How to use the metrological signal : amplification and optical comb control

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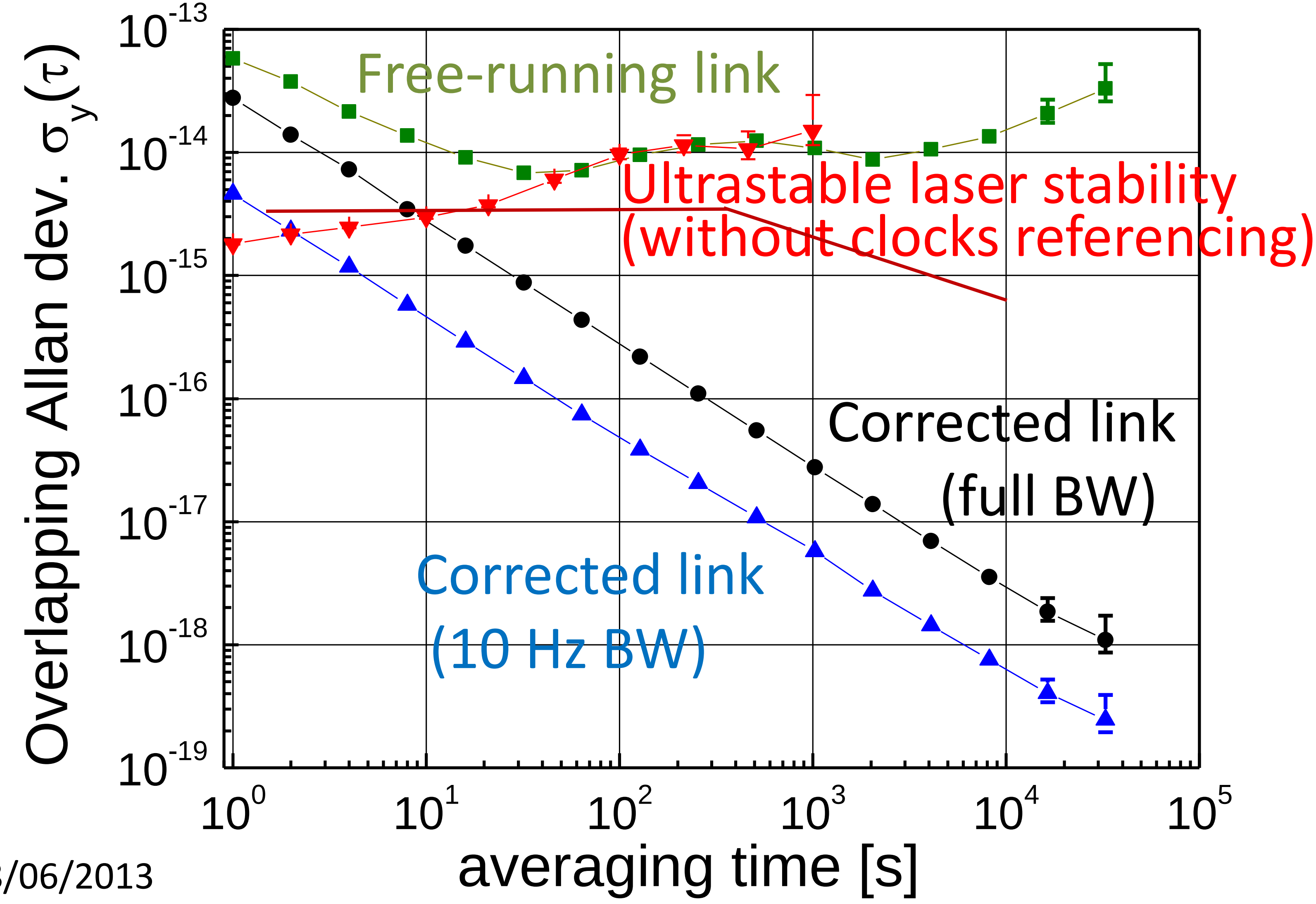
Outline

- Amplification of the metrological signal
- Stability and accuracy transfer with an optical frequency comb

Which signal will you received?

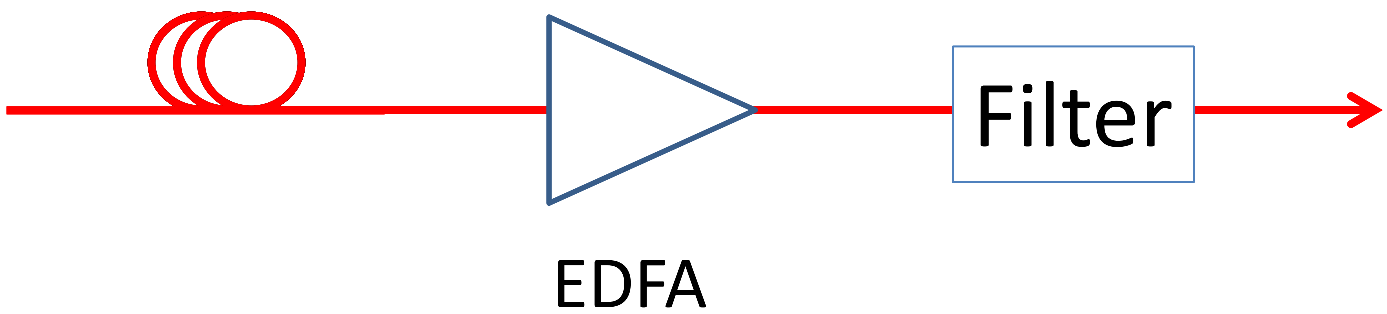
- Metrological laser signal at 1.542 µm
  - Power from 1 µW to 100 µW
  - Frequency stability ≈ 10^{-14} @ 1 s (full BW)
  - Frequency accuracy ≈ 10^{-14}
- This stability degrades after propagation in a local optical fiber
  - Main effect : thermal effect, after 1 m, stability floor is ≈ 10^{-17}
  - Fiber noise DSP : 10^{-1}-100 rad^2/Hz/km @ 1 s

