Ultra-low phase-noise microwave with optical frequency combs

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OUTLOOK

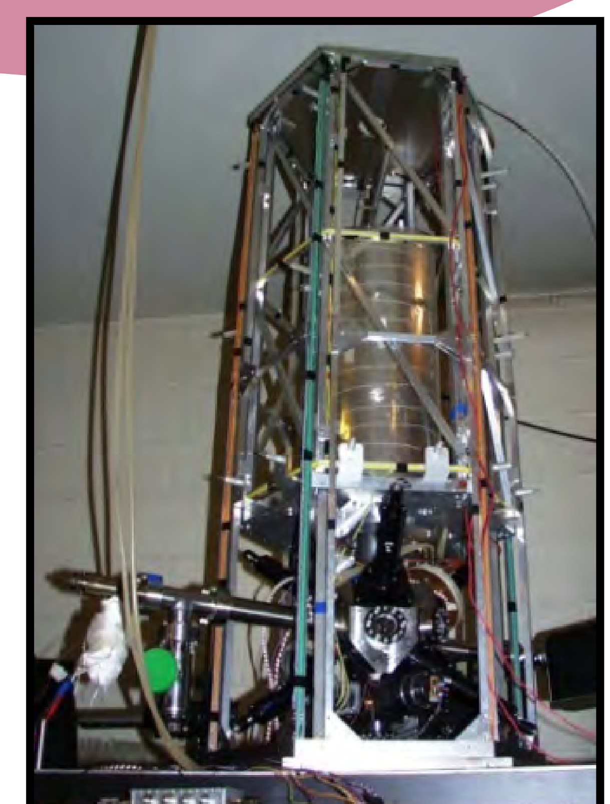
- Low phase noise μwave sources applications&state-of-the-art
- μwave photonic generation w/ frequency combs (FC)
- Issues w/ photonic generation: S/N, AM to PM , meas. tech….
- Developments on low noise FC

Low Phase Noise sources applications

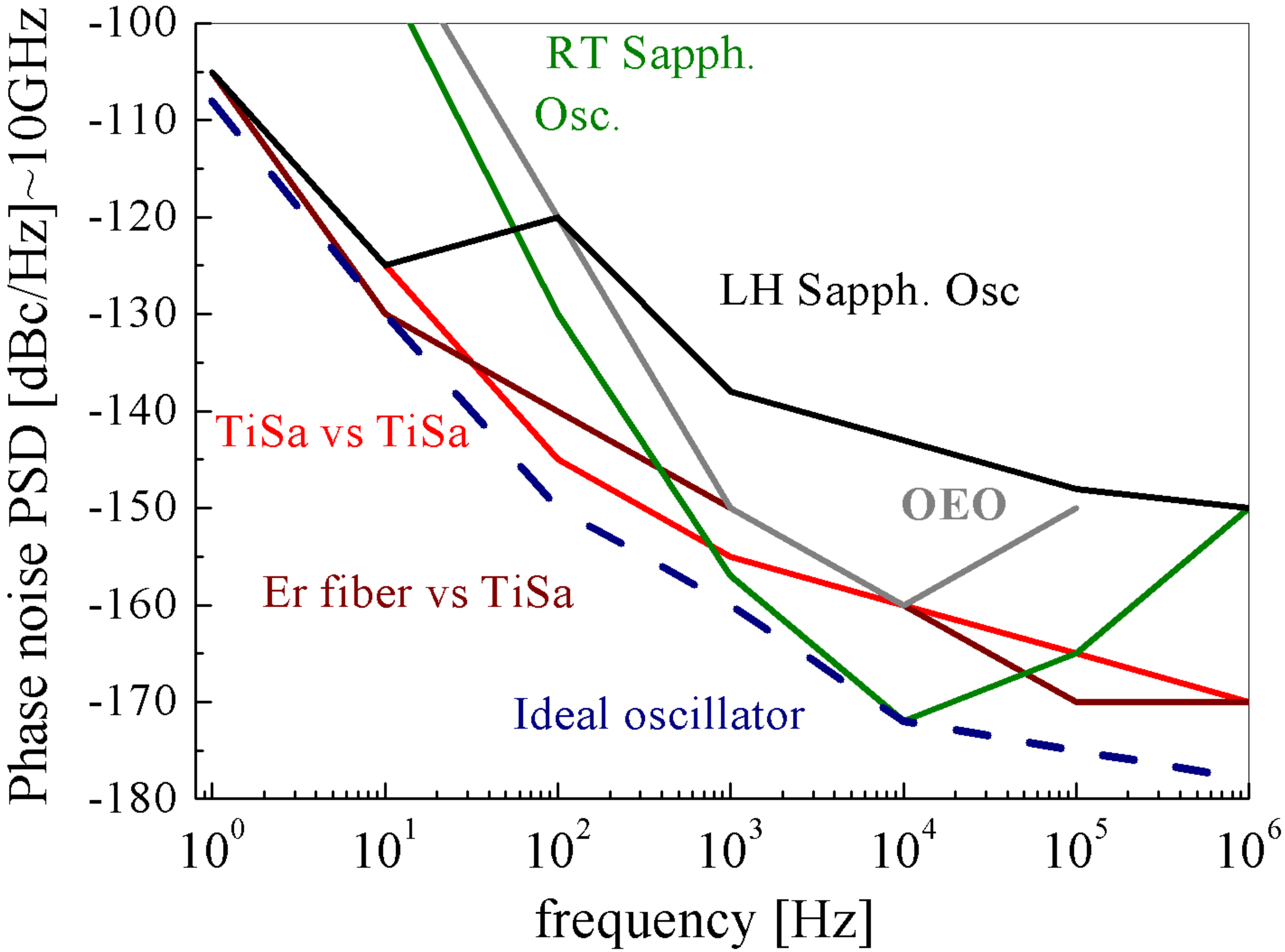
Military
- ➢ Defense radar systems

Frequency metrology:
- o Atomic clocks
- o Time reference distribution

Large scale experiments:
- ✓ Advanced VLBI
- ✓ particle accelerators



LOW PHASE NOISE μW OSCILLATORS : STATE-OF-THE ART



Low phase noise µW oscillators : state-of-the art

- **Ultra low ϕ-noise (low jitter) µwave sources (~10GHz)**

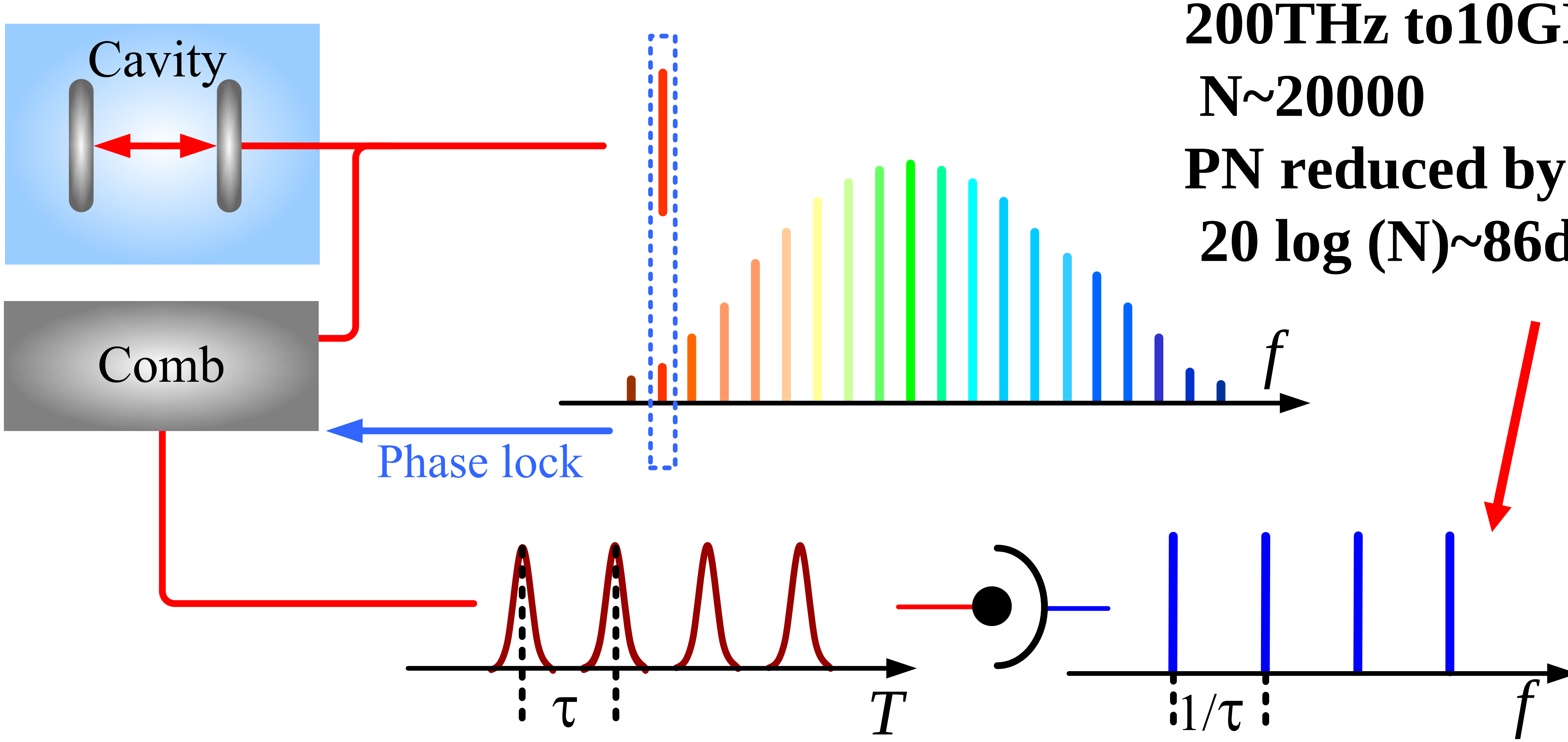
  - Room temp. sapphire oscillator [Raytheon, UWA, Australia]
    -40dBc/Hz @ 1Hz, -170dBc/Hz @ 100kHz from carrier
  - Cryogenic sapphire oscillator [UWA,IPAS (Au), FEMTO-ST (Fr)]
    -105dBc/Hz @1Hz, -140dBc/Hz @ 10kHz from carrier
  - Opto Electronic Oscillator [Oewaves (Usa), LAAS, FEMTO-ST (Fr)]
    -40dBc/Hz@1Hz, -160dBc/Hz @ 10kHz
  - Frequency combs [NIST (Usa), SYRTE (Fr)]:
    -105dBc/Hz@1Hz, -160dBc/Hz @ 10kHz

