Peignes de fréquences optiques pour génération micro-onde à très bas bruit de phase

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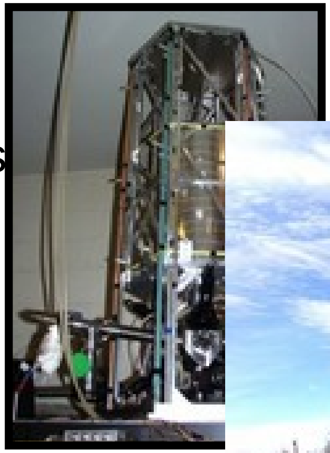
Low-noise μwave : motivation

Existing very low ϕ-noise μ-wave sources (~10GHz):

- Room temp Sapphire osc.
  (Raytheon, formerly Poseidon Australia):
  -40dBc/Hz @ 1Hz, -170dBc/Hz @ 100kHz from carrier
- Cryogenic Sapphire oscillator
  (UWA, FEMTO-ST, ULISS):
  -100dBc/Hz @1Hz, -140dBc/Hz @ 100kHz from carrier
- Opto Electronic Oscillator
  (JPL/OEwaves):
  -40dBc/Hz@1Hz, -160dBc/Hz @ 10kHz
  (large resonances after that)

Applications:

- atomic frequency standards
- radar
- VLBI
- synchronization of particle accelerators
- time reference distribution
- telecommunication
- …



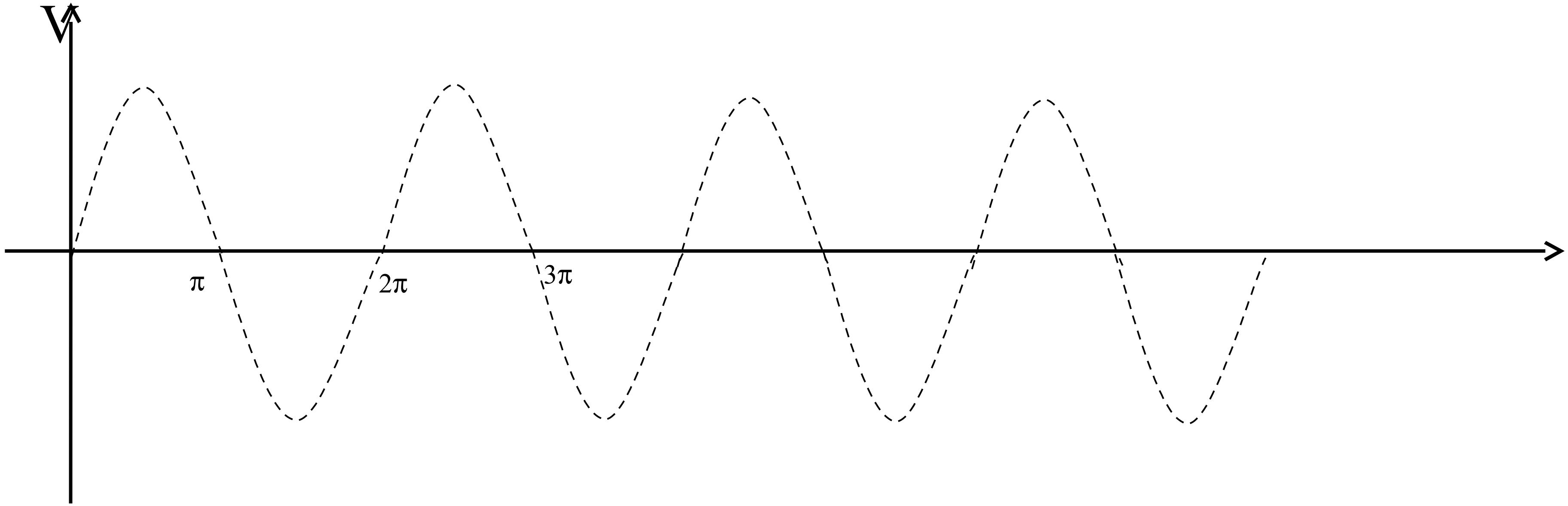
Frequency division, effect on phase noise

fc [Hz] → fc/N [Hz]   then $\Delta\phi$ → $\Delta\phi/N$ [rad]

$S_\phi(f)$ [dBc/Hz] → $S_\phi(f) - 20.\log10(N)$ [dBc/Hz]

Large noise reduction if N is large…

Exemple : divide by 2



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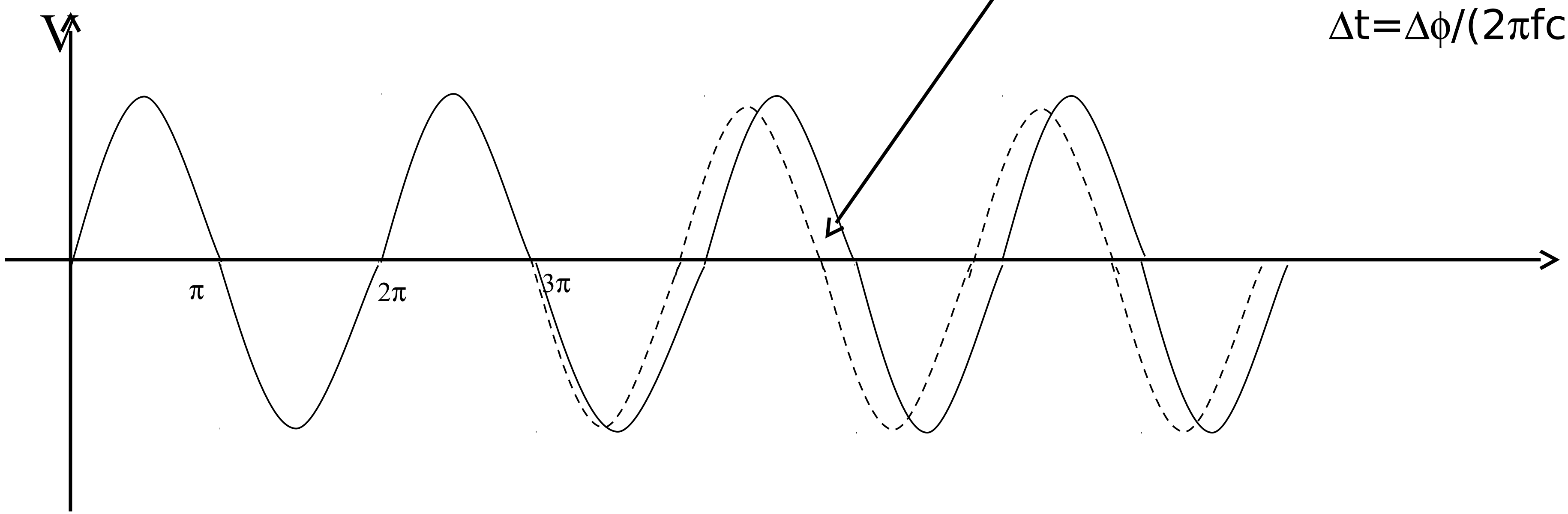
Dephasing $\Delta\phi$ → time delay $\Delta t = \Delta\phi/(2\pi fc)$



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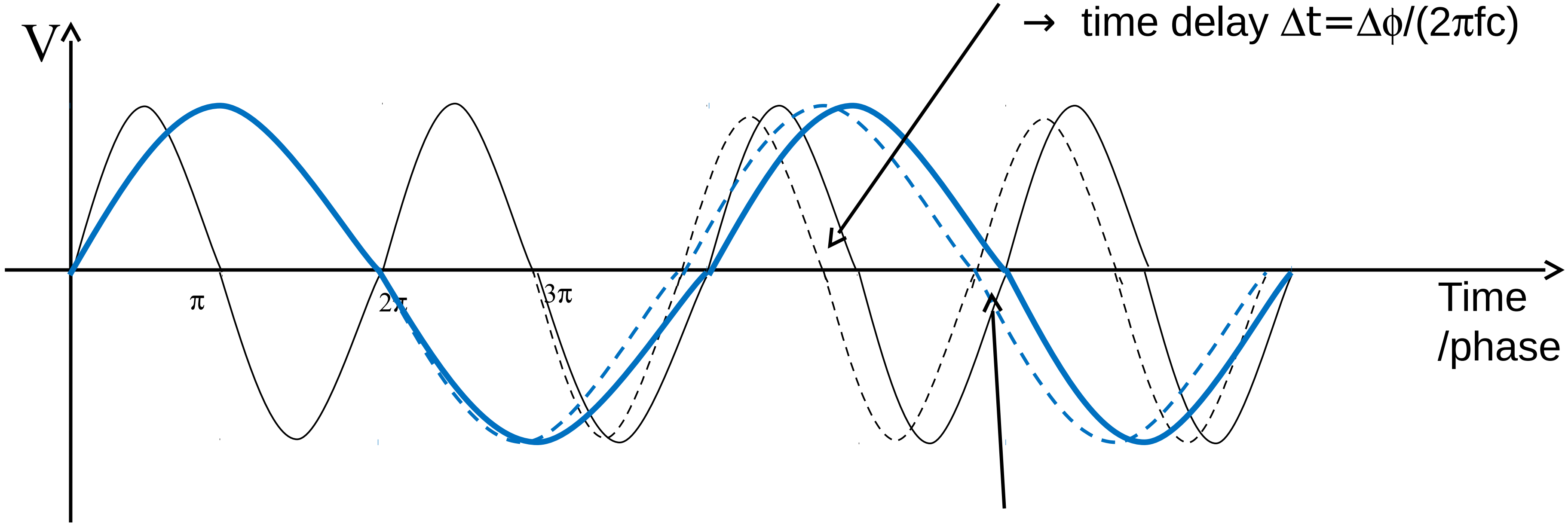
Large noise reduction if N is large…

