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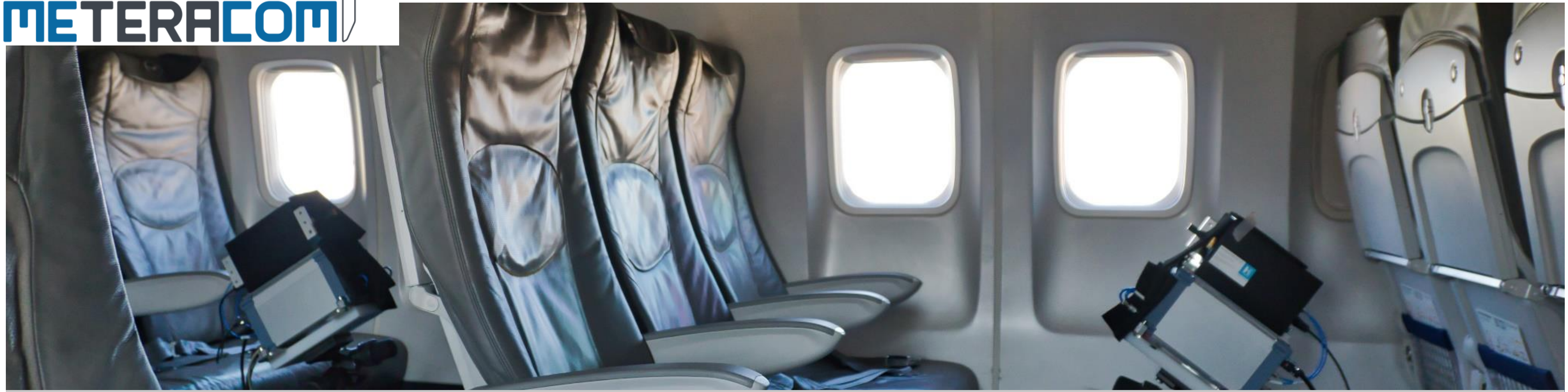

Ultra-low phase noise frequency synthesis for THz metrology using low-jitter femtosecond pulse laser

J. Christoph Scheytt, Meysam Bahmanian, Saeed Fard

1st International Workshop on Metrology for THz Communications, Braunschweig, 28 June 2022