The ultimate oscillator

<-105dBc/Hz@1Hz, <-170dBc/Hz @ 10kHz

PHOTONIC µW GENERATION W/ FREQUENCY COMBS

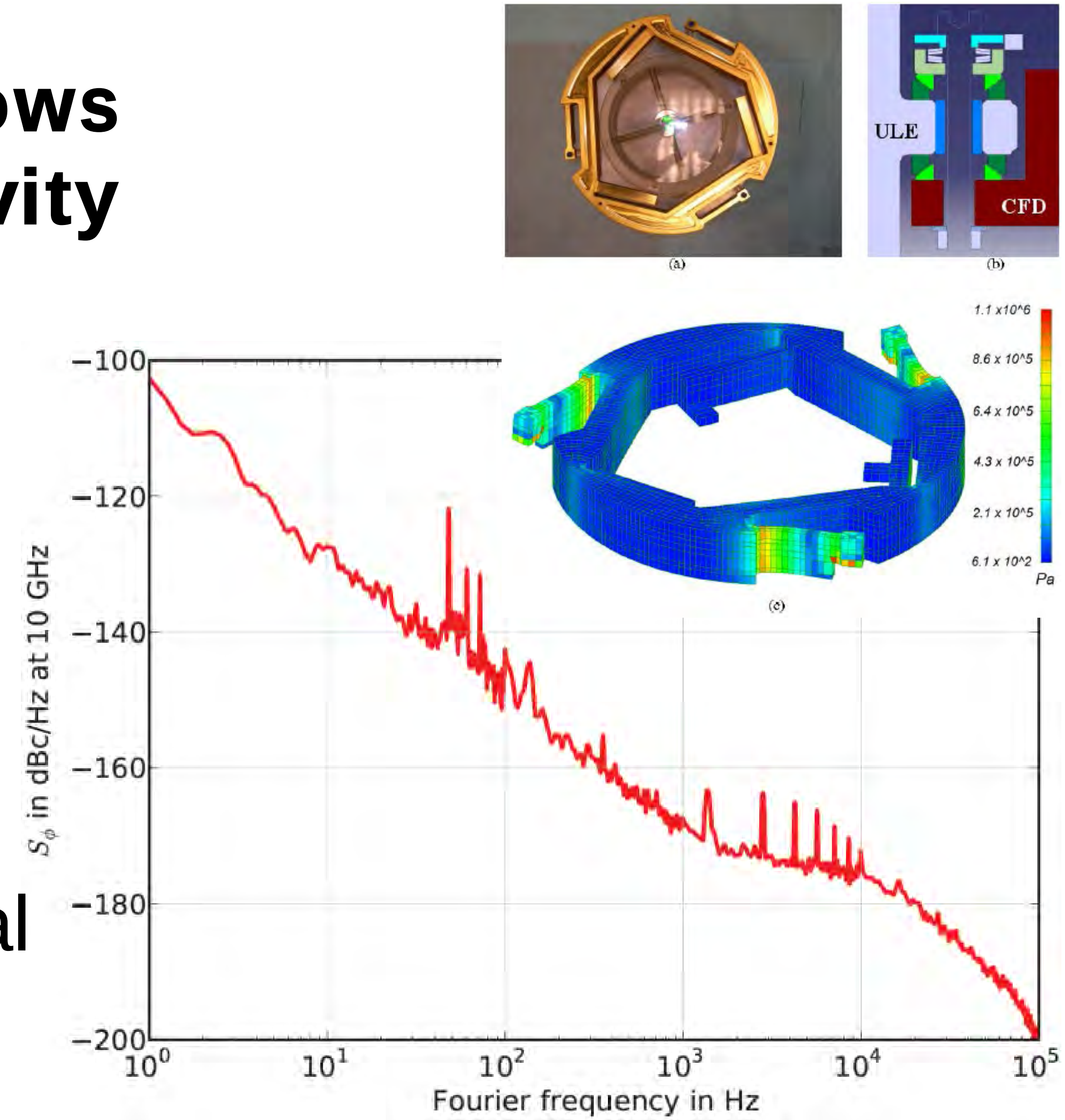
Frequency Combs is frequency divider from optics-to-µW



- ✓ no cryogenic, easy operation, potentially compact
- ✓ very phase low noise low&high Fourier frequencies
- ✓ multiple output microwave frequencies, tunable

ULTRA STABLE OPTICAL CAVITIES

- **Ultra stable lasers (USL) shows very good spectral purity (cavity stabilisation)**
  - Compact, transportable and vibration insensitive high finesse optical cavities available
  - The challenge is to obtain an ideal division from optical down to μW frequencies.



ϕ-noise PSD @ 10 GHz carrier from USL at 200THz <u>(ideal division)</u>

PHOTONIC GENERATION : COMBS REQUIREMENTS

- **intrinsic low phase&intensity noise (RIN<140dBc >10kHz)**
- **wide control BW >1MHz (noise&BW are coupled)**
- **high repetition rate > 1GHz**
- **output power >100mW (but with low noise)**
  - Er/Yb fiber lasers (noise mod./low, compact, robust, >200MHz)
  - Yb KWG, Calgo doped crystals (low noise, BW ok, >200MHz)
  - Er doped crystals (low noise, low BW, ~100MHz Er)
  - Ti:Saph (very low noise, complex, large footprint, >1GHz)
  - Micro combs (noise?? , small factor form, >10GHz)

Low phase noise laser combs major players

- **Several research groups develop combs&modelocked lasers for low phase noise &timing jitter**

✓NIST (Ti:Saph, Er, Yb fiber lasers, microcombs, USA)

✓MIT (Ti:Saph, Er, Yb fiber laser, USA)

✓DESY [Er fiber laser, Germany]

✓KAIST [Er, Yb fiber lasers, Korea]

✓ETH, EPFL, CSEM [microcombs, Yb/Er crystals, Switzerland]

