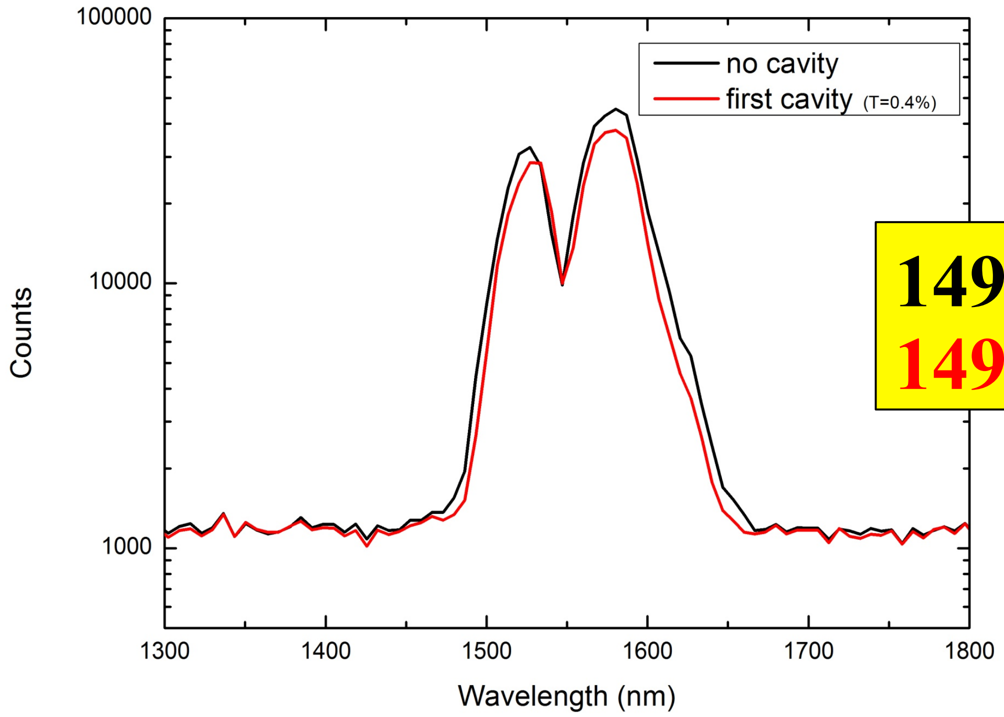
F-P with metallic coated mirrors

Spectral coverage



1490 – 1630 nm
1490 – 1630 nm

Final Power : 30μW with a loss factor of 15000

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Conclusions

Dielectric cavities:

- ADVANTAGES:
  - ✓ high R → 2 cavities
  - ✓ low power losses
- DISADVANTAGES:
  - ✓ limited spectral coverage → 1500 – 1650 nm
  - ✓ not enough power for spectral broadening
  - ✓ worsening suppresion due to further amplification

Metallic cavities:

- ADVANTAGES:
  - ✓ no dispersion → octave spanning
- DISADVANTAGES:
  - ✓ low R → 3 cavities
  - ✓ high power losses

G. Schettino *et al. Exp Astron* (2011) **31**:69–81

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...and perspectives

- Microcavity OFC
  - ✓ Directly emitting at high repetition rate
  - ◆ Difficult to control and stabilize

- EOM generated OFC:
  - ✓ Directly emitting at high repetition rate
  - ◆ Limited spectral coverage
  - ◆ Difficult to produce rep. rate high than 10 GHz
  - ◆ Optical reference to be stabilized

Grazie della attenzione

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