Metrological signal stability with a 540-km link



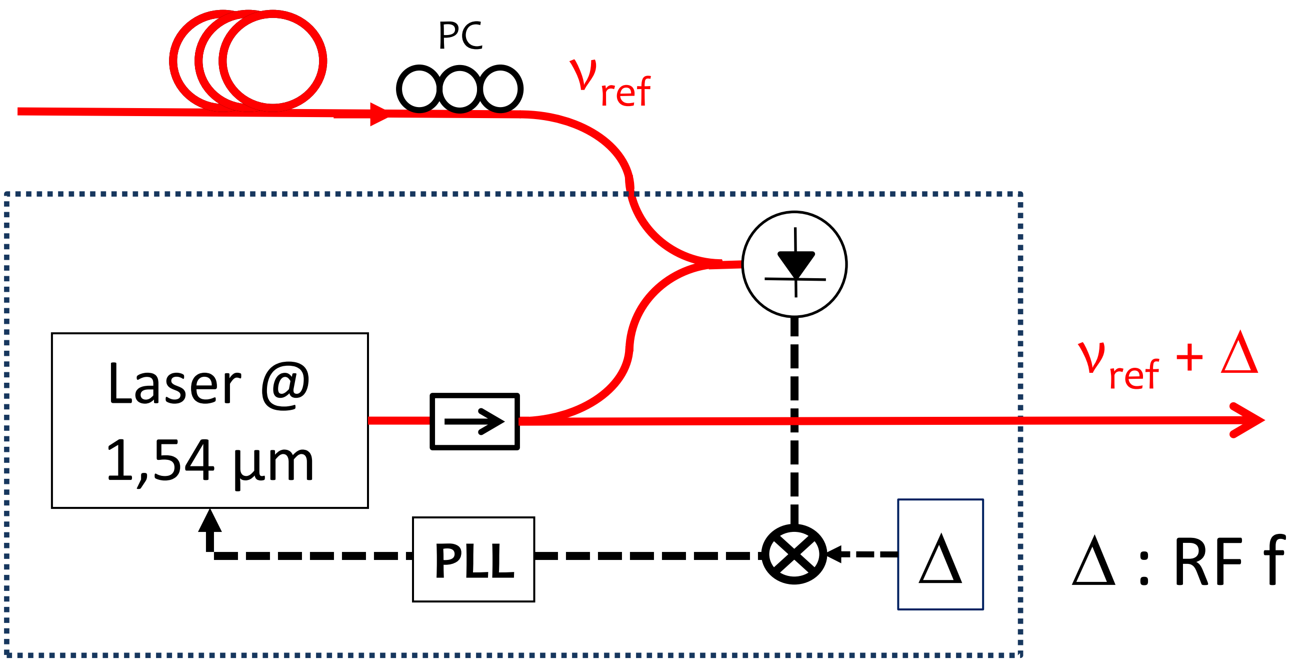
Amplification (I)

- Depending of applications, the signal should be amplified
- Method # 1 : Erbium-doped fiber amplifier + DWDM filter (to eliminate the wideband ASE)



Amplification (II)

- Method #2 : optical tracking
  - Local laser phase-locked to the metrological signal
  - Local laser can be stabilized to an ultra-stable cavity



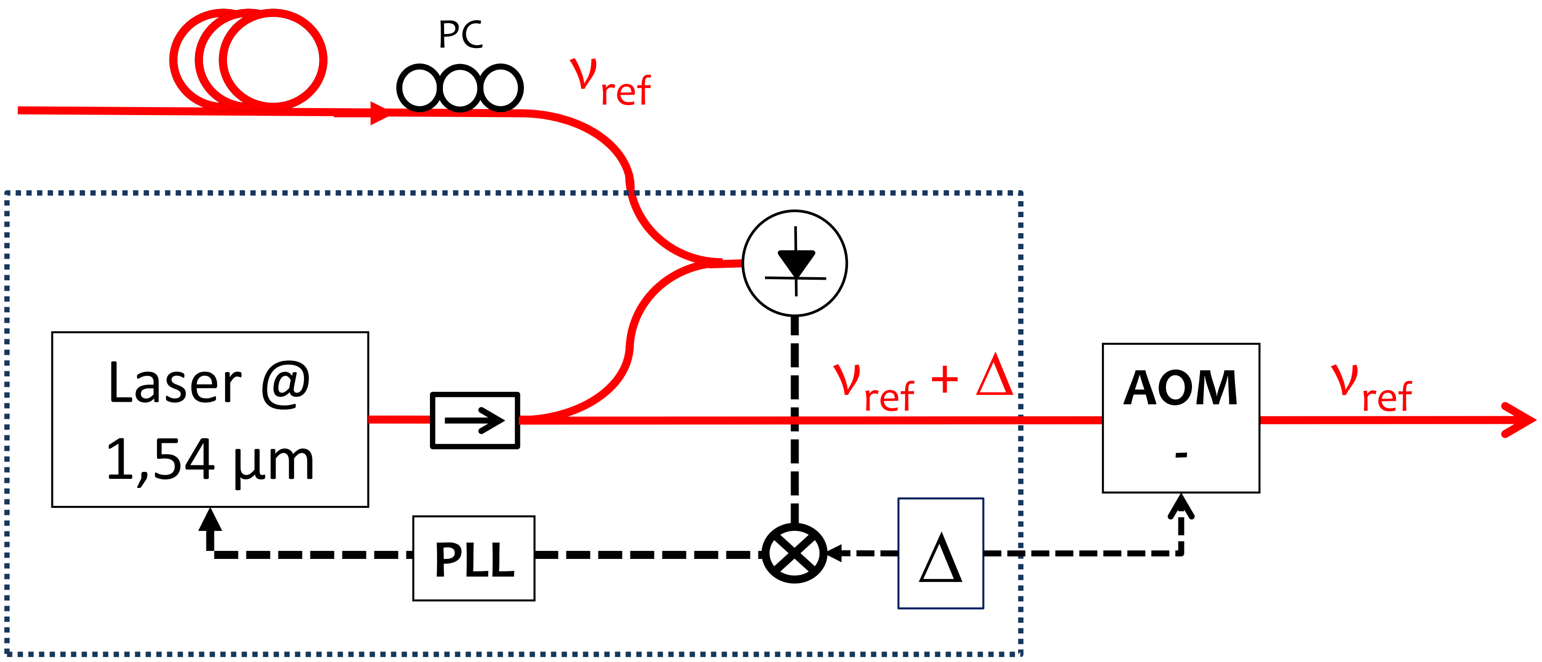
Δ : RF frequency

Local RF frequency

- Usual RF frequency (from synthesizer)
  - Accuracy 10^{-6}
  - If Δ=100 MHz, accuracy 100 Hz $\rightarrow 5\times10^{-13}$ @ 200 THz
- GPS-disciplined low-noise RF oscillator
  - Accuracy $< 10^{-10}$
  - If Δ=100 MHz, accuracy 0.01 Hz $\rightarrow 5\times10^{-17}$ @ 200 THz

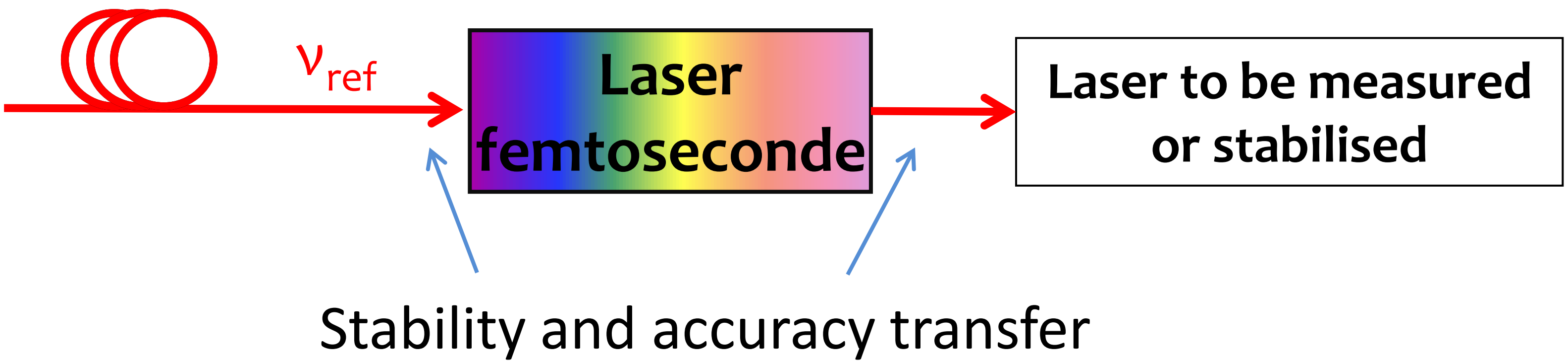
Amplification (III)