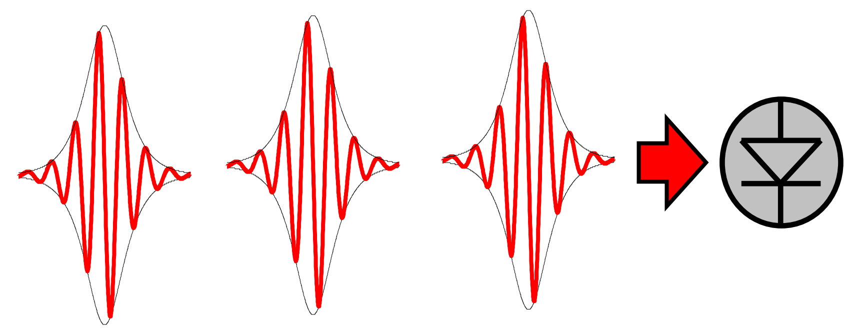
✓This work

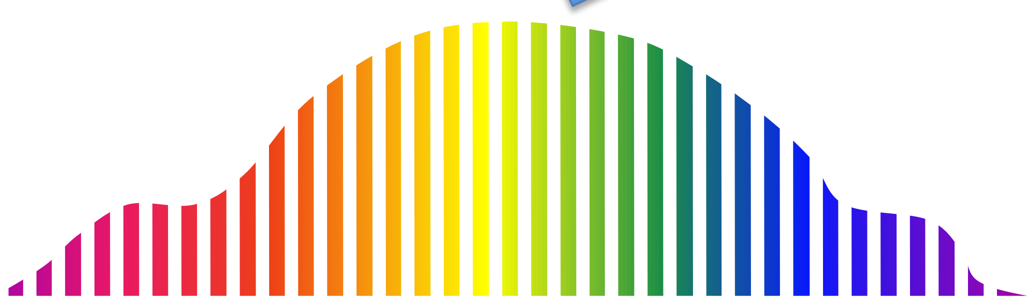
Detection of short&intense laser pulses

- **Two different techniques**

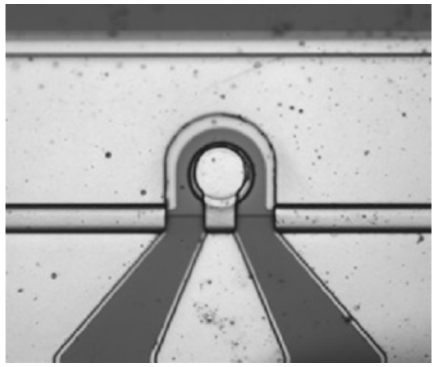
Direct photo detection

high power linear photodetectors



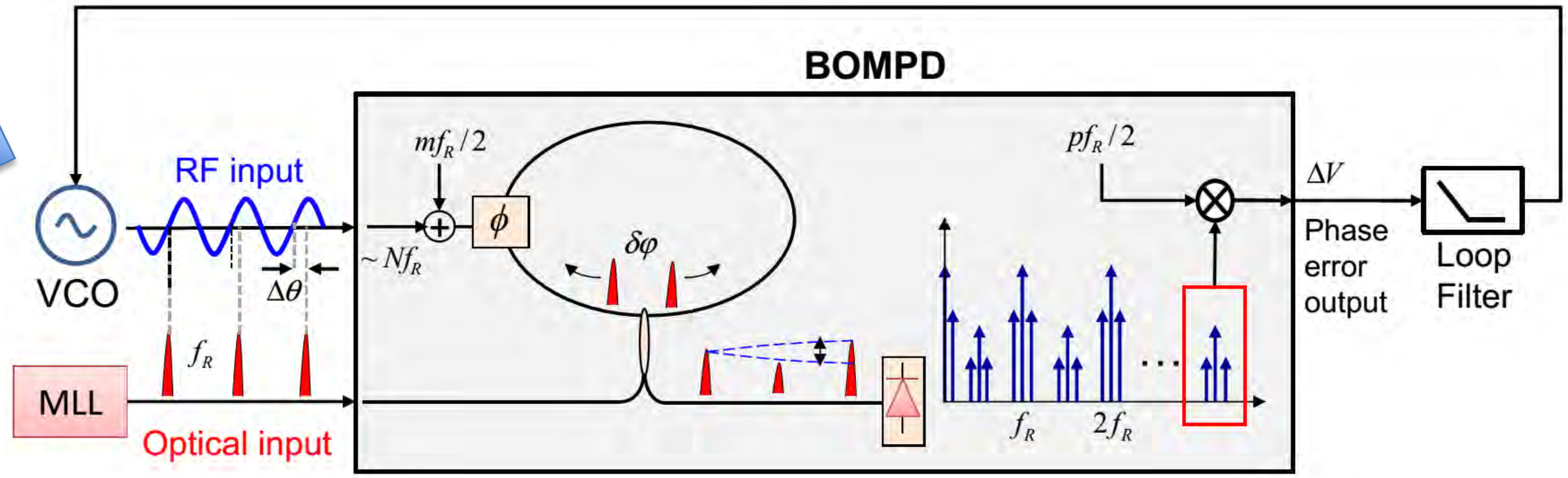


MUTC



PIN

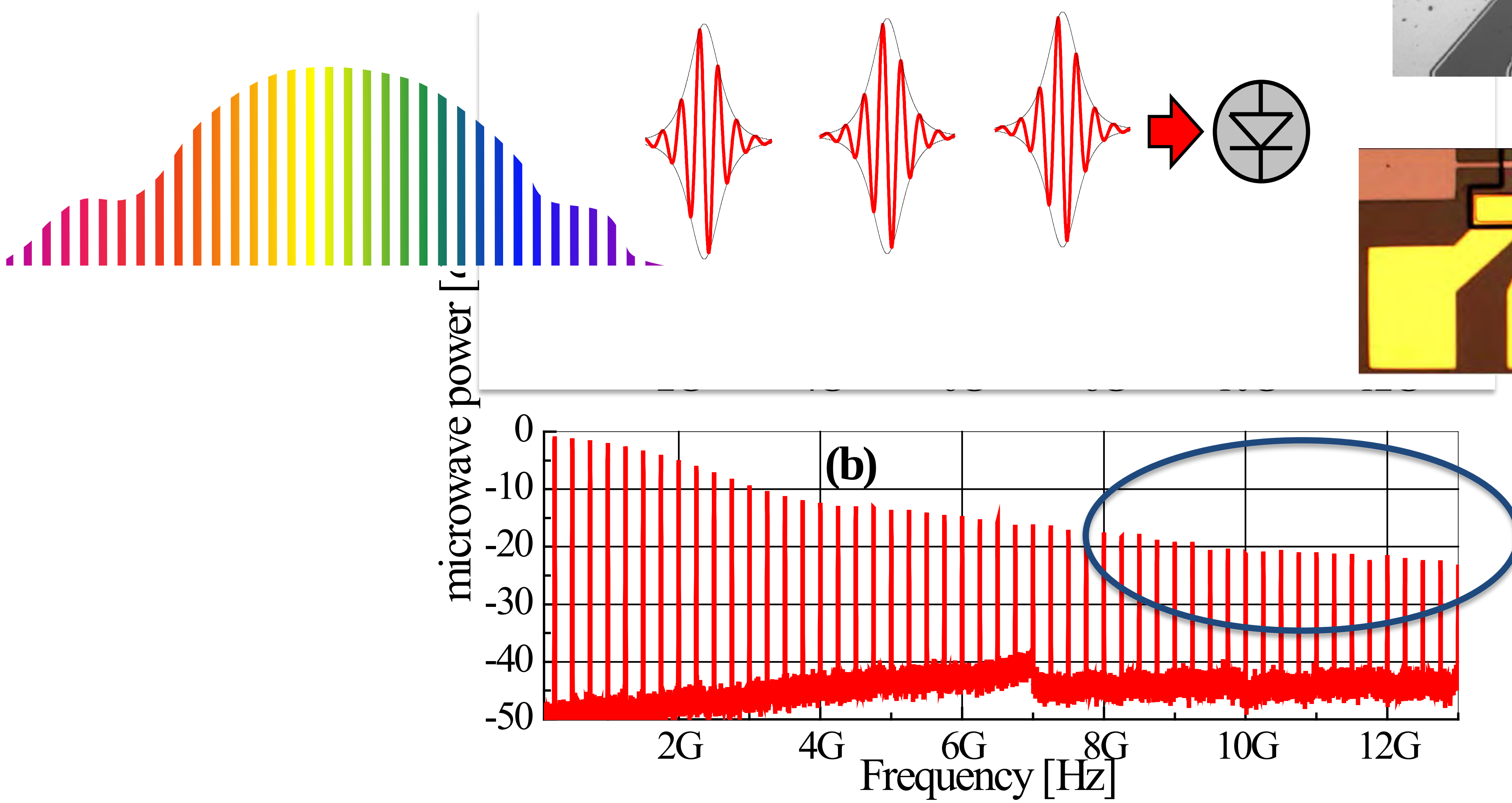
Balanced optical to microwave detector (Kärtner)

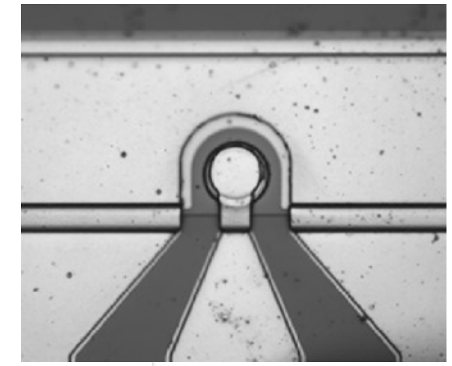


Photodiode detection issues

Direct photo detection

high power photodetectors





MUTC

PIN

saturation@high harmonic rank

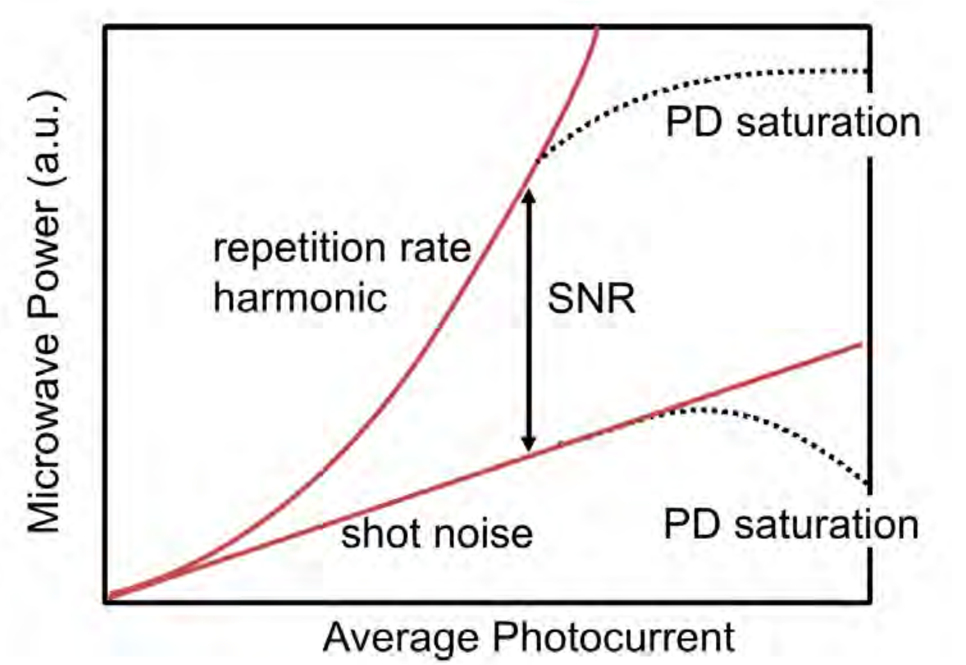
pulse energy spread μwave spectrum over the

Photodiode detection S/N : some numbers

S/N >170dB

Shot Noise $2I_{PD}q$ $I_{PD@10GHz}$ >50 mA

Shot noise formula not valid
phase noise short optical pulses <1ps
[Quinlan et al, NIST]
gain ~10dB