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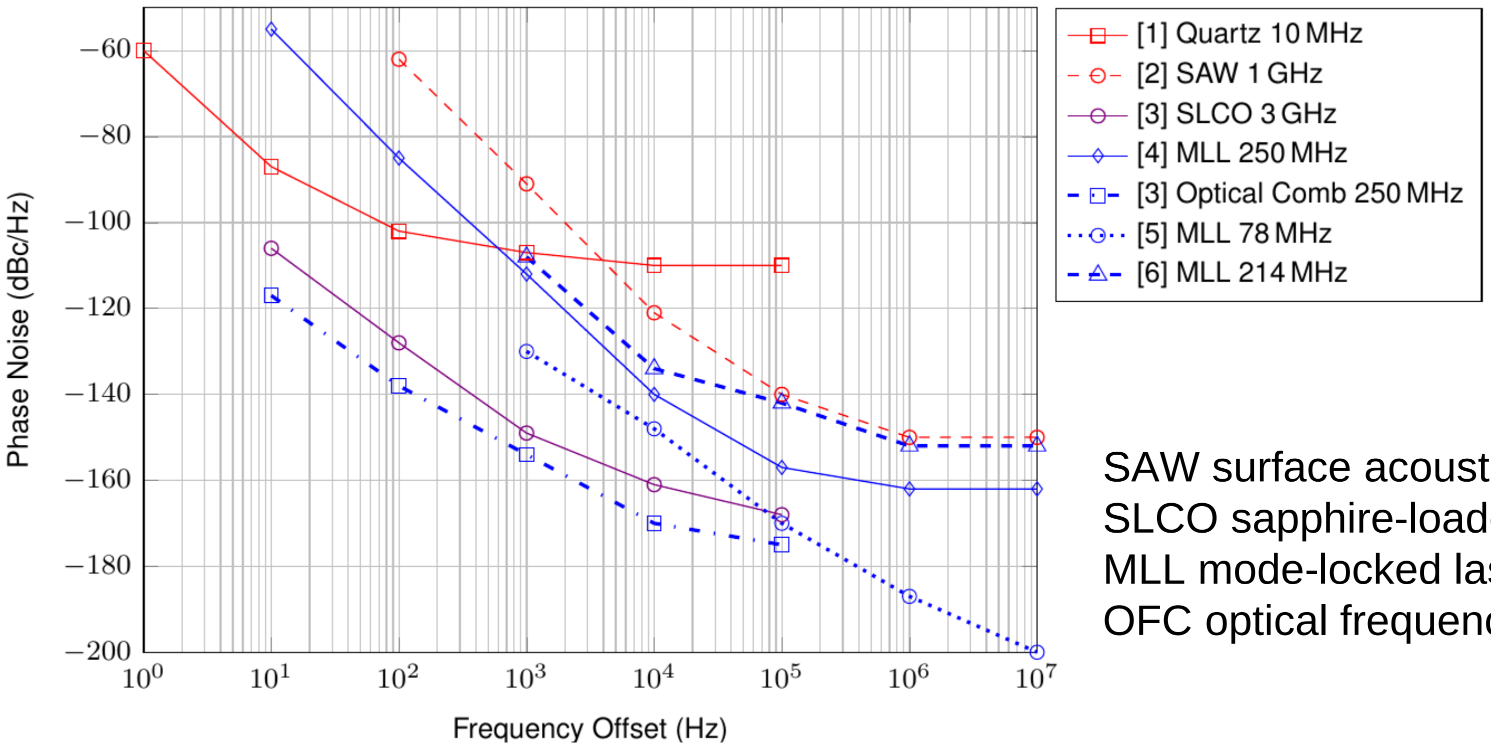
- Principle and modeling of OEPLL
- 2-20 GHz Ultra-low noise OEPLL frequency synthesizer
- 77 GHz OEPLL frequency synthesizer
- Conclusions

Phase noise comparison of optical and electronic oscillators

- Currently available optical / electronic oscillator technologies
- Phase noise plots normalized to 10 GHz



SAW surface acoustic wave
SLCO sapphire-loaded cavity oscillator
MLL mode-locked laser
OFC optical frequency comb

Phase noise comparison of optical and electronic oscillators

- Optical oscillators provide better phase noise than electronic oscillators

- Reasons:
  - Q-factors of optical resonators,
  - Mode-locking for extreme high peak pulse power at moderate DC power
  - Operating in high THz (no thermal noise)
  - …

- Optical pulse trains of MLLs with jitter of less than 13 as rms measured[1]
- Typical oven-controlled quartz oscillator jitter around 20 to 30 fs rms

[1] A. J. Benedick, J. G. Fujimoto, and F. X. Kartner. Optical flywheels with attosecond jitter. *Nature Photonics*, 6:97–100, 2012.