- Method #2 : optical tracking



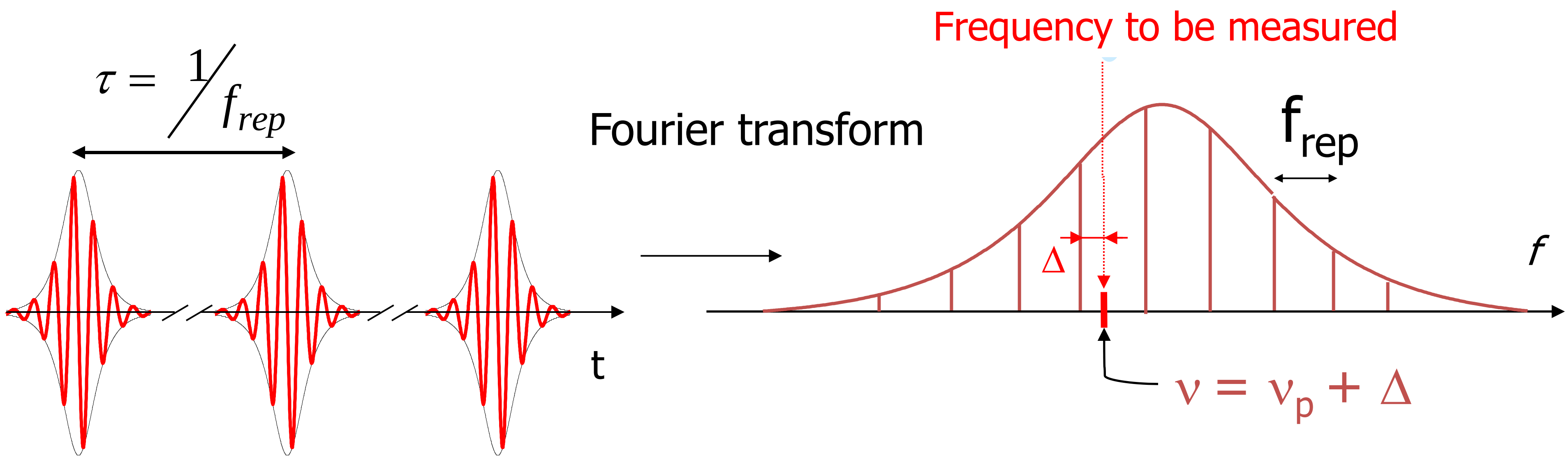
Stability transfer to another frequency

- An optical frequency comb enables to transfer the stability and accuracy to other frequencies
- Two steps



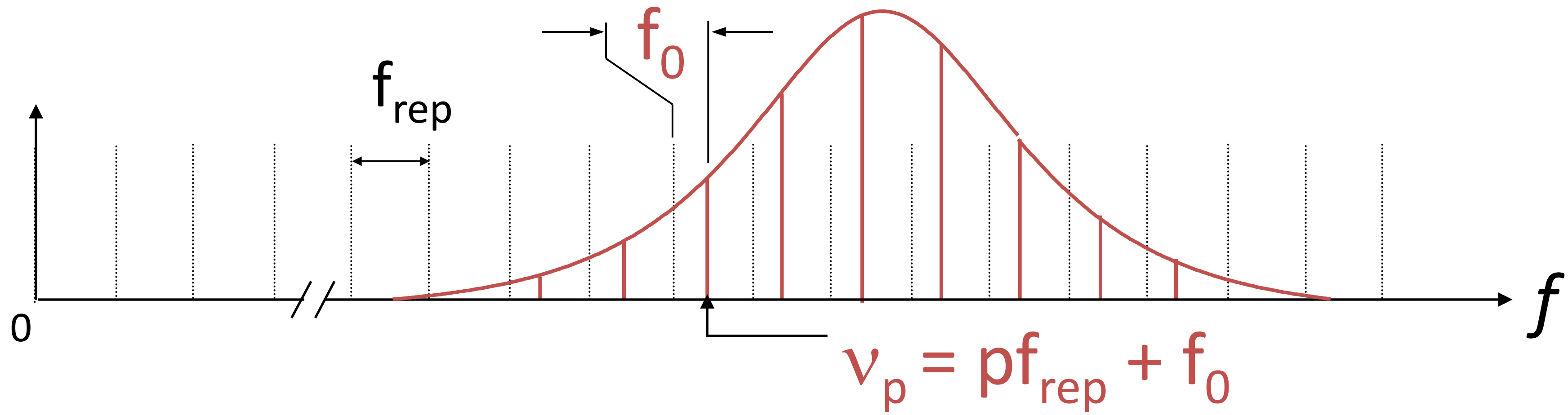
A femtosecond laser as optical frequency comb

fs laser : pulses of duration 10-100 fs every $1/f_{rep}$ (1-10 ns)

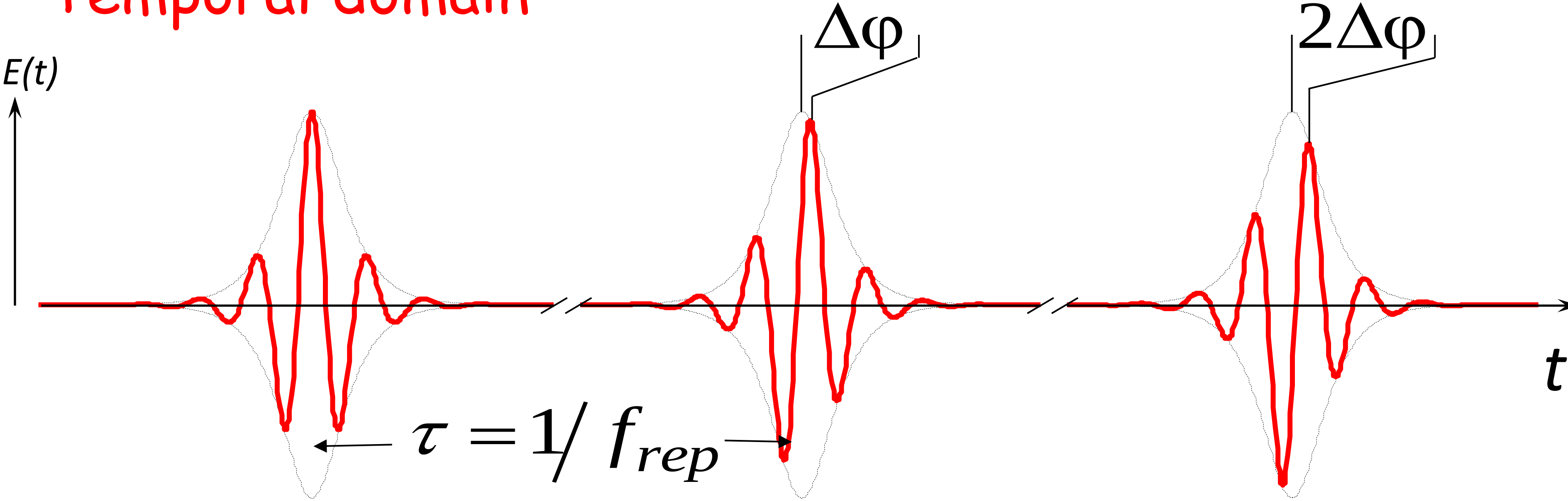


- f_{rep} : fine scaling (f_{rep} ~ 100 MHz -1 GHz)
- optical frequency ~ $p \times f_{rep}$ with p an integer ~ 10^4 to 10^6