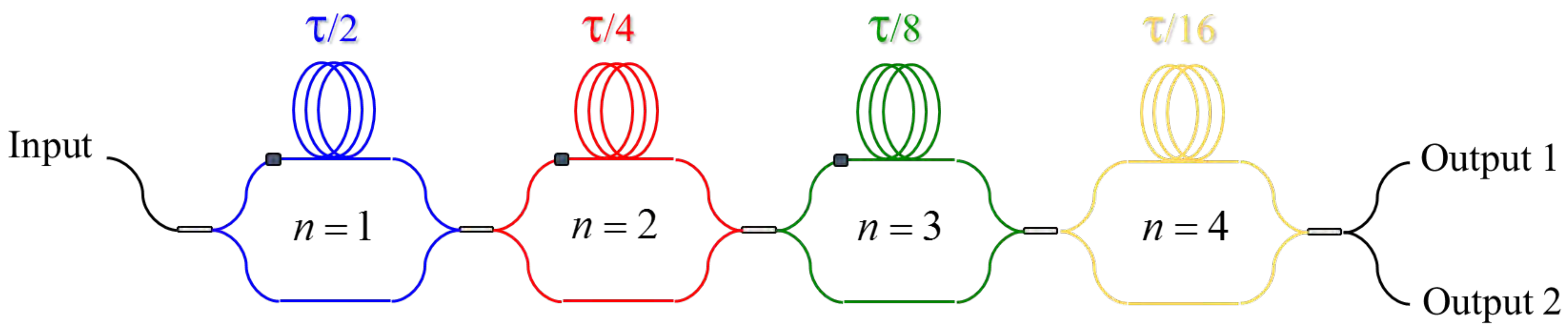
Thermal noise
load R 50 Ω $\propto k_B T R$ signal> a few dBm@10GHz

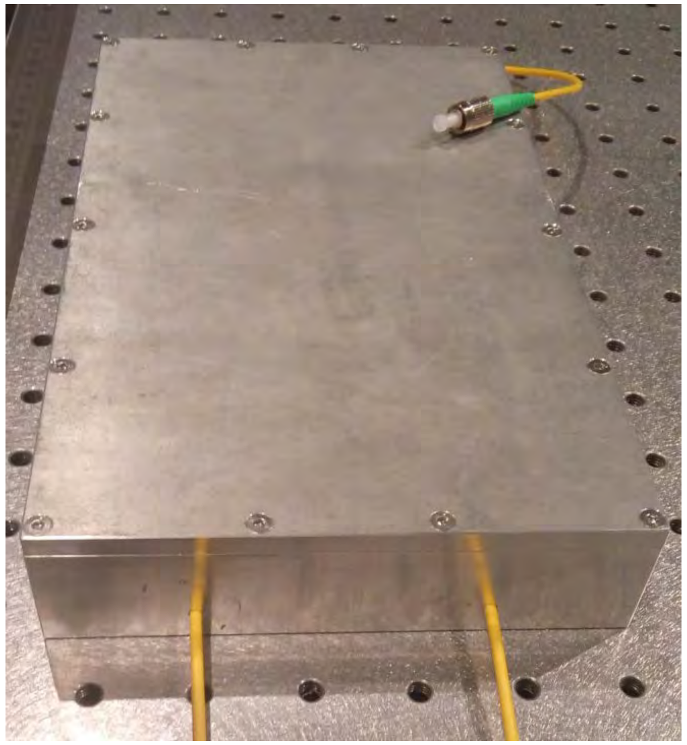
Amplification noise, flicker noise, μW insertion losses….

Pulse Repetition Rate Multiplication

interleaving optical pulses w/ delay ½ rep. rate frequency x2

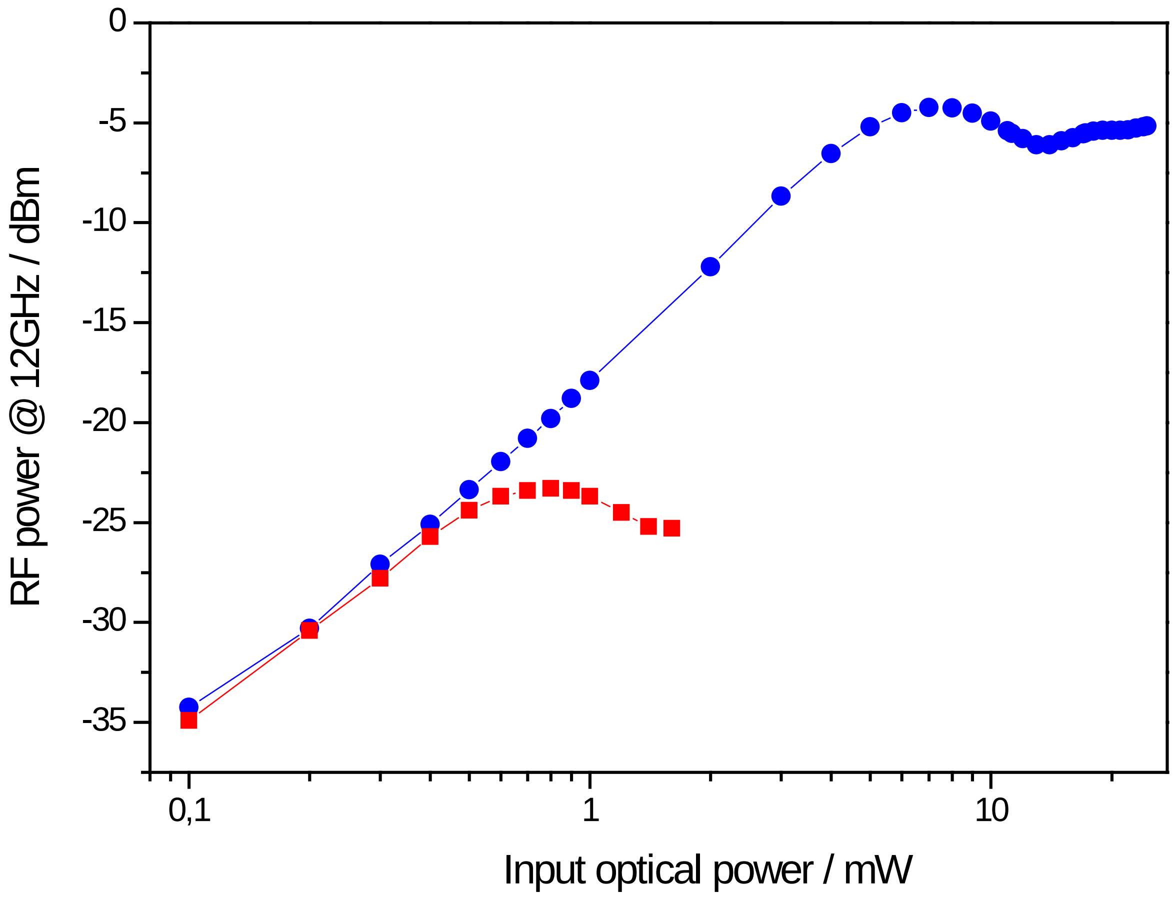
process can be cascaded w/ ¼ and then ⅛ …..