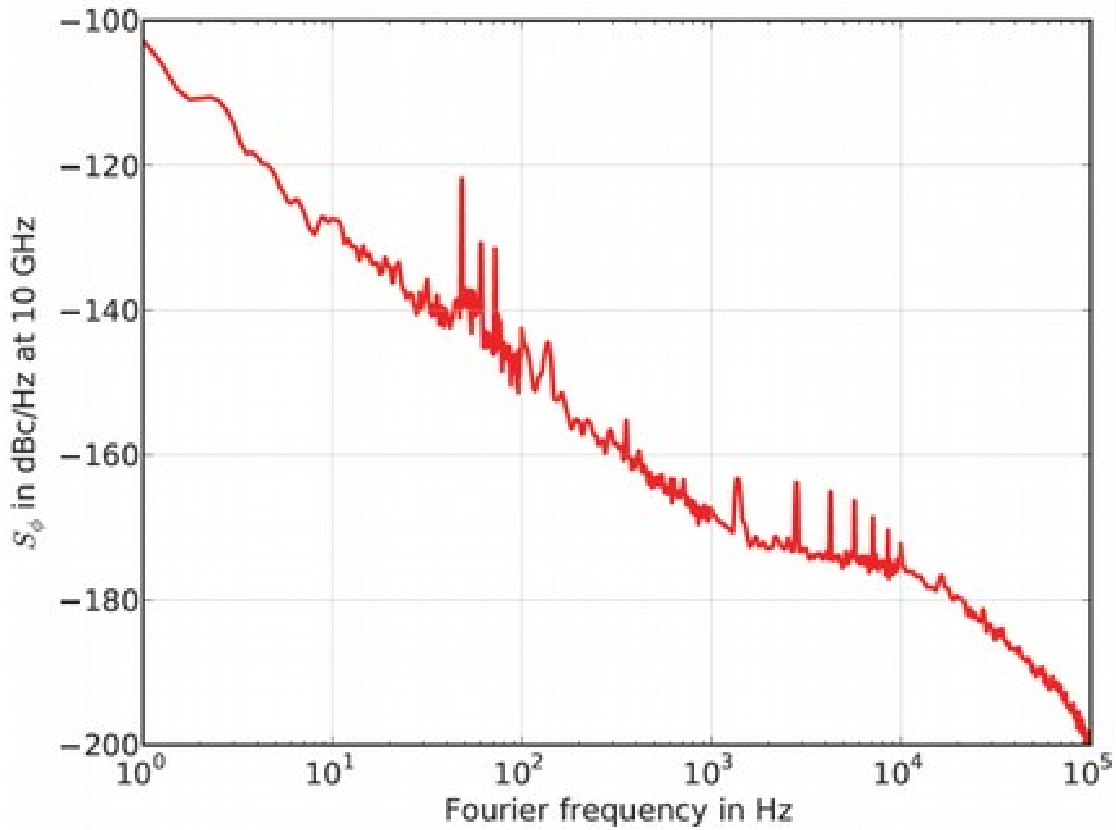
Exemple : divide by 2

Dephasing $\Delta\phi$ on fc
→ time delay $\Delta t = \Delta\phi/(2\pi fc)$



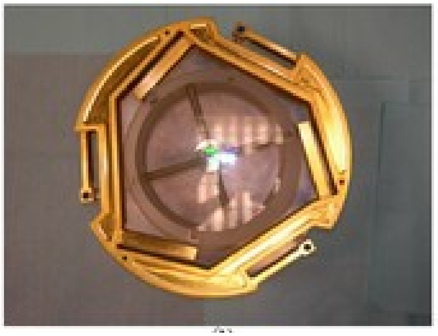
time delay $\Delta t = \Delta\phi/(2\pi fc)$ on fc/2
→ dephasing $\Delta\phi' = \Delta\phi/2$ on fc/2

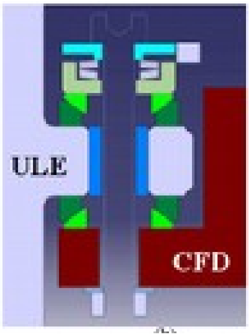
USL transferred to µ-wave (<u>projection</u>)



A robust 4.5×10^{-16} (@1s) level USL cavity (designed following space industry standards and methods)
→ 10cm long cavity with rings

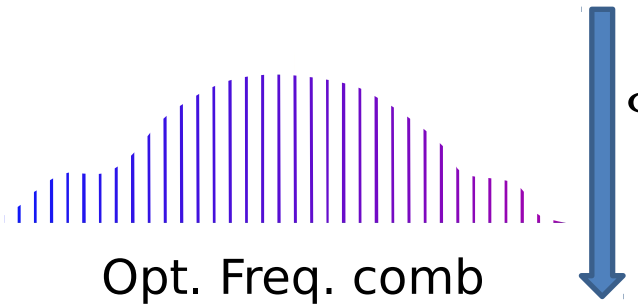
Prototype designed for transport +/-10g and operation at zero-2g
Currently existing lab prototype





Φ-noise of a 10 GHz carrier obtained by frequency division of the space-prototype USL at 200THz (SODERN/CNES/SYRTE), by a frequency comb, <u>assuming perfect division</u>

200 THz (λ=1.5µm)



Opt. Freq. comb

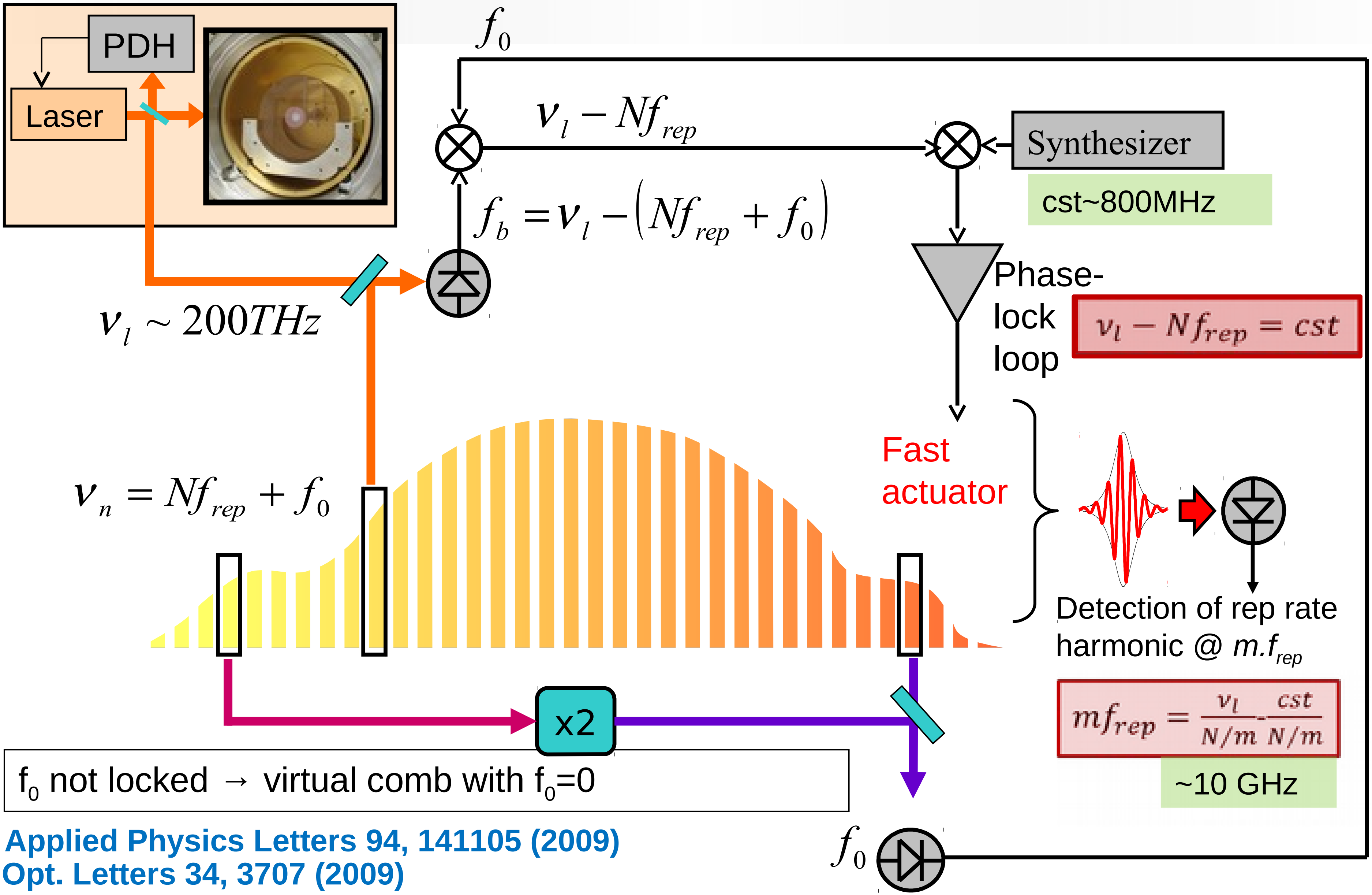
Φ-noise
→ -20.log(20000)
= -86dB (!!!)