- Frequency domain



- Temporal domain

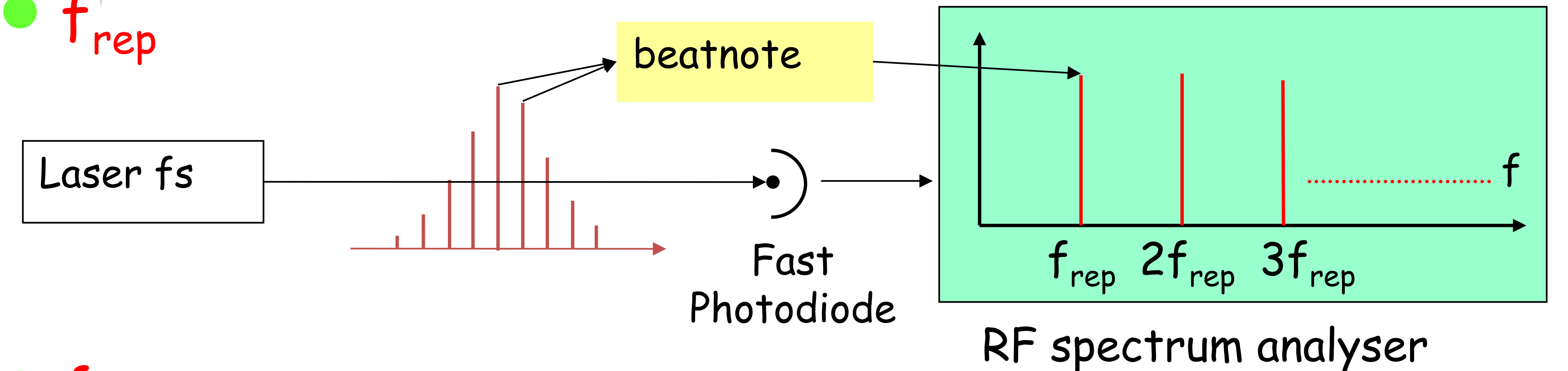


Dephasing of mode p between 2 pulses

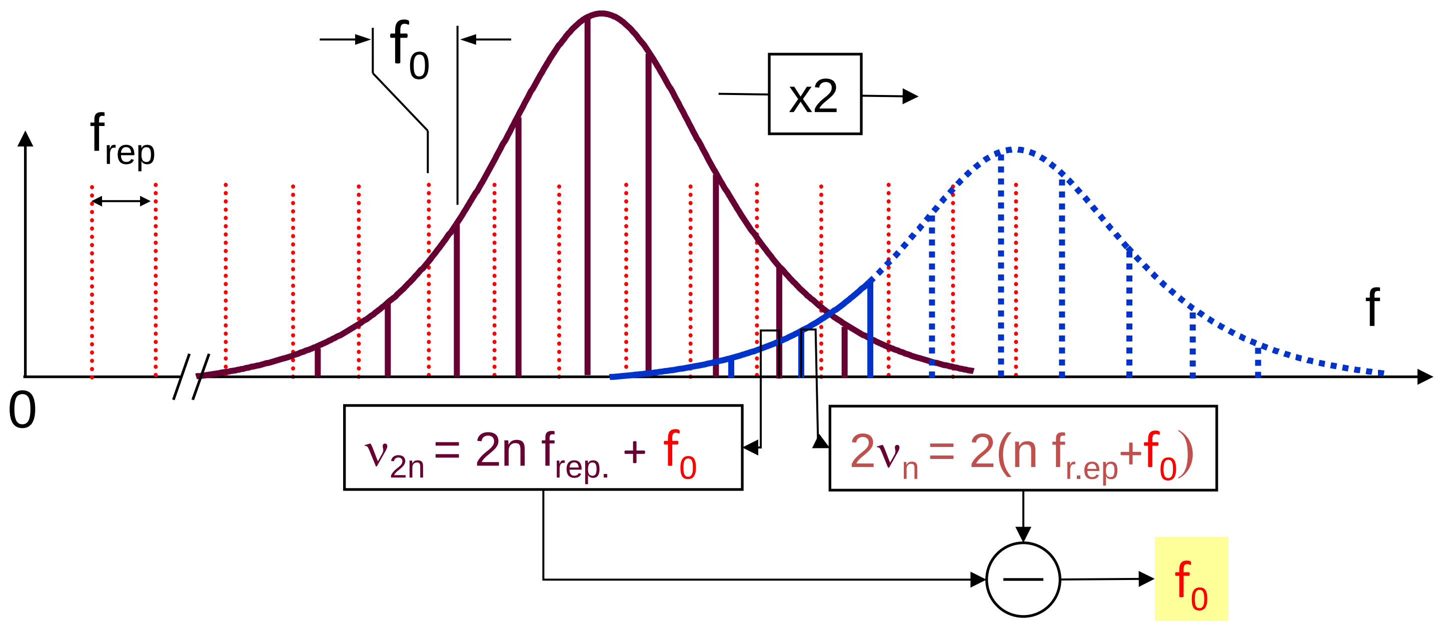
$$2\pi\nu_p\tau = 2\pi p + 2\pi f_0\tau \rightarrow \Delta\varphi$$