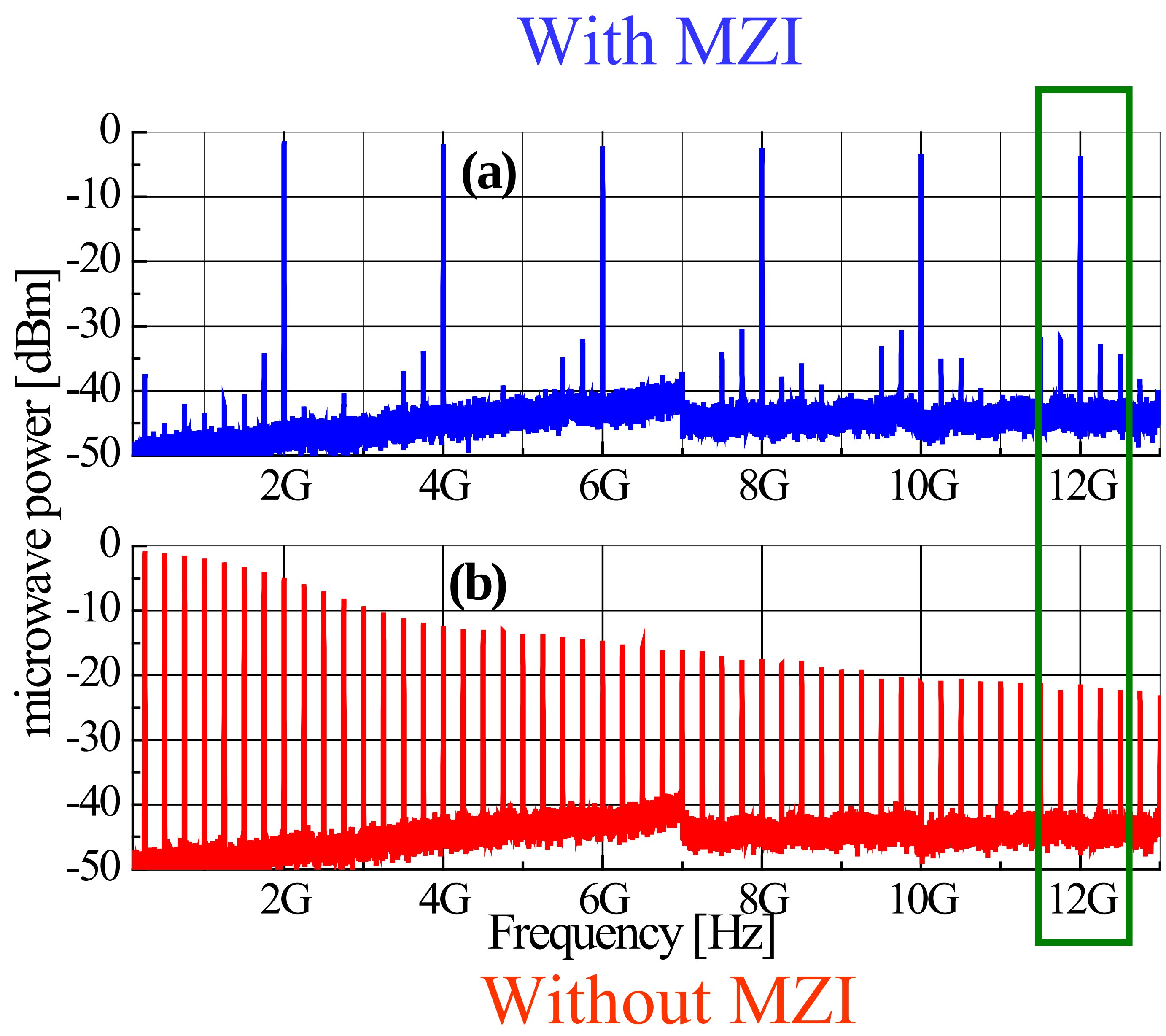




- ✓ Single mode couplers 50/50 (<1%)
- ✓ fusion spliced
- ✓ 4 stages -> f_{rep}x 16
- ✓ compact : 20cm ╳ 30cm
- ✓ robust: no alignment& stable
- ✓ cost effective
- ✓ Low optical losses ~3dB