10 GHz

Opt. Express 20, 25409 (2012)

cnes

Low noise µ-wave generation with comb
(optical frequency divider scheme)



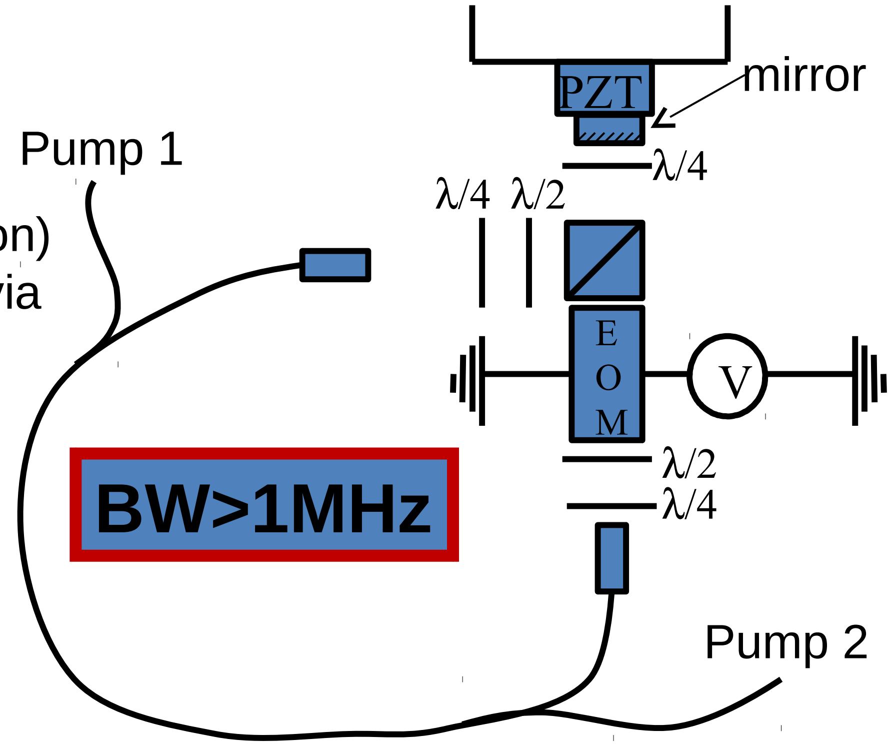
f_0 not locked → virtual comb with f_0=0

Applied Physics Letters 94, 141105 (2009)
Opt. Letters 34, 3707 (2009)

Er-fibre comb with intra-cavity EOM

<u>WHY ?</u>
large feed-back BW difficult for Er fs lasers
 - pump diode current : rather low response, ~100kHz max BP (with good phase-advance electronics…)
 - PZT : resonances ~40kHz BW
Free-running high Fourier frequency phase noise is hard to kill with phase-locking

<u>HOW ?</u> (in coll. with MenloSystems)
-Add a fast actuator (EOM) in the fs laser cavity
-Used as a voltage-controlled group delay actuator
(index <n> controlled by V ; linear polarization)
- Good alignment to decrease cross-talks (via polarization and amplitude)



IEEE UFFC 59, 432 (2012)
also Newbury et al. Opt.Lett. 34, 638 (NIST)
also Hong et al. Opt. Exp. 18, 1667 (NMIJ)

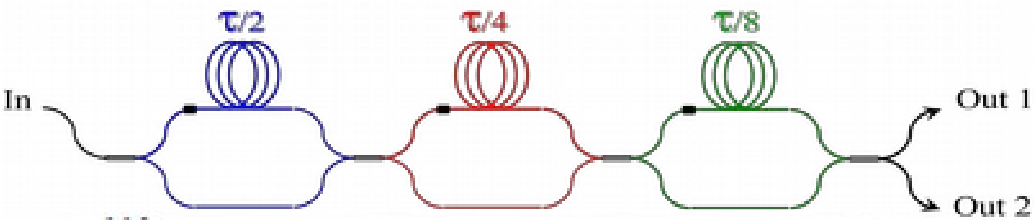
(Note : no output coupler represented here)

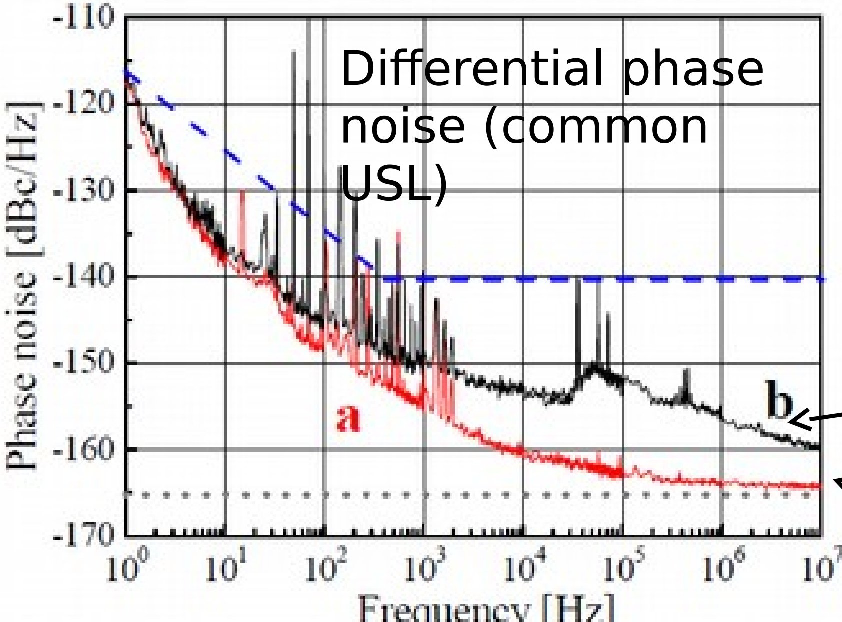
Increase SNR for lower white phase noise floor

<u>Thermal noise (Johnson-Nyquist) :</u>

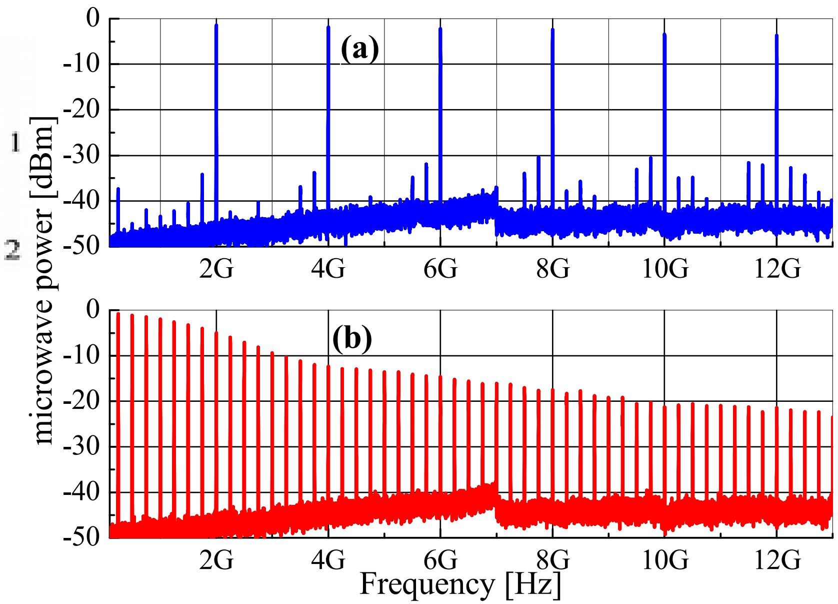
A 0 dBm µ-wave signal cannot have a white phase noise limit better than -177dBc/Hz
Solution : increase µ-wave power

- higher optical power+more linear PD
  (in coll. with Discovery semiconductor)
- high rep rate fs laser / external rep rate multiplication
  → less power in undesired harmonics,
  more in the harmonic of interest





Differential phase noise (common USL)



2 combs 2 MZM 2 PD
(excess phase noise to investigate)

1 combs 2 MZM 2 PD

Optics Letters 36, 3654 (2011)