Self-referenced optical frequency comb

- f_{rep}



- f_0



Comb frequency control

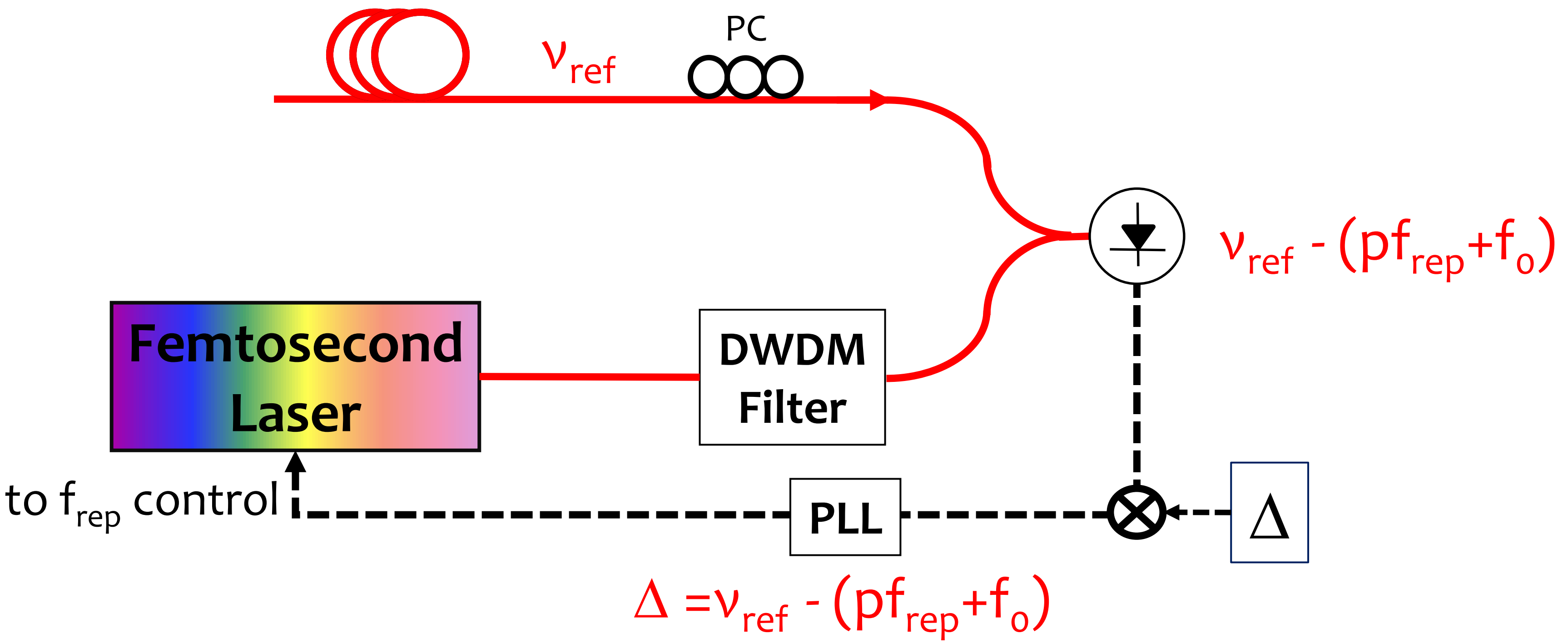
- Every mode frequency depends of the two RF frequencies :

$$\nu_p = pf_{rep} + f_0$$

- f_{rep} and f_0 should be stabilized in order to control the comb modes frequencies
- f_{rep} is controlled with the metrological signal (optical frequency reference)
- f_0 is free or controlled with a RF frequency reference

Stabilisation of f_{rep}

- Beatnote between the metrological signal and the nearest mode of the comb



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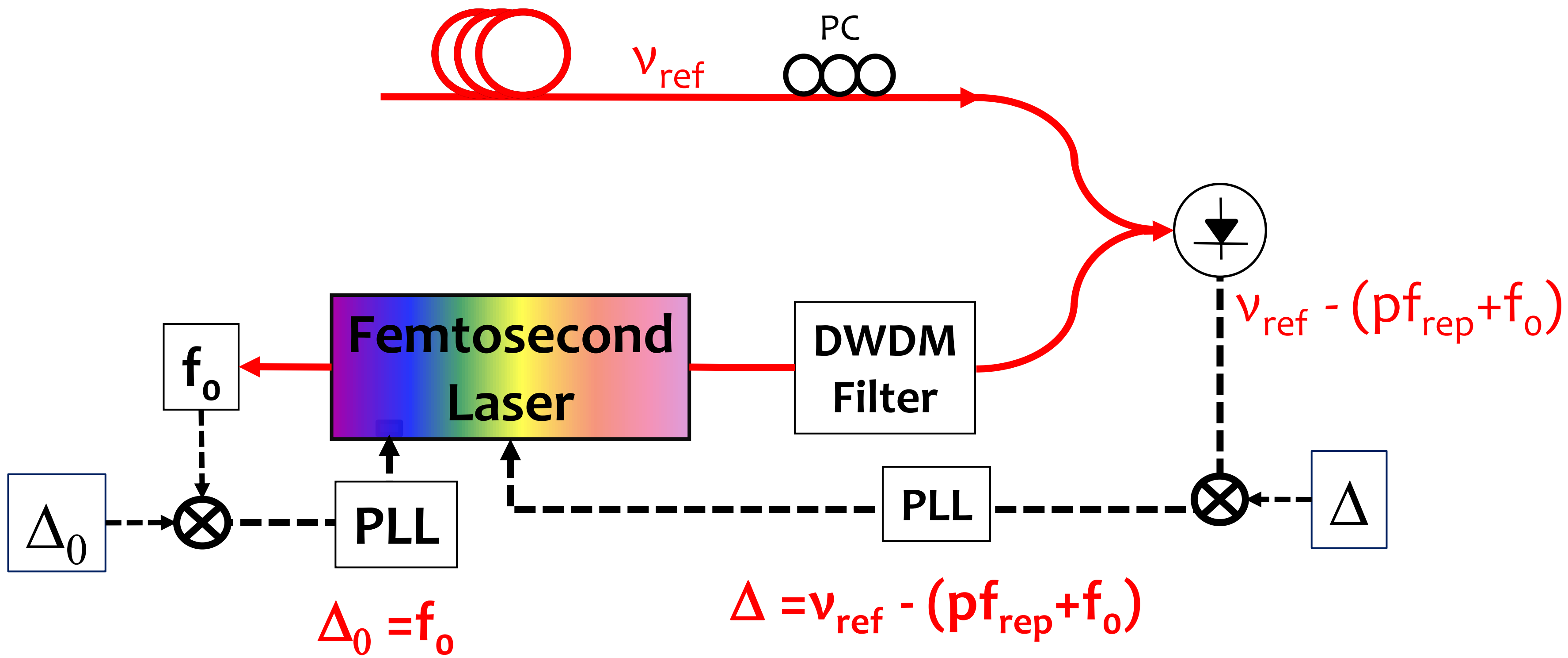
Stabilisation of f_0