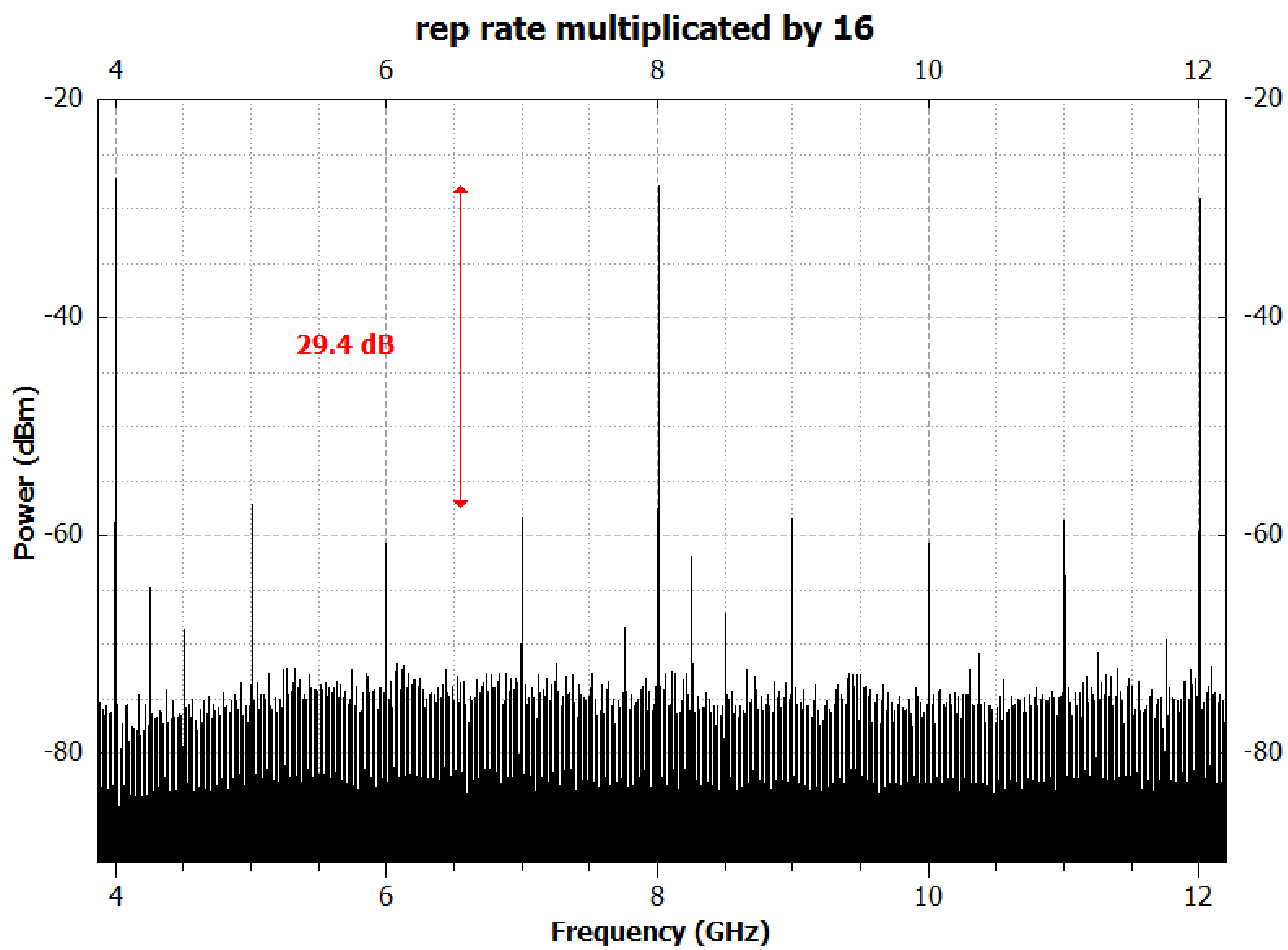
Repetition Rate Multiplication

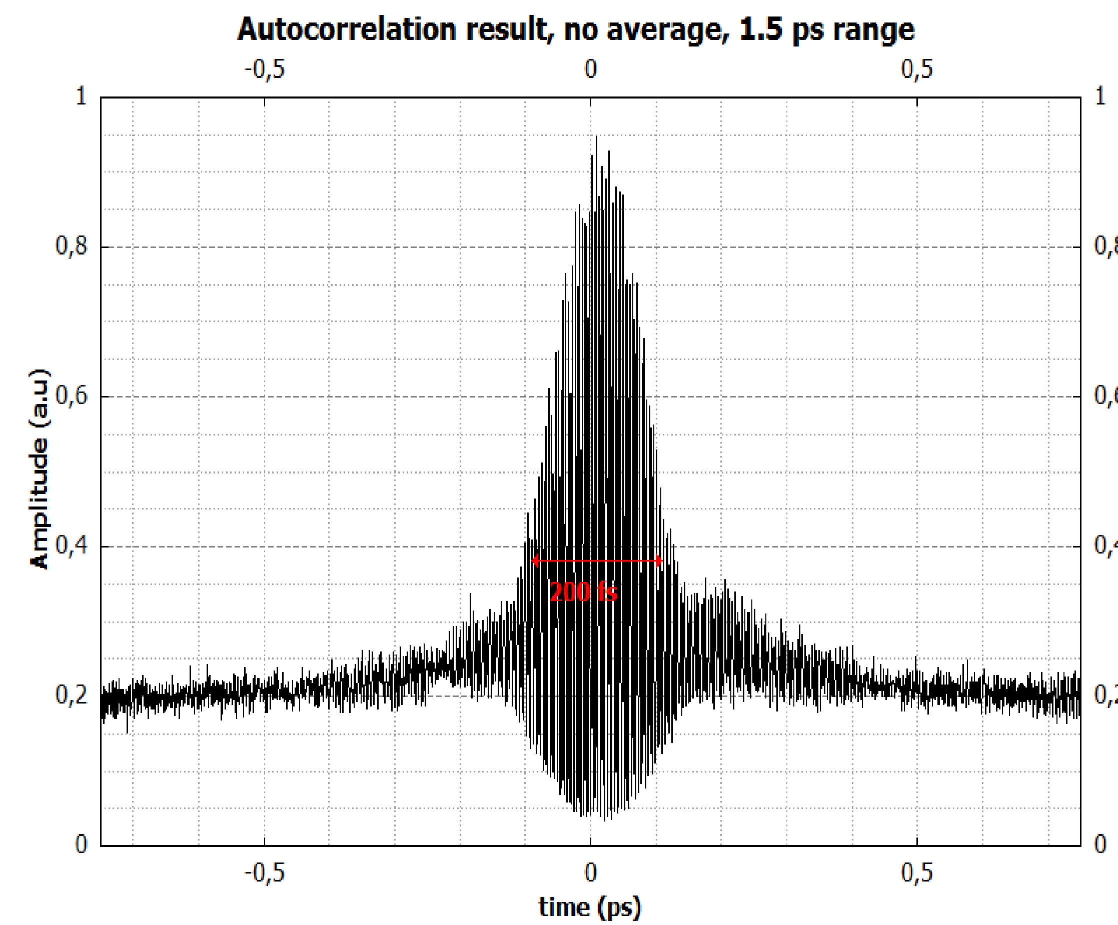


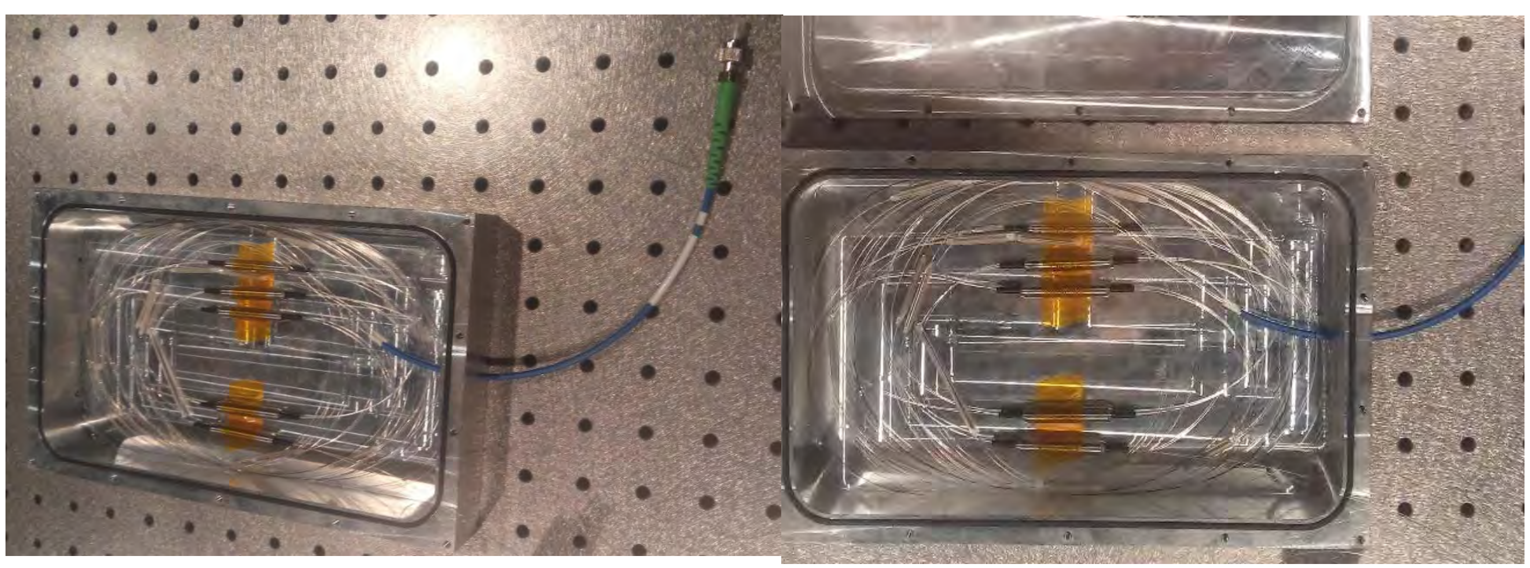


- ✓ Suppression of unwanted harmonics ~30dB(length&amplitude matching)
- ✓ Simpler microwave filtering

X16 PM Repetition Rate Multiplication

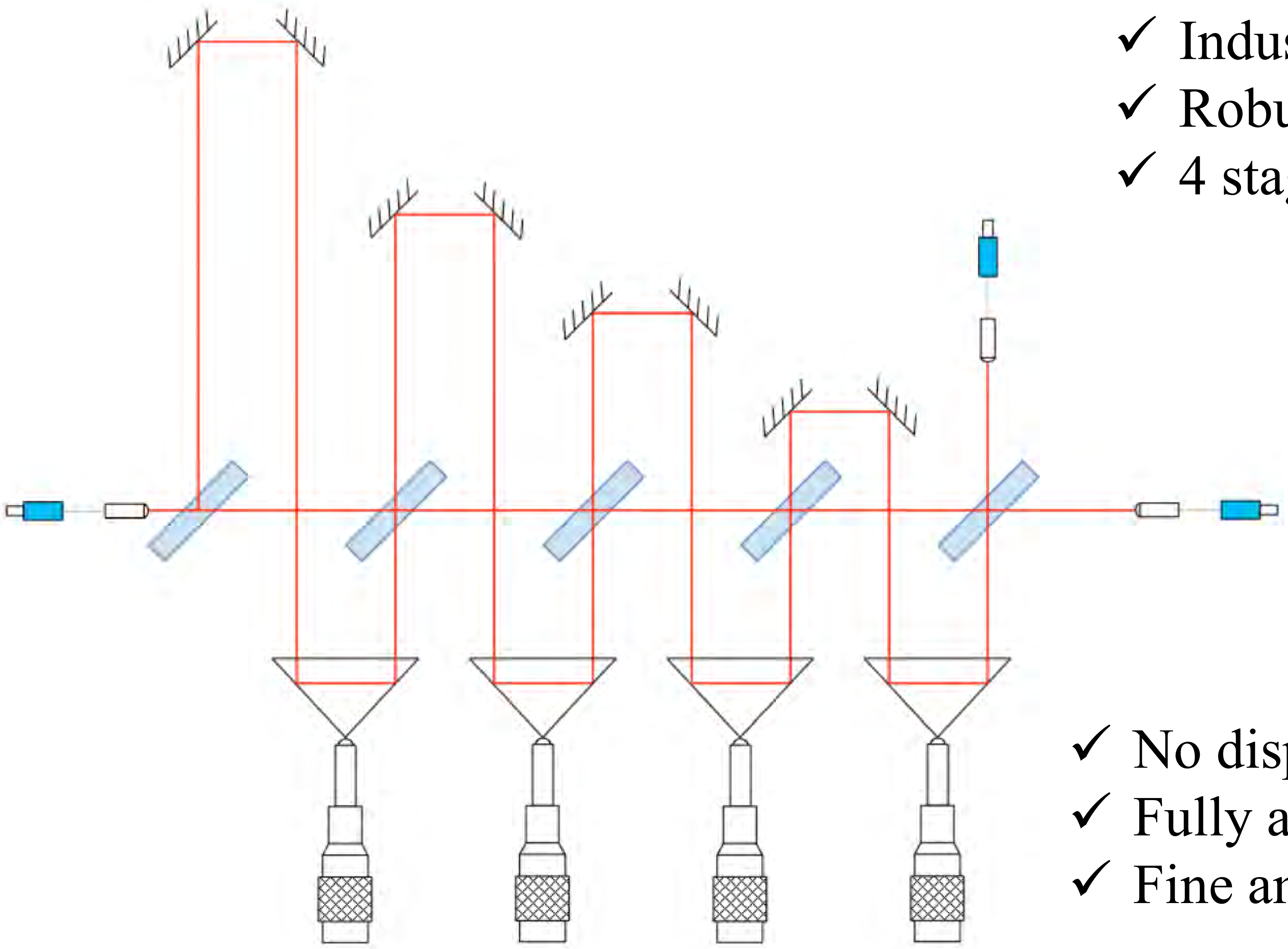






- ✓ PM couplers 50/50 (<1%)
- ✓ 4 stages -> f_{rep}x 16
- ✓ low losses <3.5dB
- ✓ recompressed pulse ~200fs

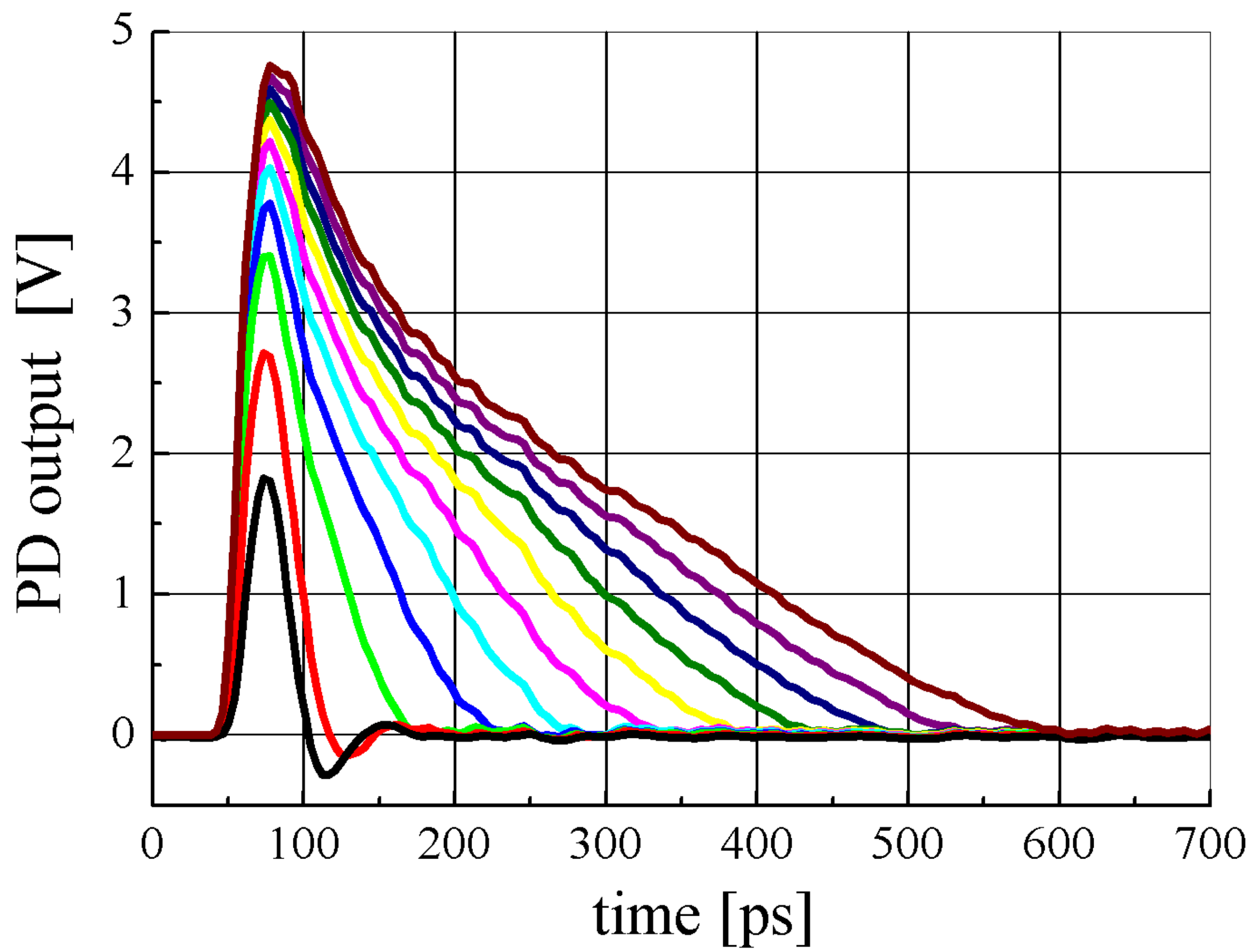
Free Space Repetition Rate Multiplication