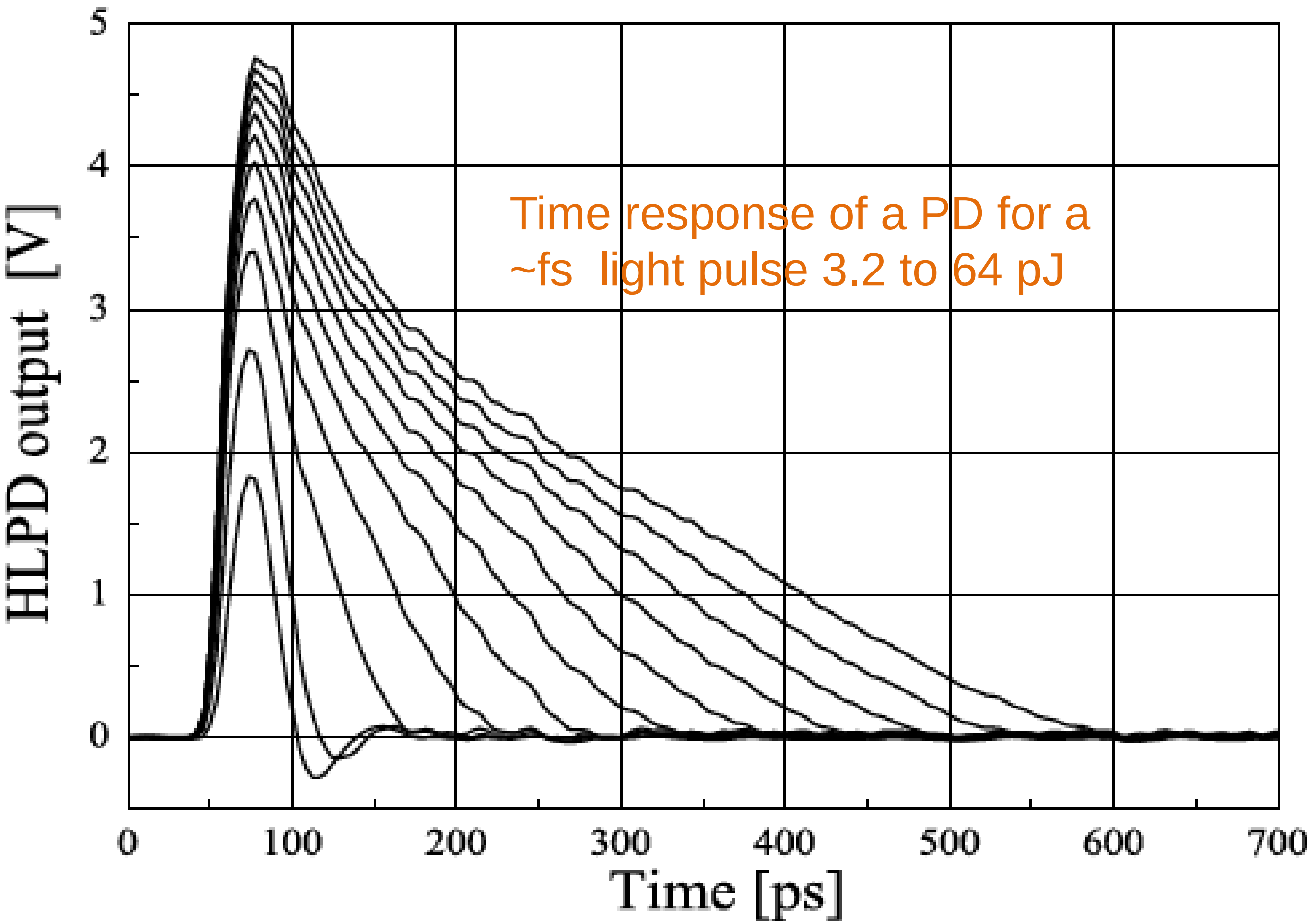
AMPM conv. in f_{rep} and harmonics photodetection

amplitude fluctuations of the fs laser induce fluctuations of phase of f_{rep} (and its harmonics)

→ possible to lock amplitude (but only at low Fourier frequencies)
1.2×10^{-16}@1s generated µwave / 100as synchro

App. Phys. Lett. 96, 211105 (2010)

→ or analyze carefully the physics…

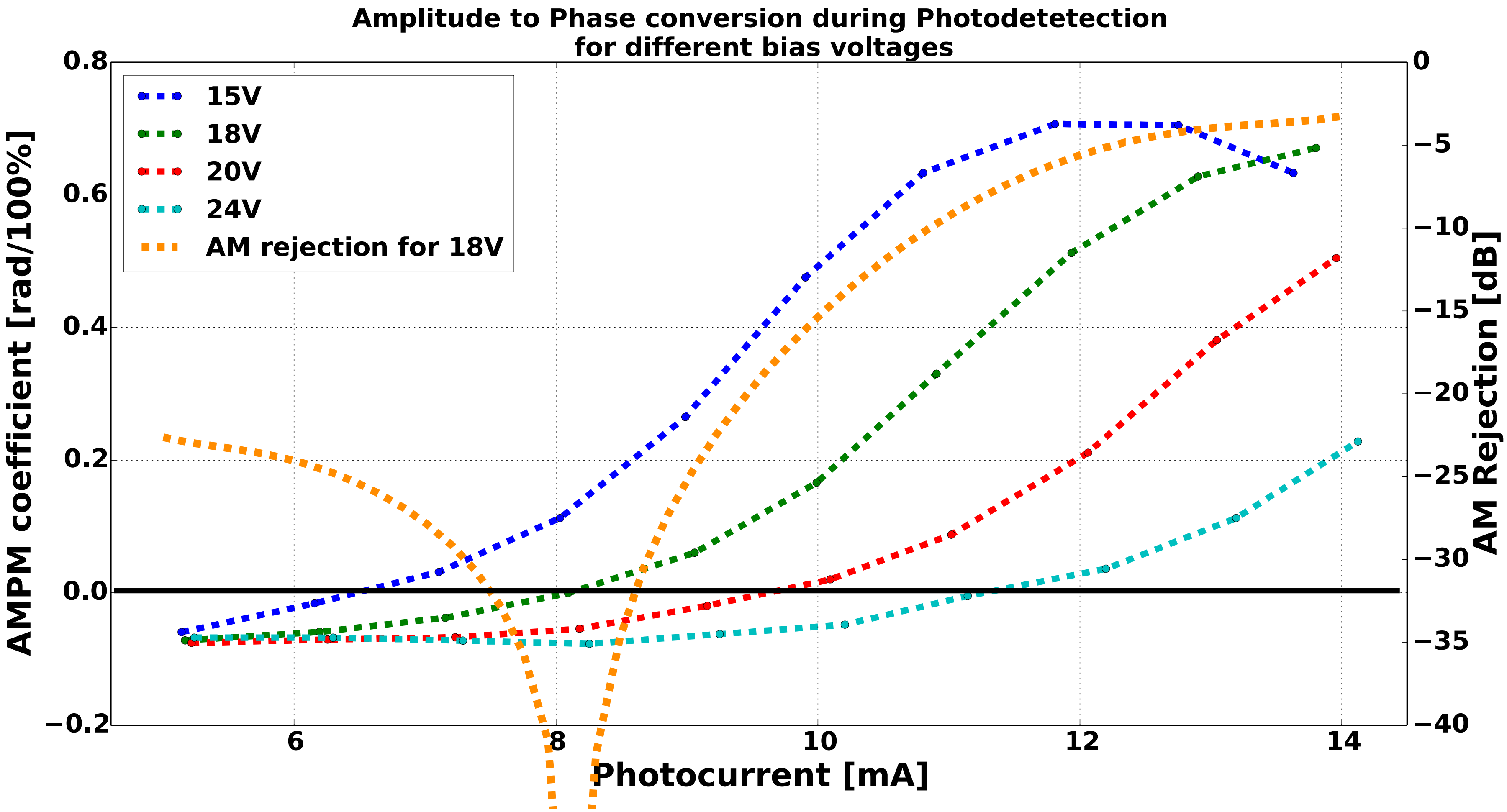


By space-charge screening effect, close to saturation, the PD response is asymmetric