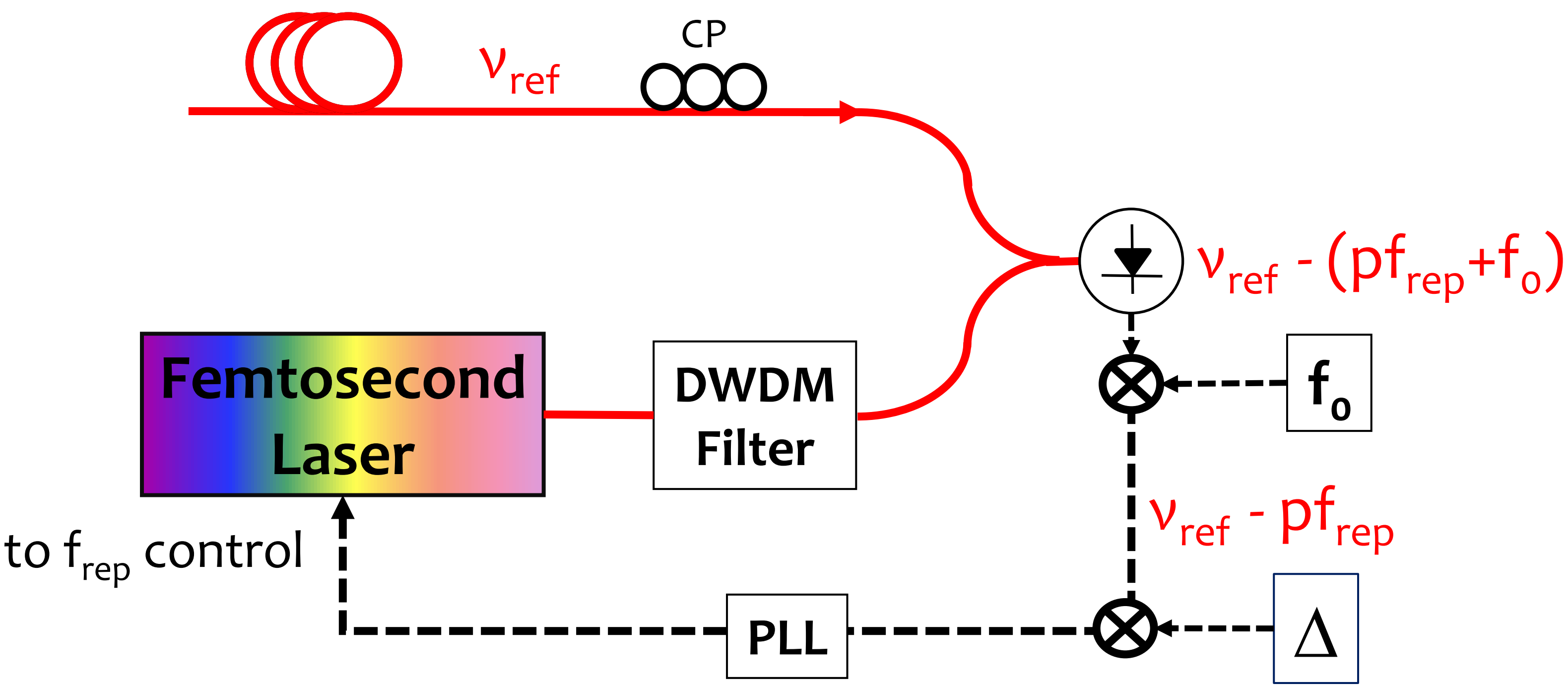
- Stabilization to the local RF frequency reference



- Comb stability and accuracy depend on the local RF reference

Removal of f_0

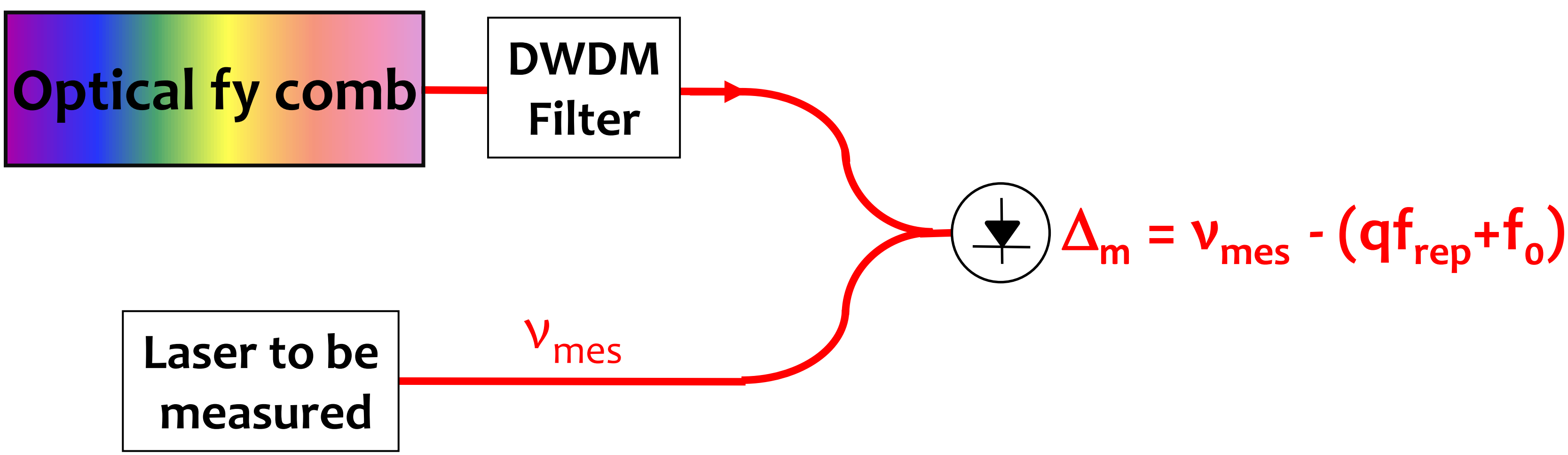
- f_0 can be removed from the optical beatnote and let free



$\Delta = \nu_{ref} - pf_{rep}$

Frequency measurement

- The laser frequency to be measured is inside the comb spectrum



$$\nu_{mes} = \Delta_m + (qf_{rep}+f_o) = \Delta_m + (q/p)(\nu_{ref} - \Delta) + f_o$$

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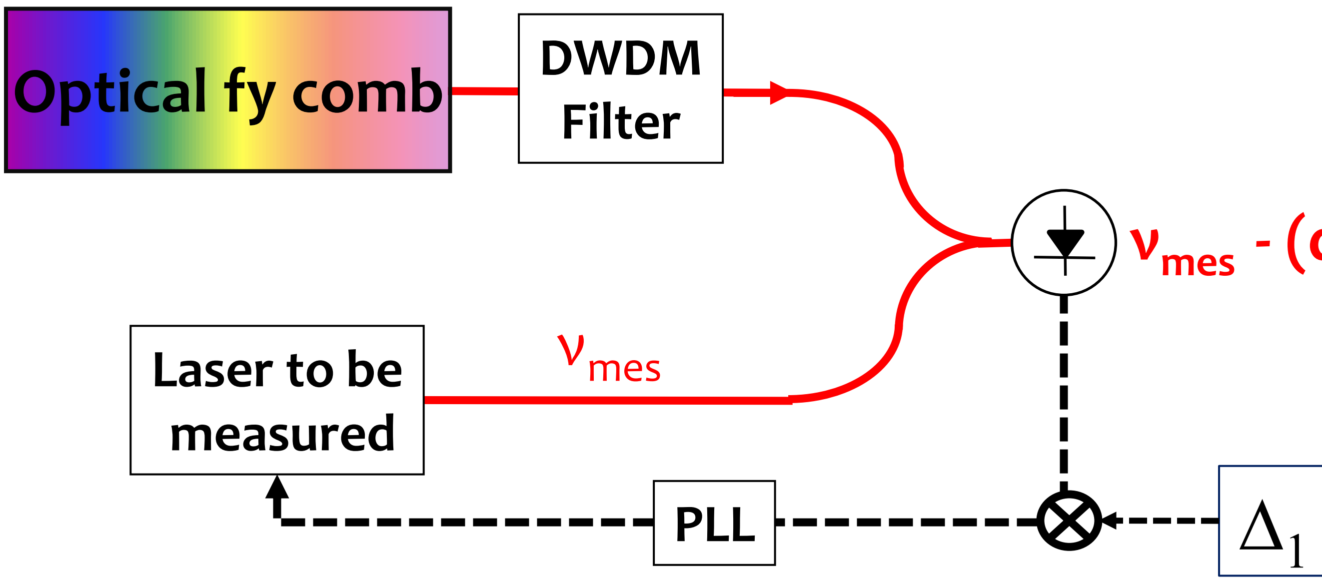
Or frequency control