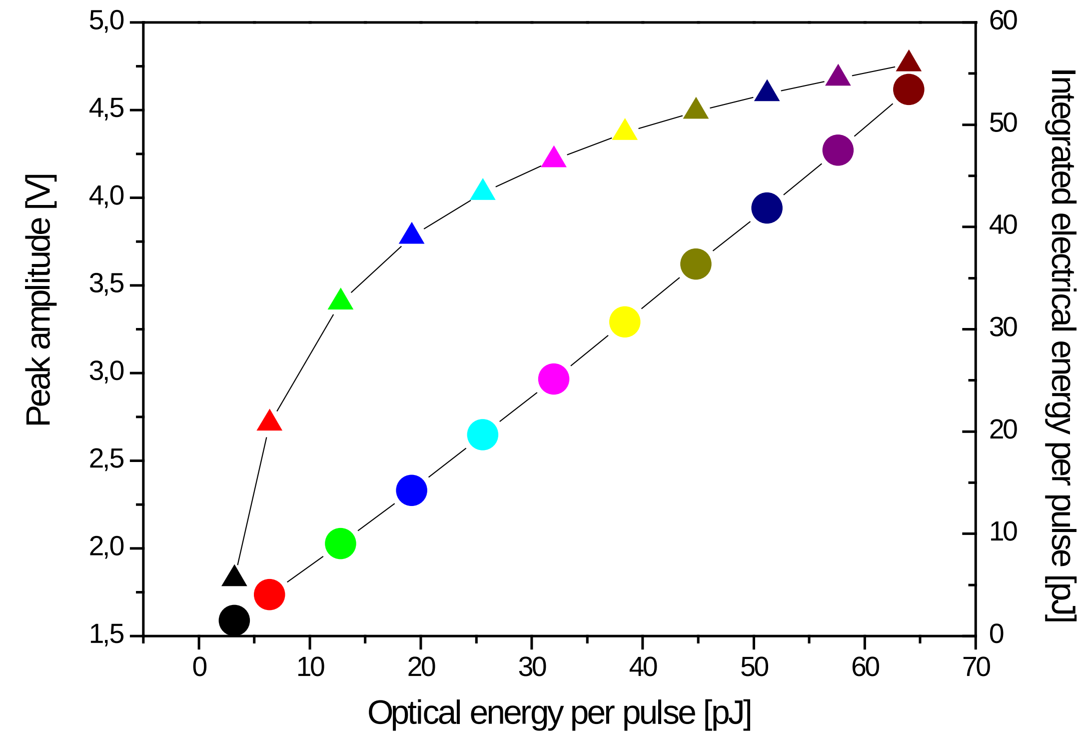
- ✓ Industrial design
- ✓ Robust
- ✓ 4 stages -> f_{rep}x 16

- ✓ No dispersion
- ✓ Fully adjustable 1%
- ✓ Fine amplitude&delay tuning

Amplitude-to-phase conversion in photodetection



Space charge screening effects



- short light pulses <1ps
- electrical pulse shape distortion
- elec. pulse ϕ shift w/ opt. pulse energy

RIN&AMPLITUDE-TO-PHASE CONVERSION

optical intensity fluctuations (RIN) ⟶ excess phase noise

AMPM factor dϕ/(dE/E)

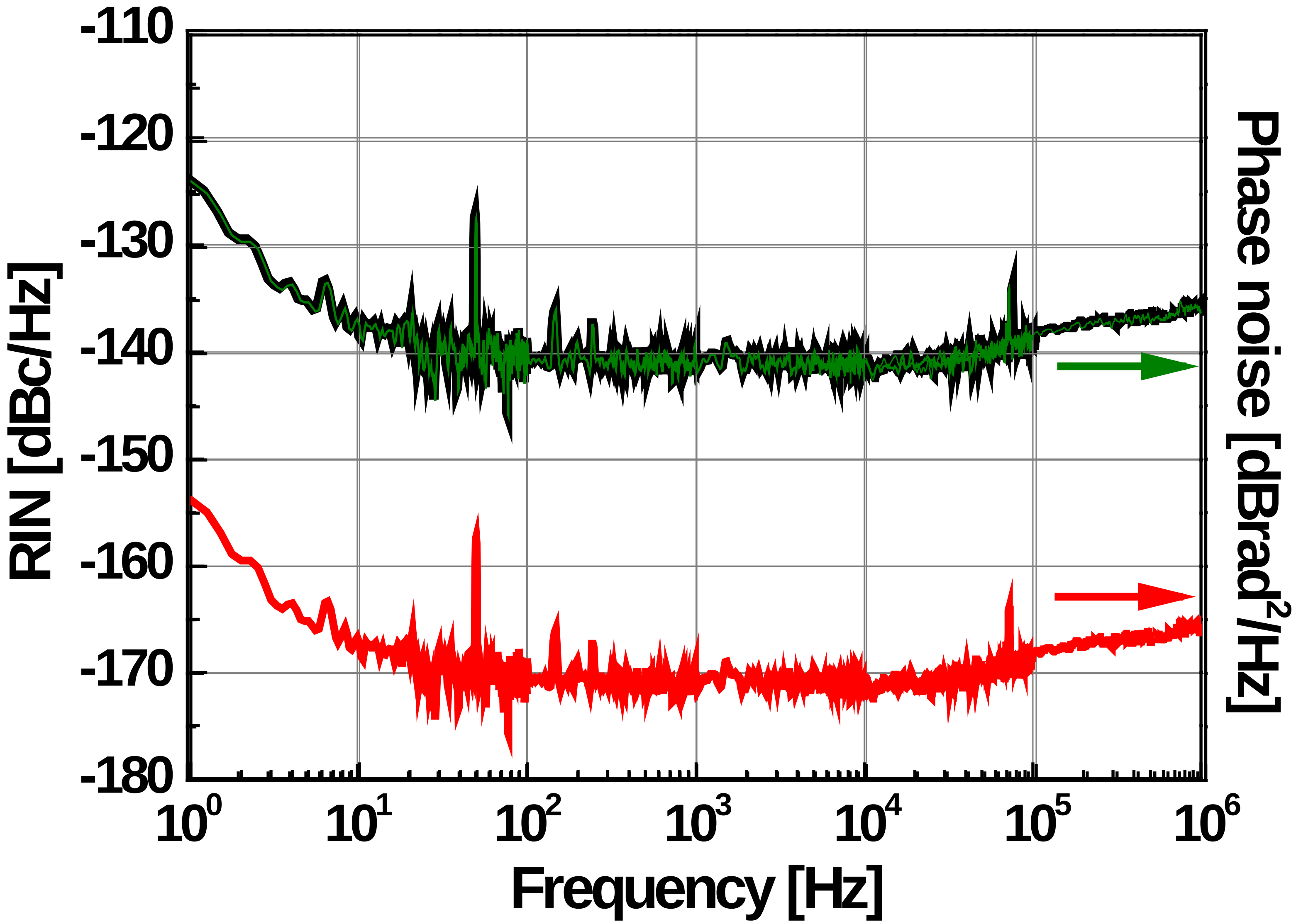
RIN-induced phase noise $S_\phi = RIN \times AMPM^2$