→ AM noise produces PM noise

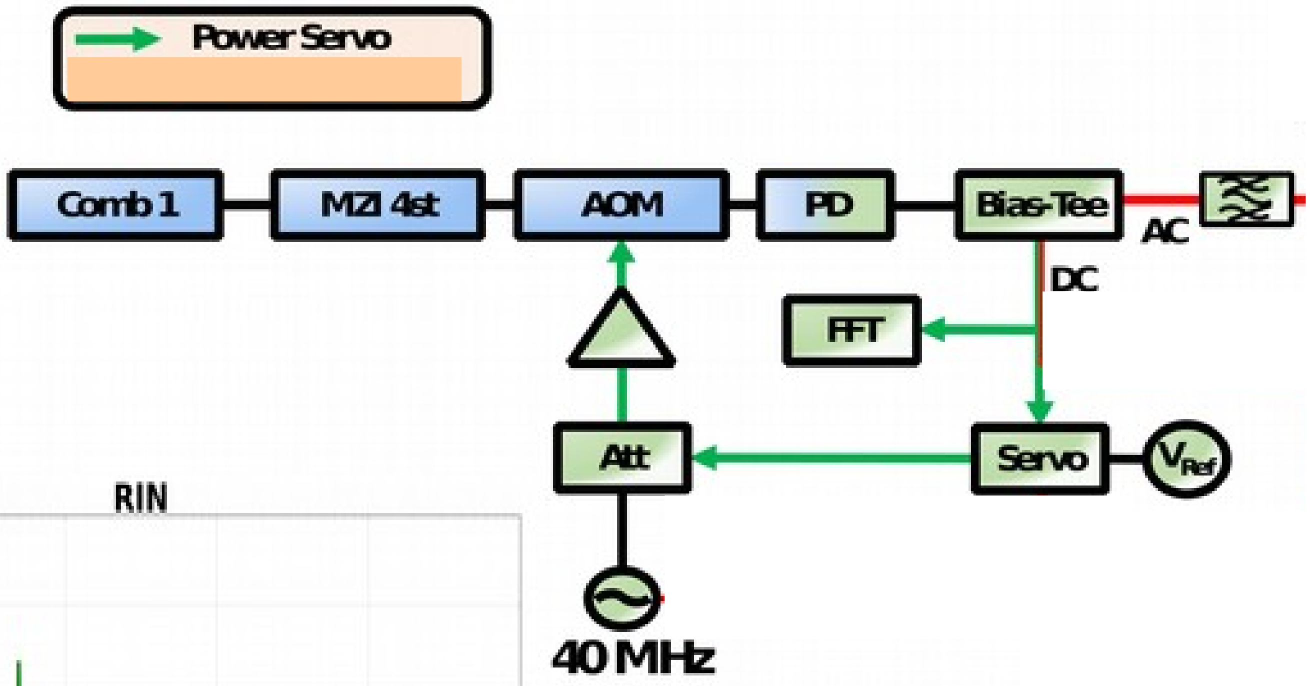
For harmonic order >1 there are special situations…

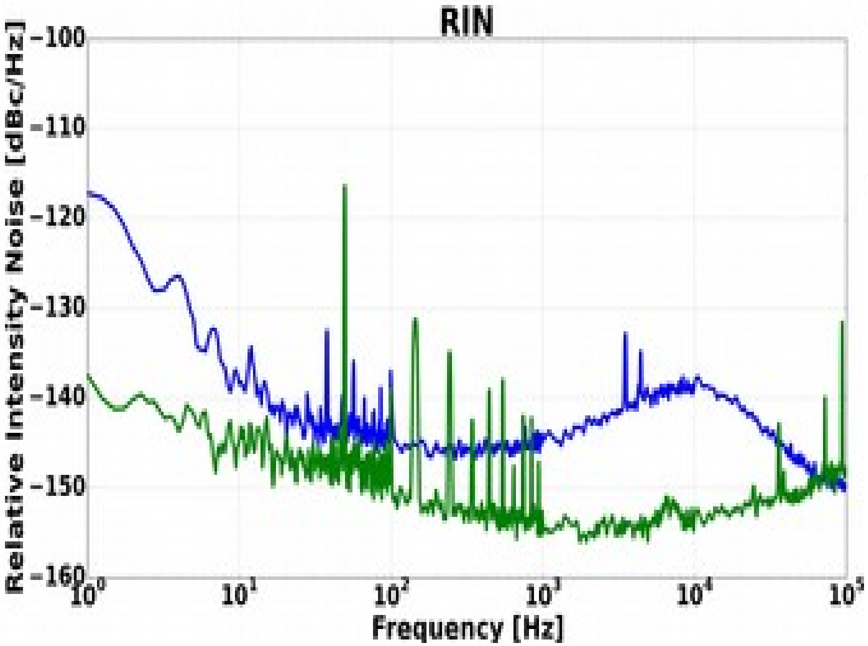
Suppression of AMPM conversion



Applied Physics B 106, 301 (2012)
Optics Letters 39, 1204 (2014)