- The laser frequency to be measured is inside the comb spectrum



$$\nu_{mes} = \Delta_1 + (qf_{rep}+f_o) = \Delta_1 + (q/p)(\nu_{ref} - \Delta) + f_o$$

Frequency accurate determination (I)

- How to determine the frequency ?
  - Determination of p and q
  - Determination of the signs

$$\nu_{mes} = \pm\Delta_m + (qf_{rep} \pm f_o) = \pm\Delta_m + (q/p)(\nu_{ref} \pm \Delta) \pm f_o$$

- You need to know f_{rep}, ν_{ref} et ν_{mes} with enough accuracy
- Or you combine two or more measurements with different f_{rep}

Frequency accurate determination (II)

- Example : the repetition rate stabilisation (after f_0 removal)

$$\Delta = \pm(\nu_{ref} - pf_{rep})$$

With ν_{ref} = 194 395 310 263 841 Hz

Δ = 150 000 000,00 Hz (10^{-10} accuracy)

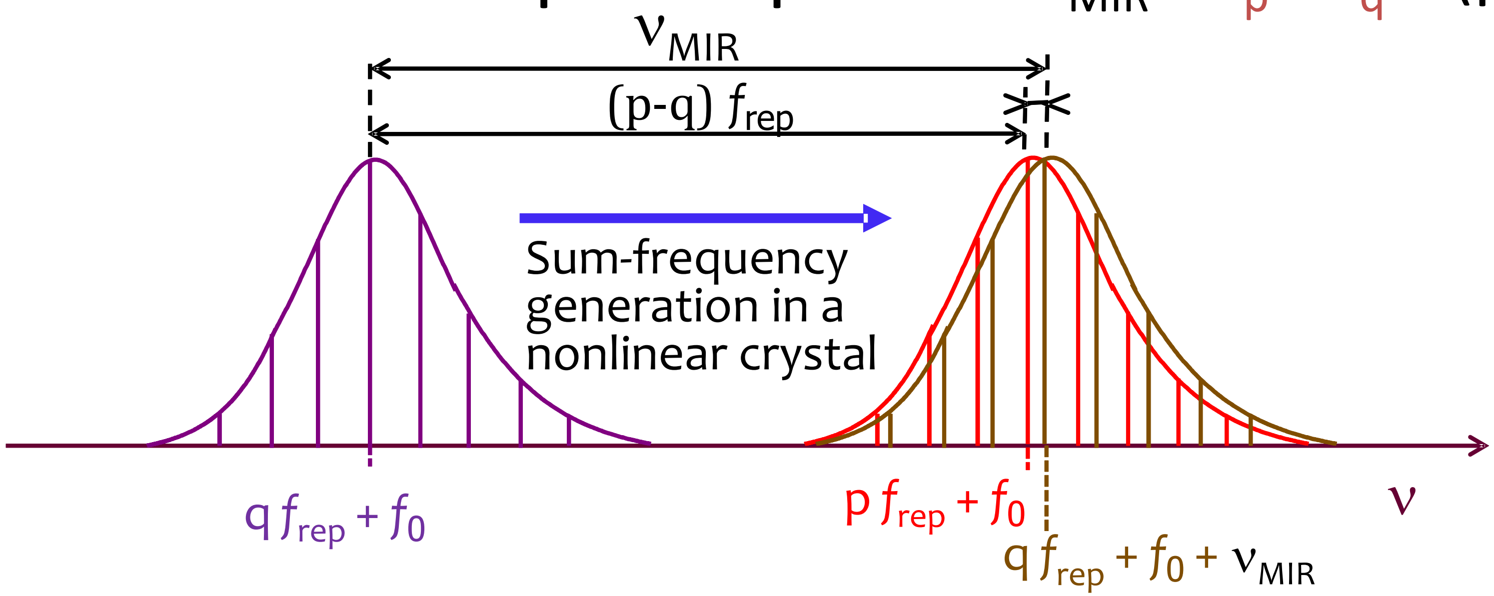
f_{rep}= 249 998 919,95 Hz

One calculate : p1= $(\nu_{ref} + \Delta)/f_{rep}$= 777 585,2004

p2= $(\nu_{ref} - \Delta)/f_{rep}$= 777 584,0004 : OK

Mid-IR frequency measurement

- Outside the comb spectrum (even with extra broadening)
- An extra set-up is required : $\nu_{MIR} \approx \nu_p - \nu_q = (p\text{-}q)f_{rep}$