Example

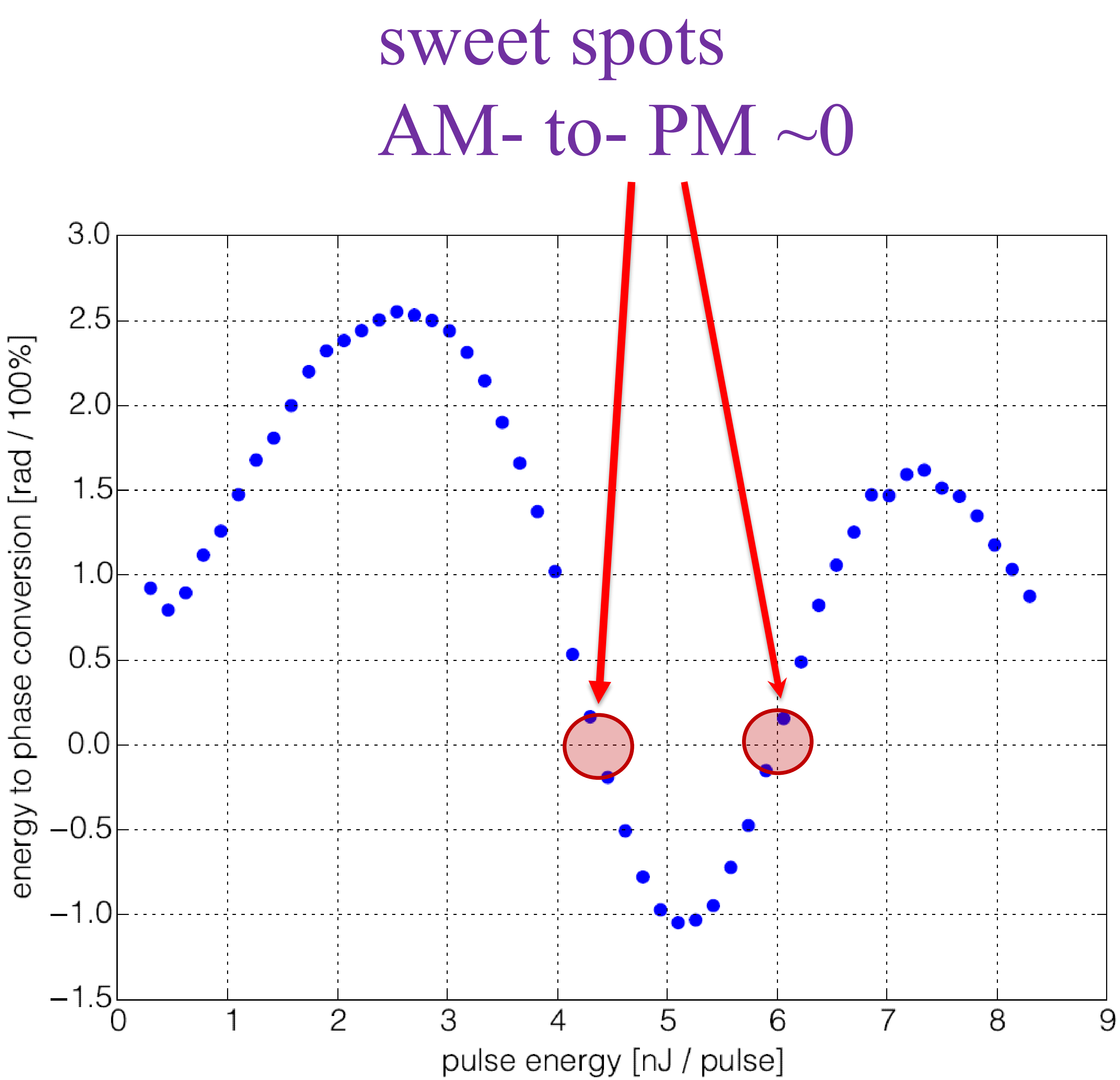
RIN → Predicted ϕ noise

1 rad 0 dB ☹

0.03 rad -30 dB ☺



RIN&AMPLITUDE-TO-PHASE CONVERSION



Stability of the zero AMPM

Low sensitivity to:

- Laser mode-lock state
- Laser repetition rate
- Laser polarization

The DARPA PureComb consortium

l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Discovery Semiconductors, Inc.®
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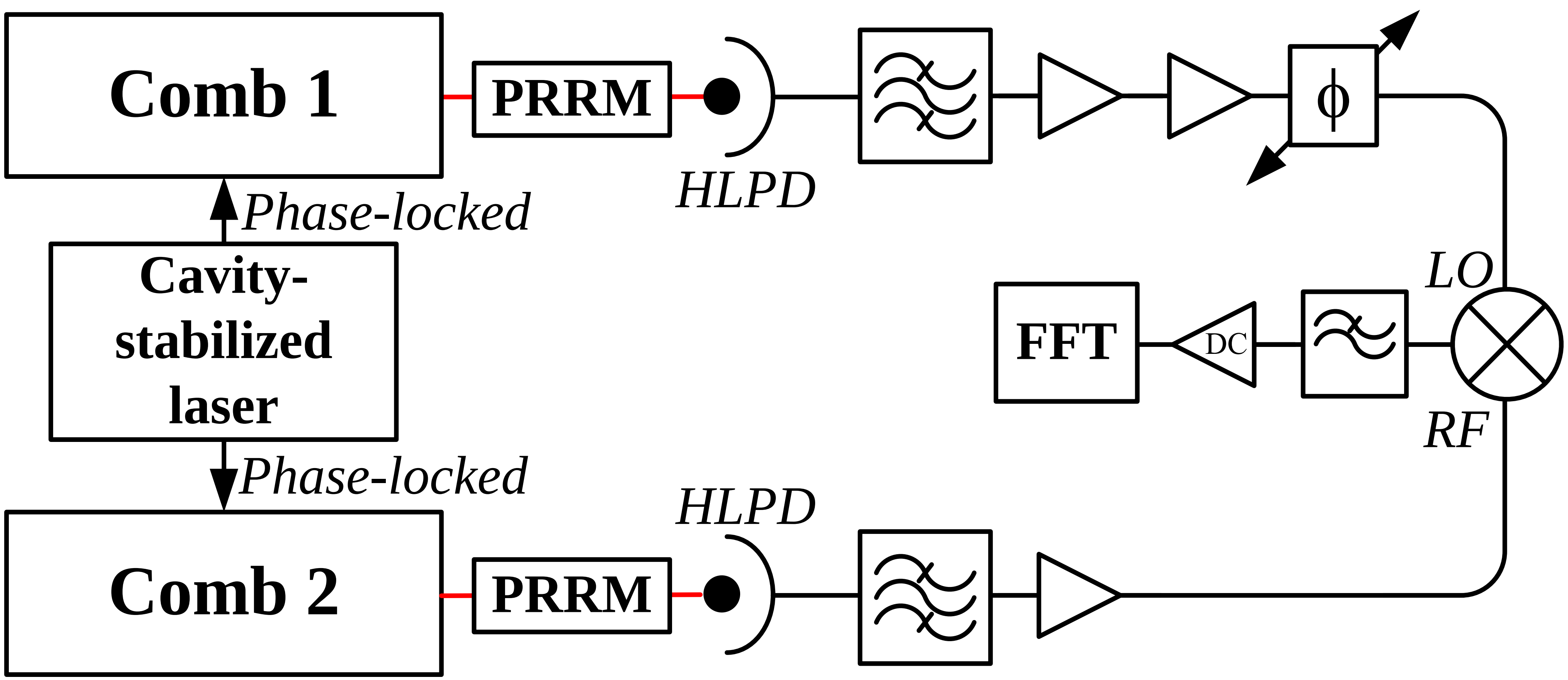
Low phase noise µW generation

Classical phase noise bridge measurement scheme

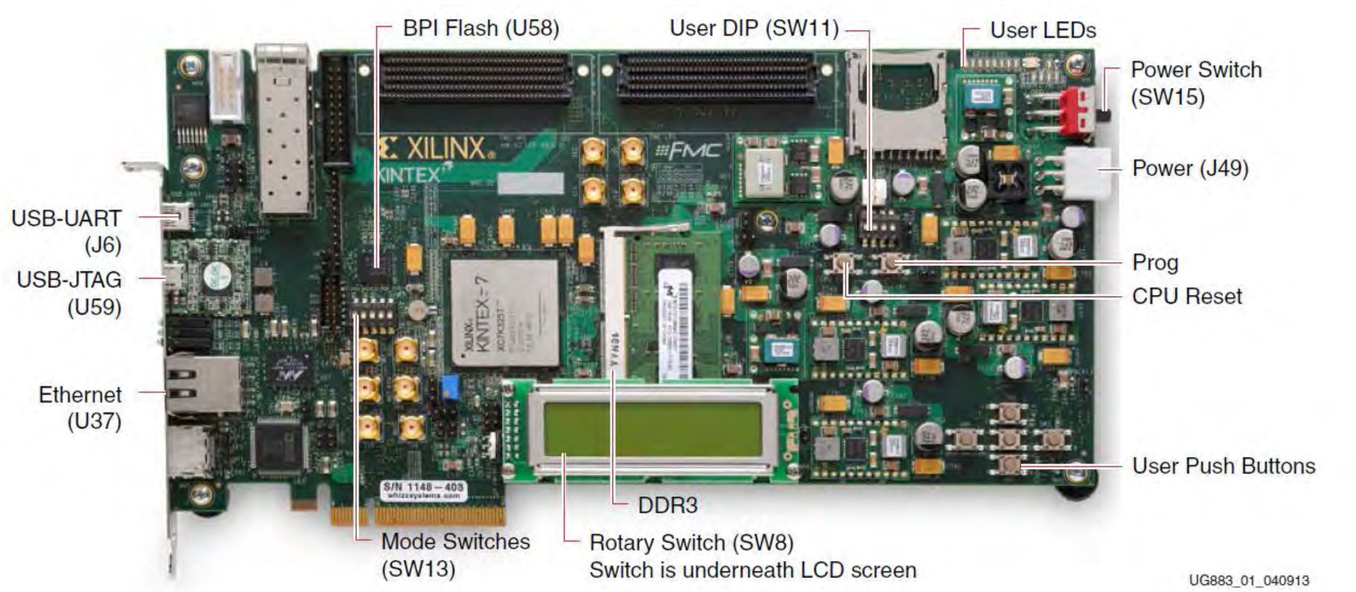
- High RF power @ 12GHz by using MZI and highly linear photodetectors
- µW amp.: ultra-low phase noise
- Low AM-PM (fine optical power tuning)



Needs two identical combs

The cross correlator (SYRTE/CNAM)

FPGA : Xilink KC705



Low noise fequency chains for clock signals
2 ~statiscally independant 250MHz

FPGA motherboard with 2 ADC

ADC : AD9467 (Analog Device)

Conversion rate + resolution	250 Msps 16 bits
Effective Number Of Bits (ENOB) à 5 MHz	12.4
Spurious-Free Dynamic Range (SFDR) à 5 MHz	97 dBFS
Aperture Jitter	60 fs rms

Clock sources :
2 home-made low noise frequency chains
Phase noise @ 100 MHz:
-165 dBc/Hz @ 1kHz offset
-178 dBc/Hz @ 100kHz offset

Phase noise PSD cross correlation measurements