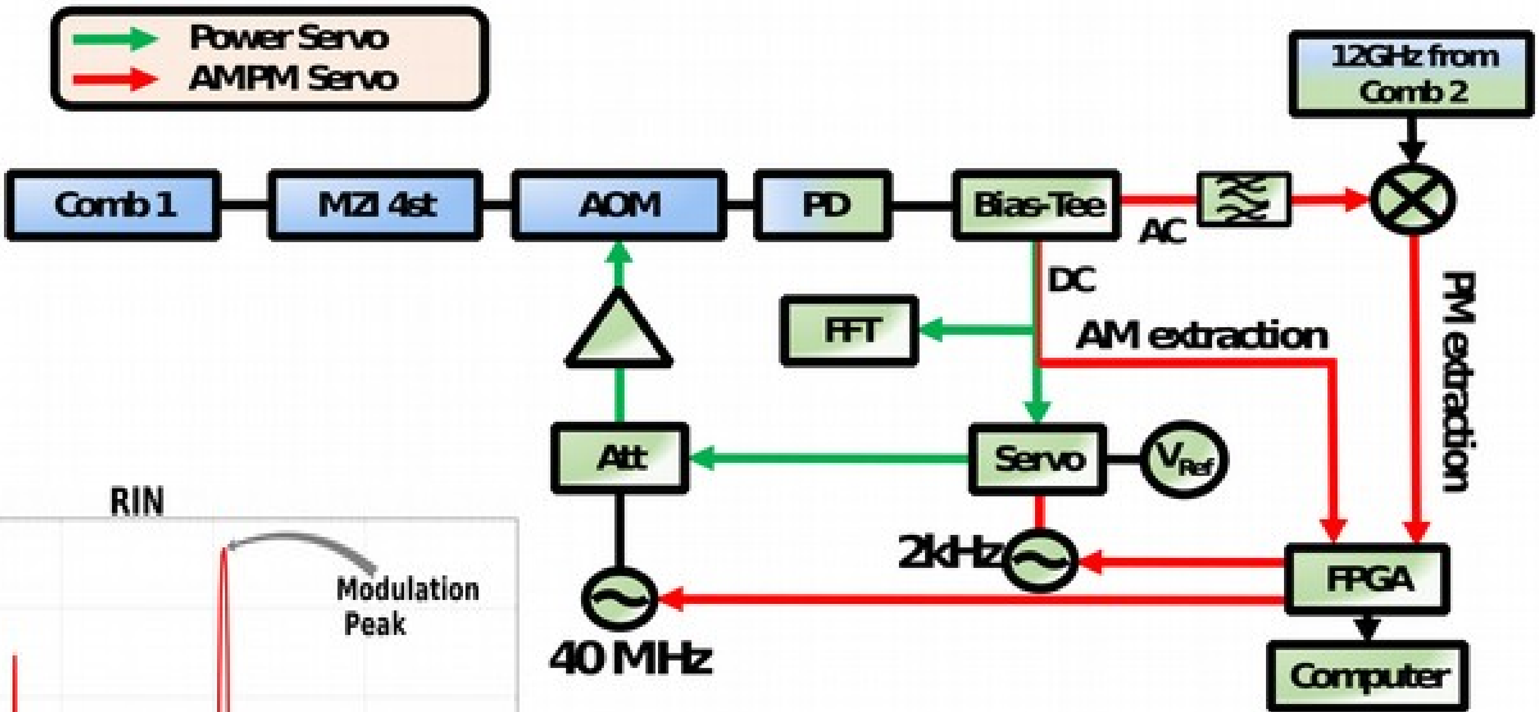
Suppression of RIN

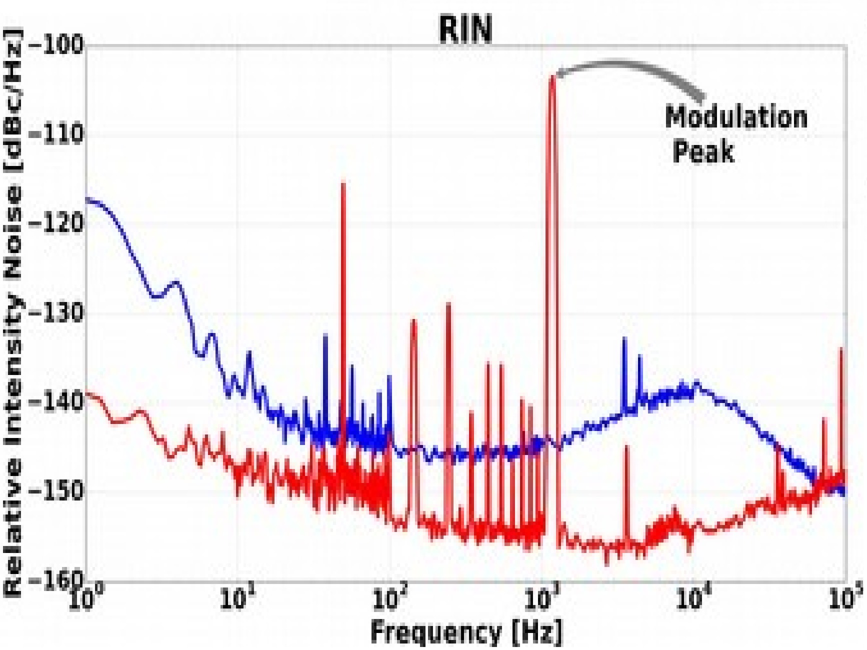




Active servo to reduce RIN

Suppression of RIN



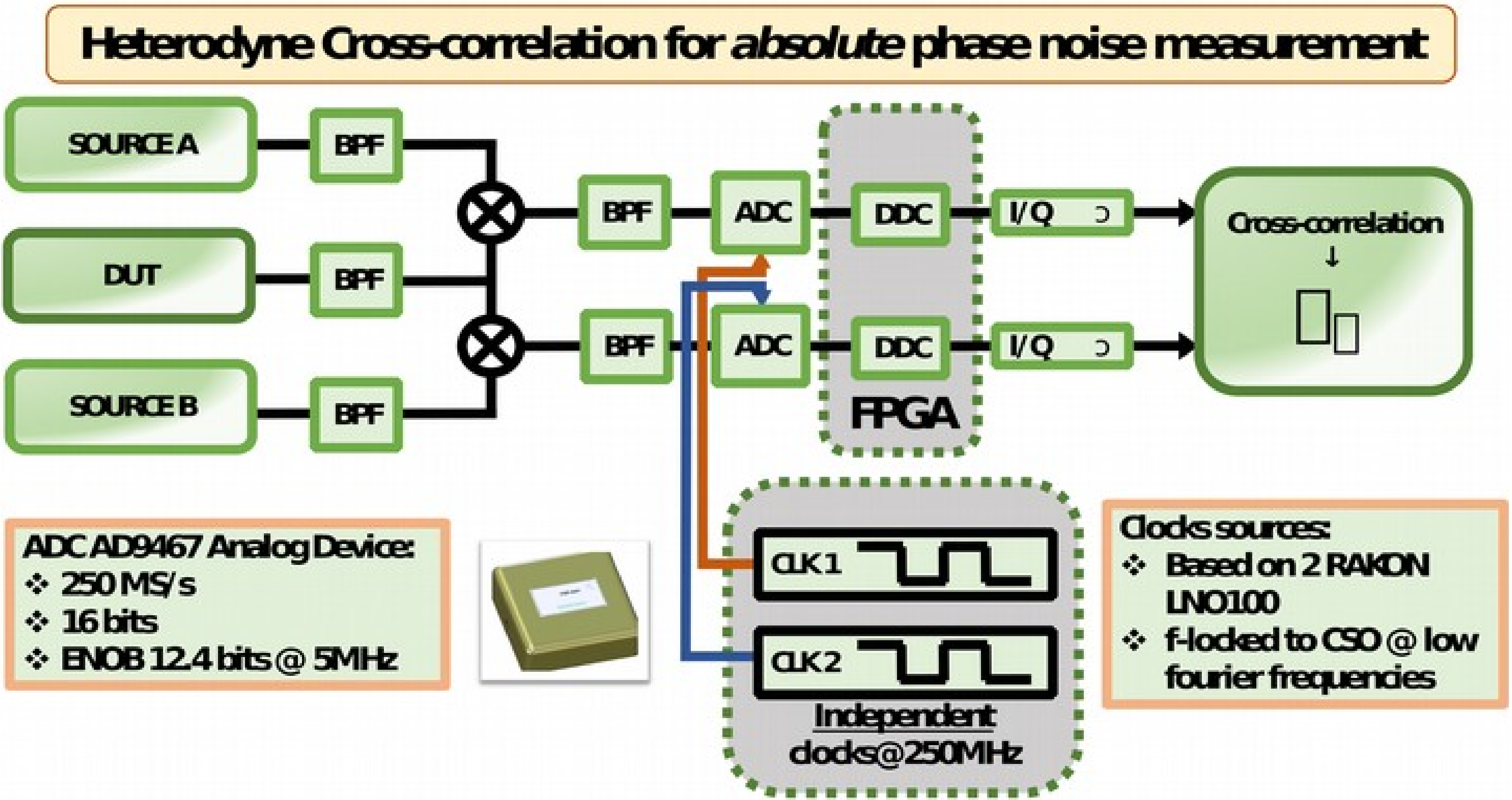


Rejection of AM effect on PM by >50dB !

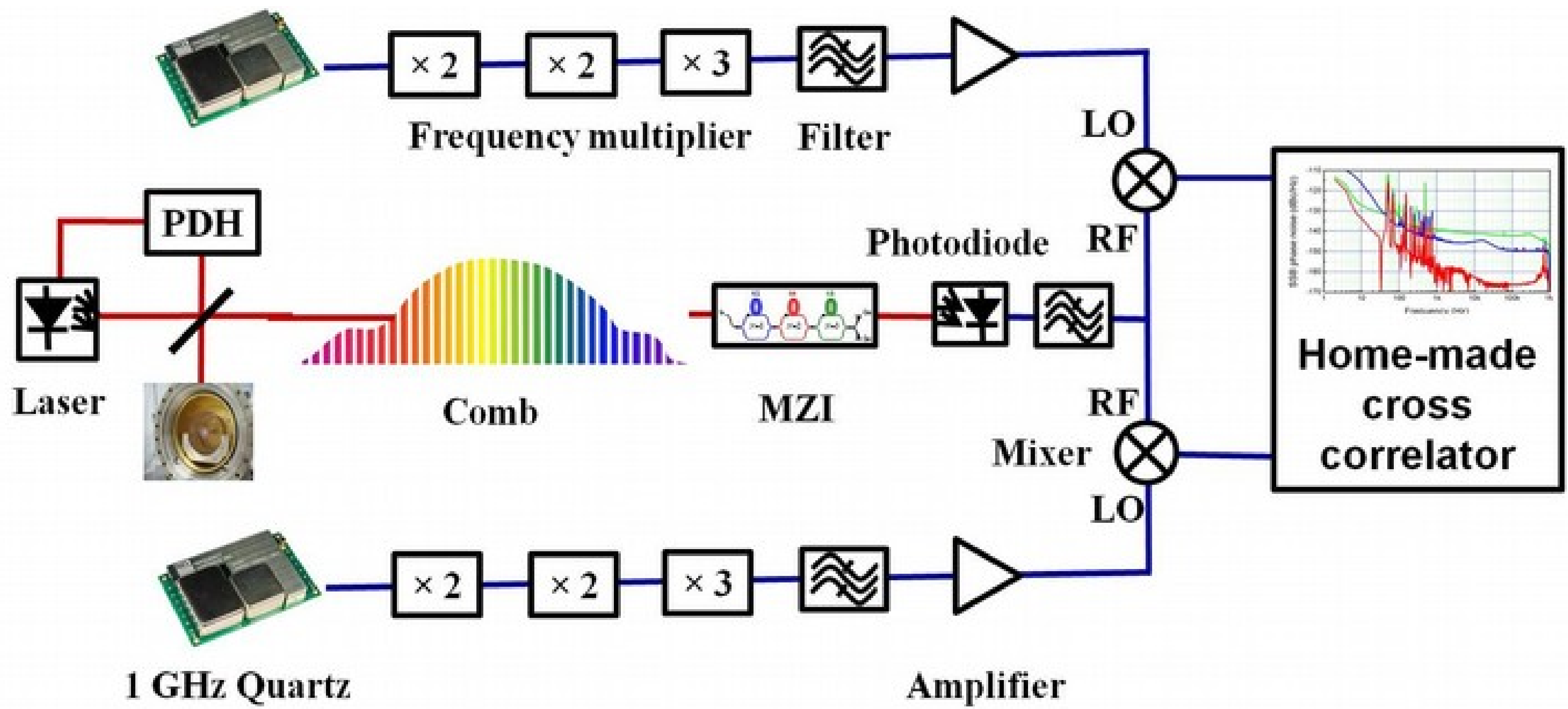
Effect of RIN on PM < -200dBc/Hz at 10kHz from carrier

Φ-noise Measurement method

At very low phase noise, cross-correlation is the technique of choice BUT tricky
Most commercial systems are homodyne → relatively high sensitivity to AM
→ We developped our own heterodyne system