➢ example : 1850 nm + 10 µm = 1550 nm

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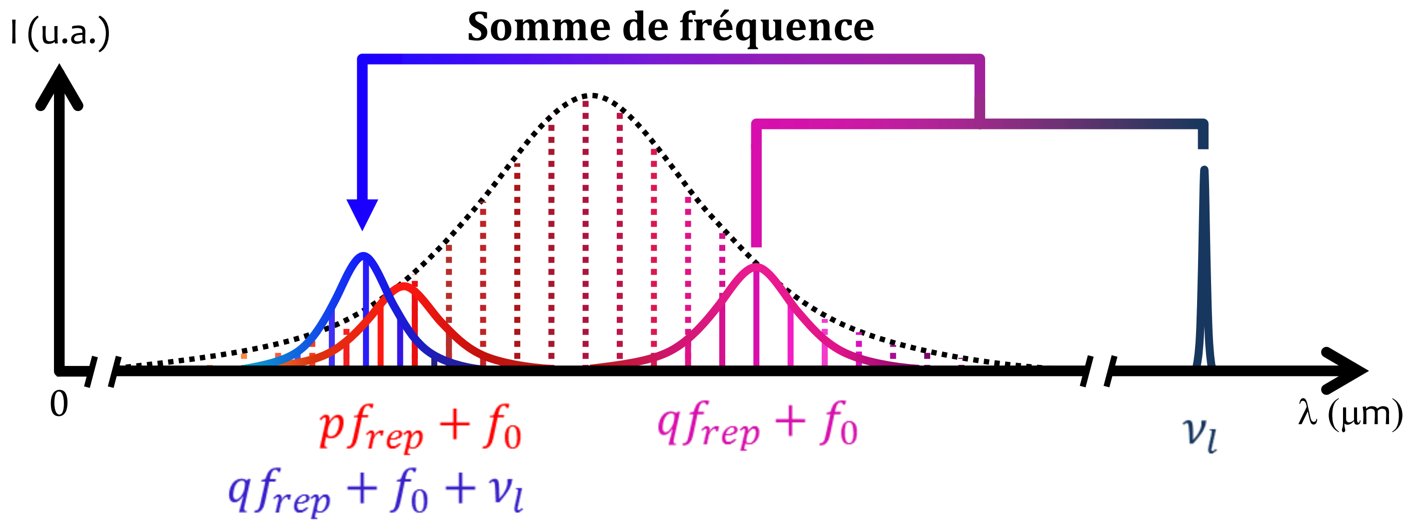
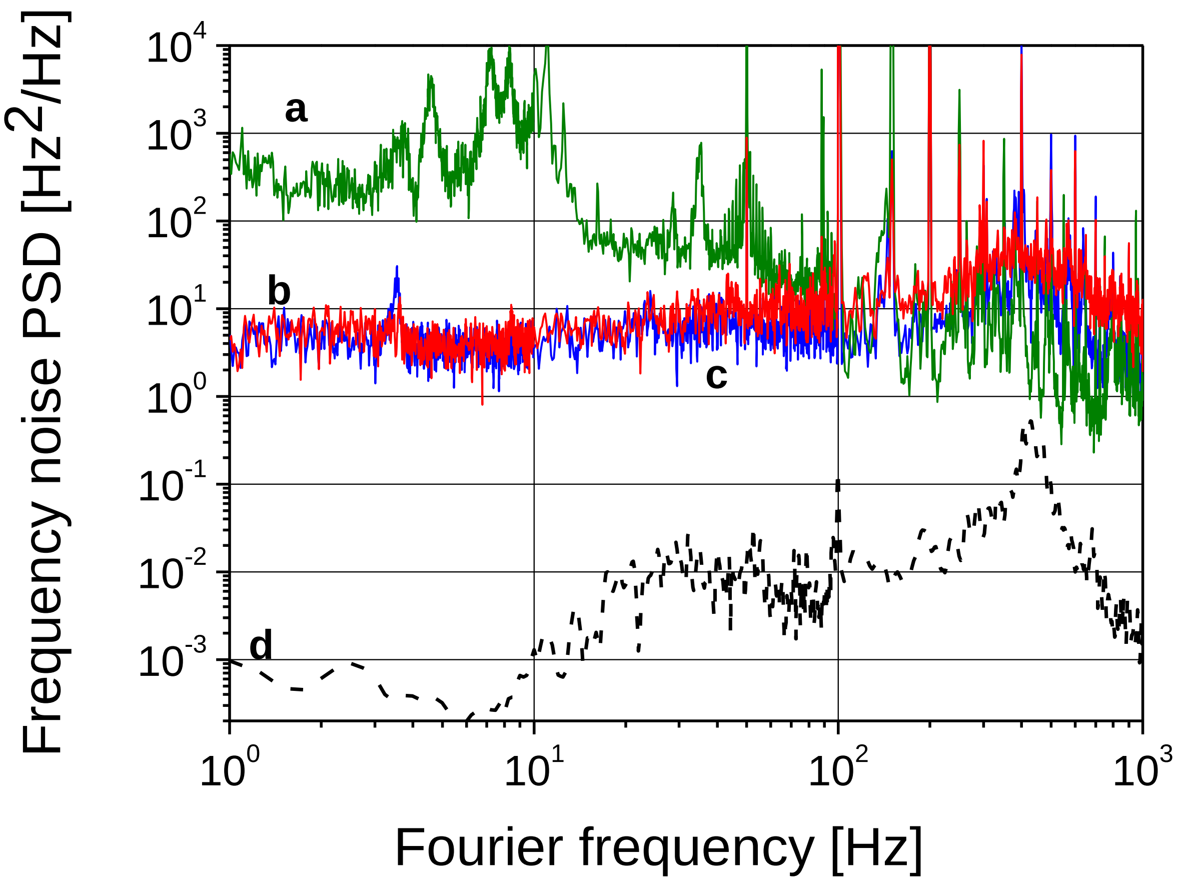
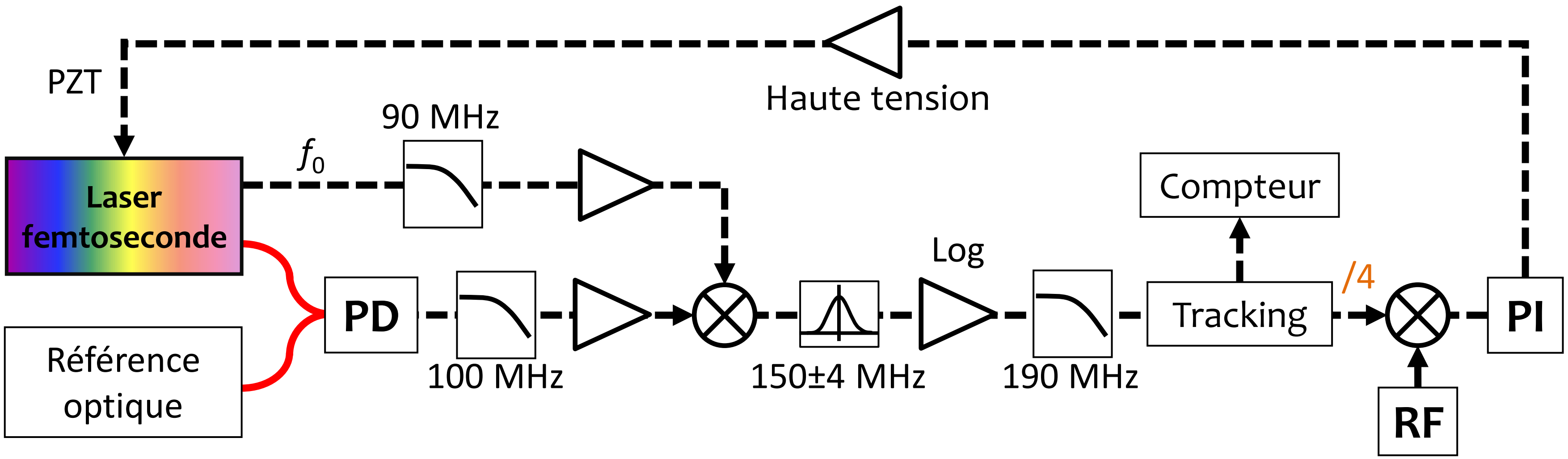
Conclusion

- Various schemes for the comb frequency control and the frequency stability and accuracy transfer
- A local RF reference frequency is required for accurate frequency transfer



Somme de fréquence
I (u.a.)
0
λ (µm)
$pf_{rep} + f_0$
$qf_{rep} + f_0 + \nu_l$
$qf_{rep} + f_0$
ν_l


Frequency noise PSD [Hz^2/Hz]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
a
b
c
d
10^0
10^1
10^2
10^3
Fourier frequency [Hz]


PZT
Haute tension
90 MHz
f_0
Laser
femtoseconde
Compteur
Log
PD
Tracking
/4
PI
Référence
optique
100 MHz
150±4 MHz
190 MHz
RF