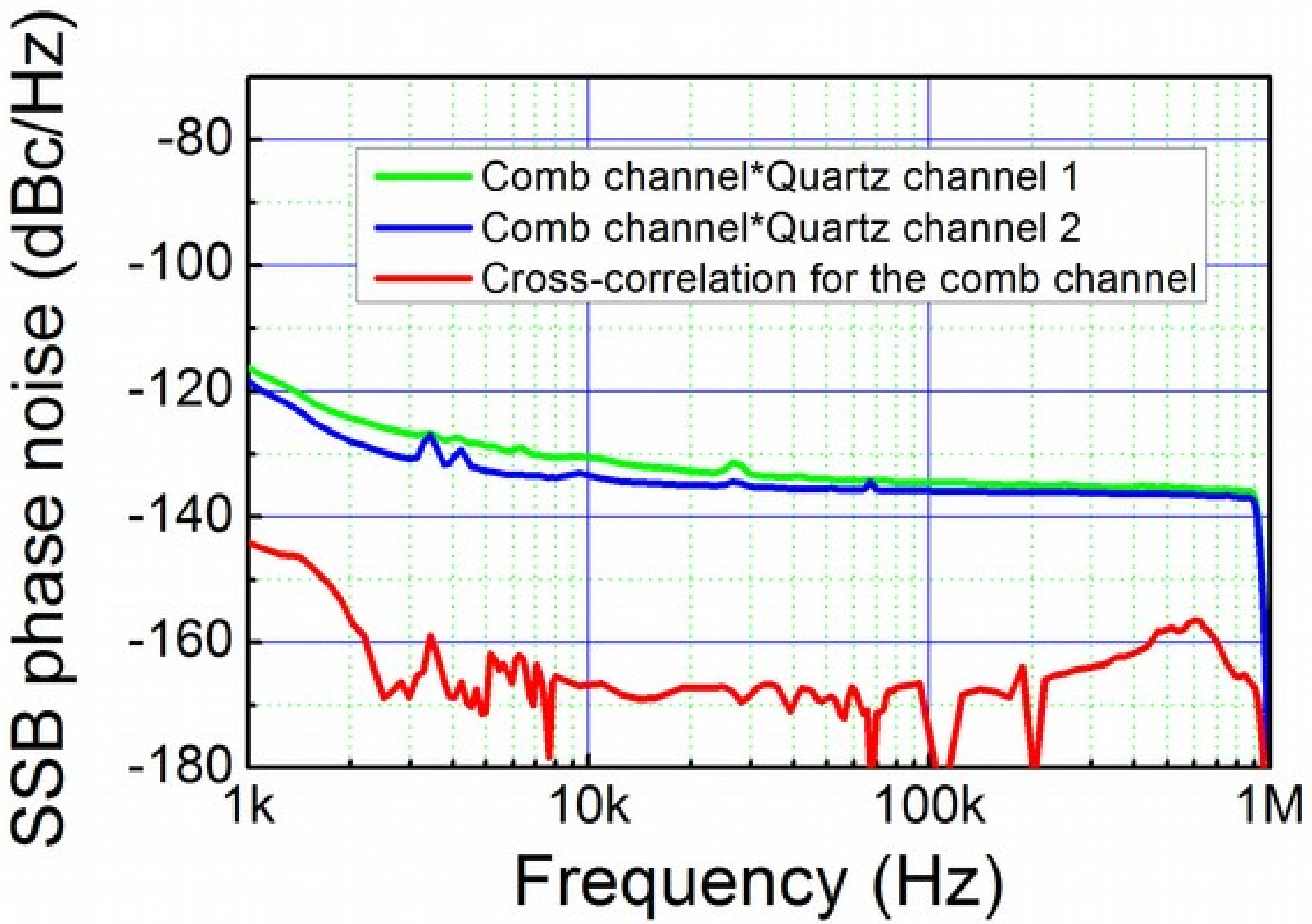


Φ-noise Measurement method (development setup)

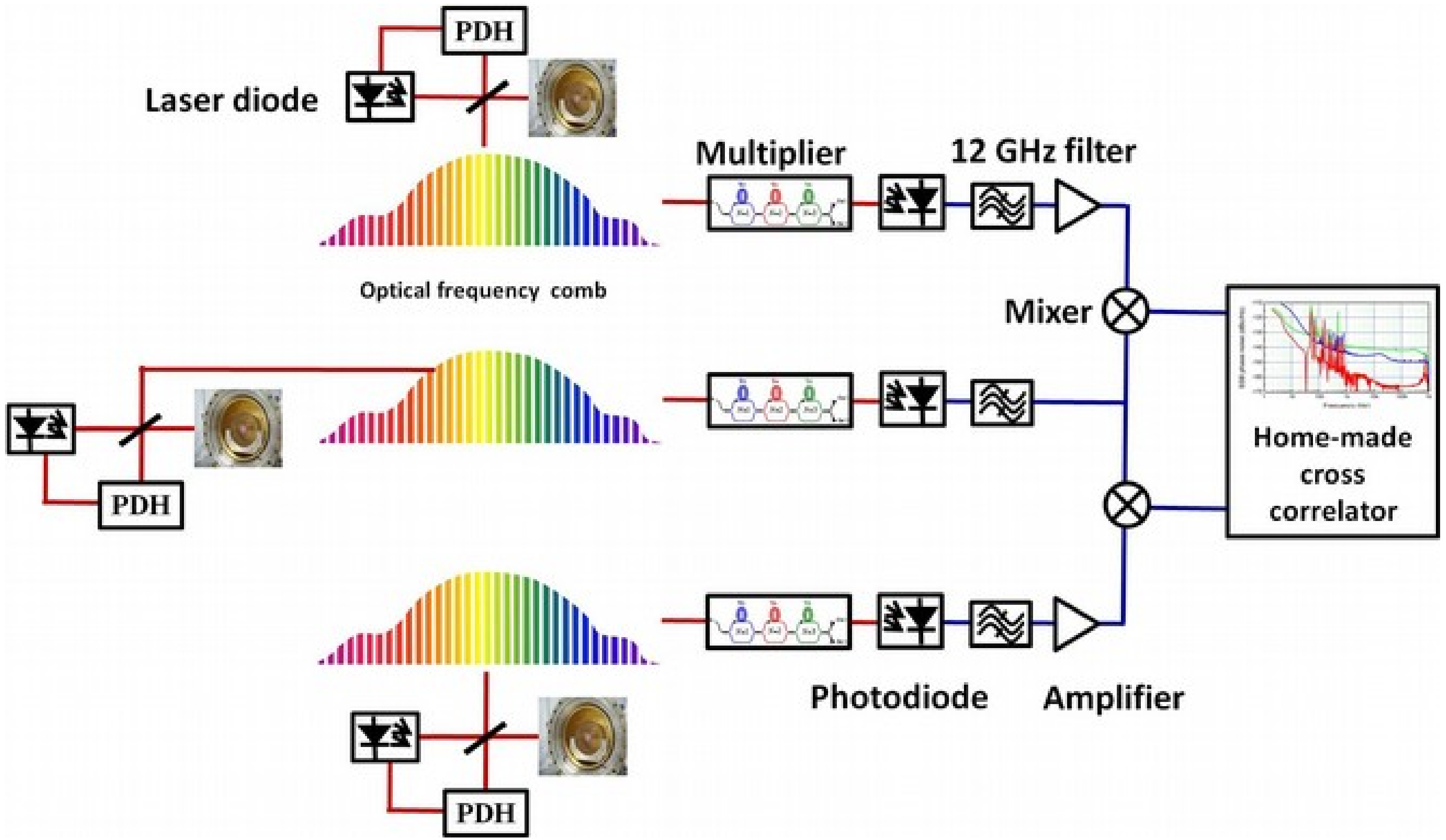


- Auxiliary sources are ~ good enough at high Fourier frequency and trivial to operate
- Cross-corelating away their noise takes time, and ways too much time for low Fourier frequencies → not useful for caracterizing noise frequencies < 1kHz

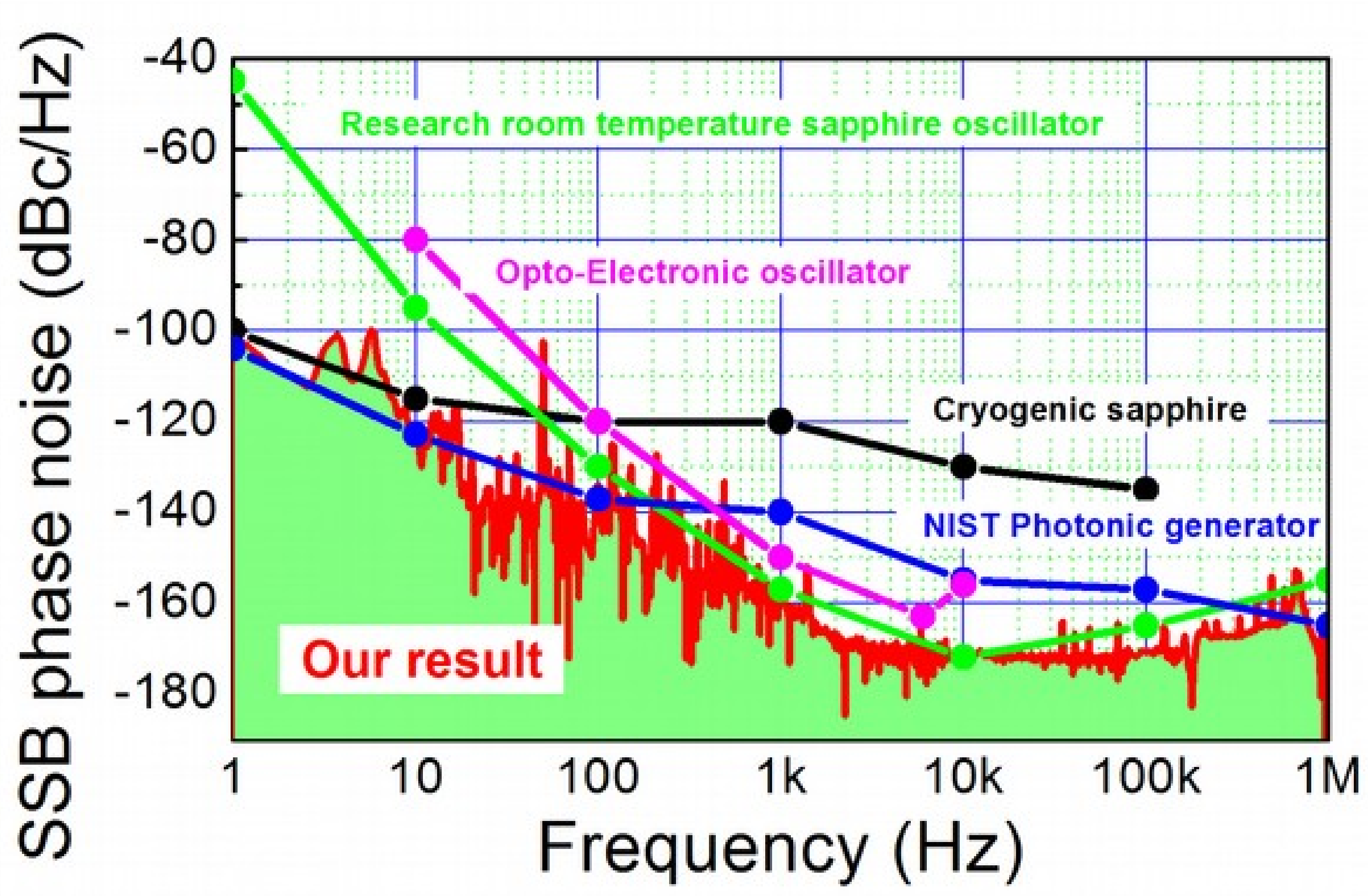
Φ-noise Measurement method (development setup)



Φ-noise Measurement method (Full setup)



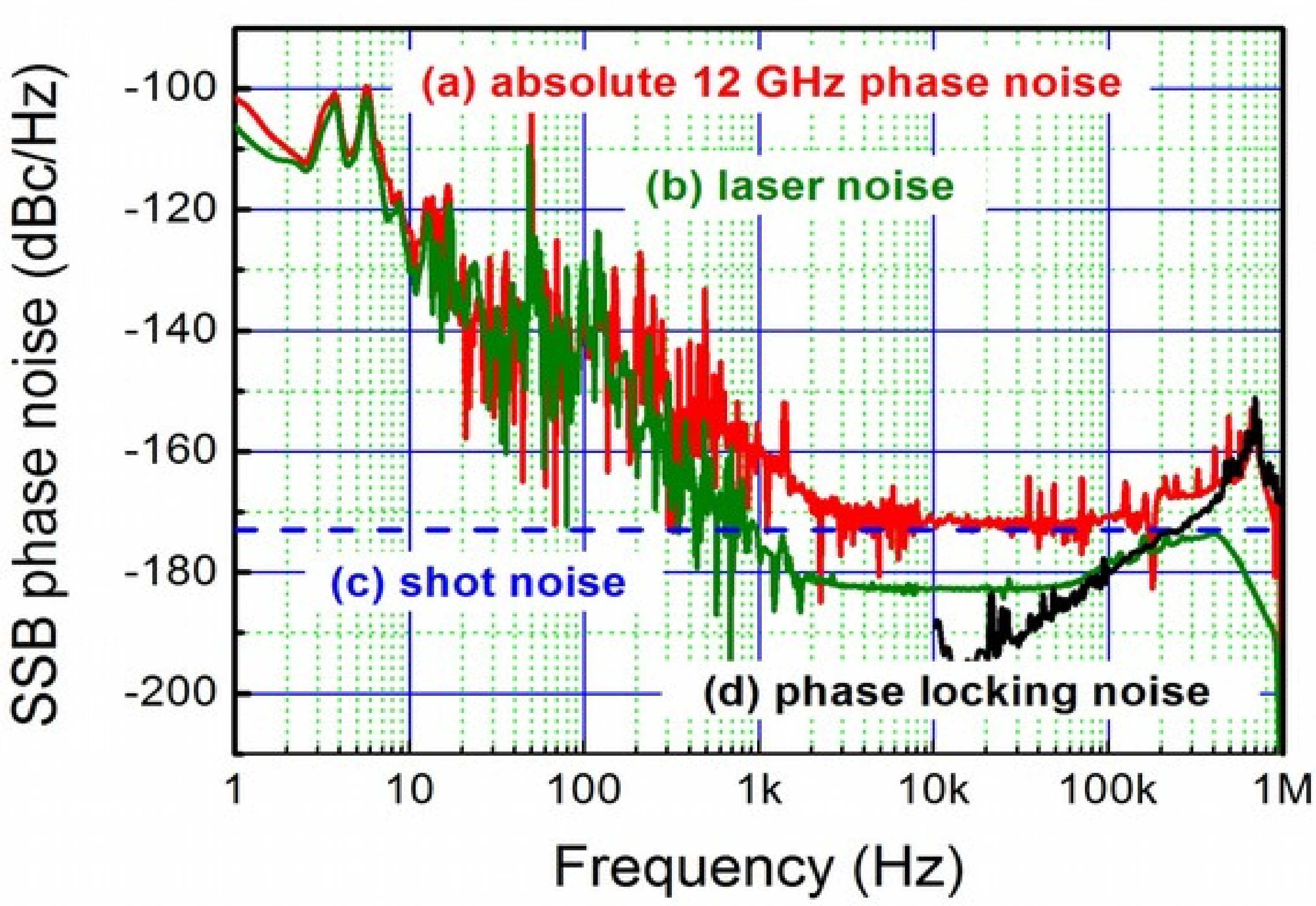
Φ-noise Measurement method (Full setup result)



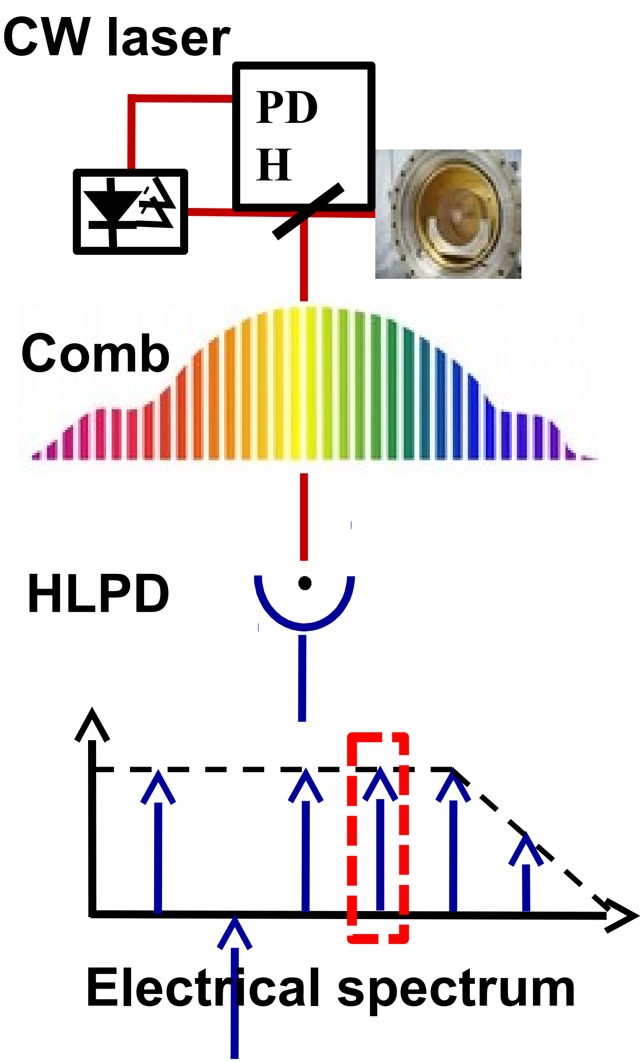
-104 dBc/Hz @ 1Hz
-172 dBc/Hz @ 10kHz and beyond

From a 12 GHz carrier

Φ-noise result analysis



Conclusion



Record ultra-low phase noise 12 GHz signal generation

-104 dBc/Hz at 1 Hz
-172 dBc/Hz at 10 kHz

Phase noise characterization by a heterodyne FPGA-based cross-correlation scheme

Noise floor below:
-180 dBc/Hz

A comb is 3U 19" rack-size (and plane/ space qualified...), USL is larger (size of a H-maser, typically) and "only" ~10^{-15} (ie ~-100dBc/Hz)
→ we are seeking better and/or more compact cw lasers for referencing the comb
→ we are seeking in-field applications ...