Image source: NIST

Optoelectronic THz frequency synthesis

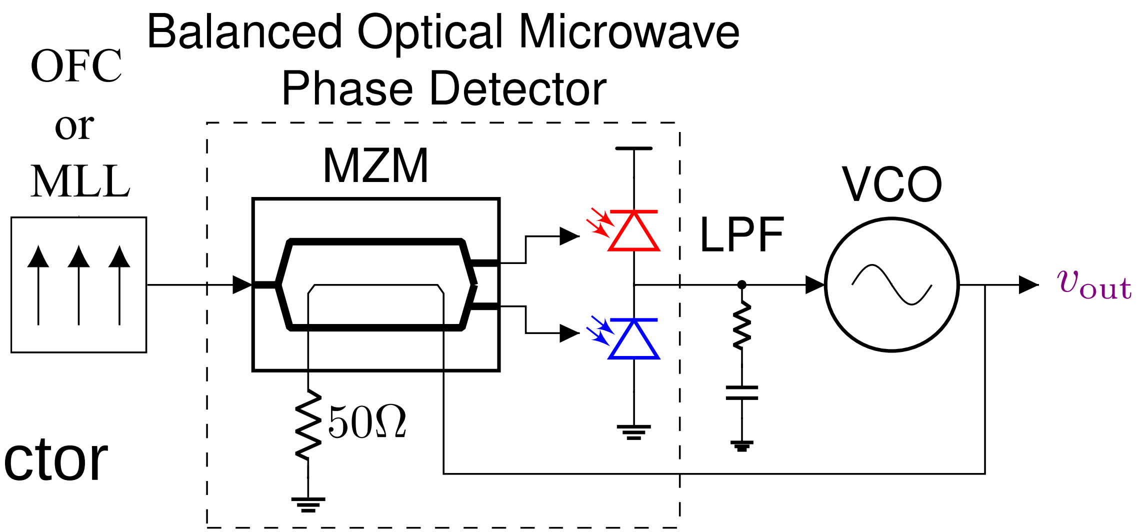
- PLL frequency synthesizer phase noise (PN) is dominated by reference PN
- PN scales with $20\log(f_{out}/f_{ref})$
- E.g. PN of 300 GHz signal by $20\log(300\,GHz/30MHz)$ = 80dB worse compared to 30 MHz reference oscillator PN (typically a quartz oscillator)

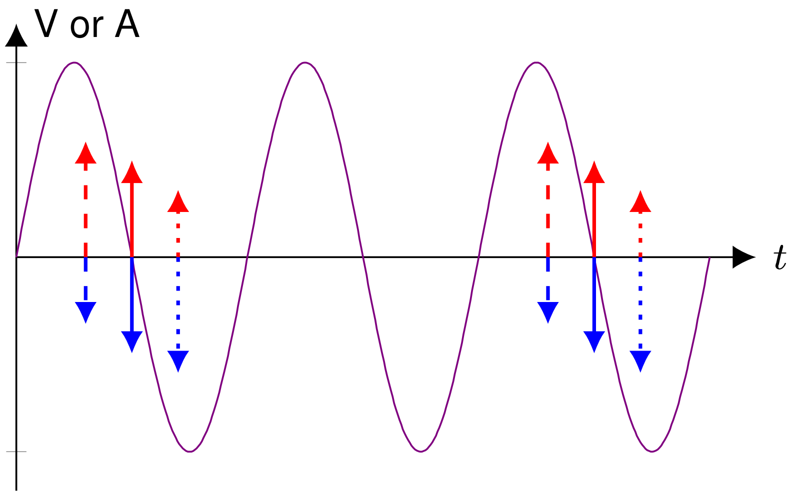
→ Conventional electronic THz PLL frequency synthesizers achieve poor PN

→ Need for ultra-low PN optoelectronic THz frequency synthesis for metrology

Optoelectronic PLL (OEPLL)

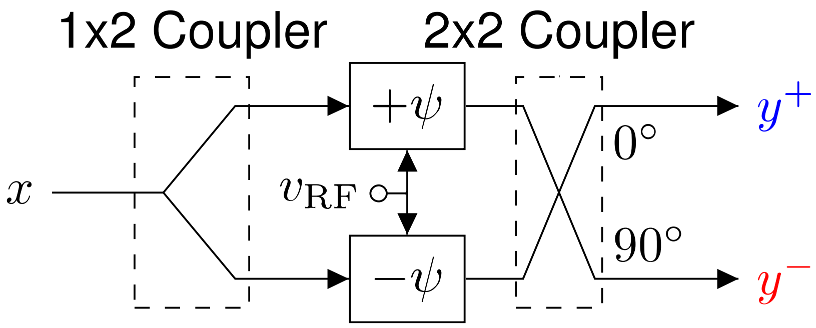
- MHz optical pulse train as reference
- Phase locking of microwave VCO to optical pulse train
- Mach-Zehnder modulator (MZM) and PDs as balanced optical microwave phase detector (BOMPD)
- RC filter integrates error current from BOMPD
- In lock condition optical pulse samples VCO signal at zero crossing

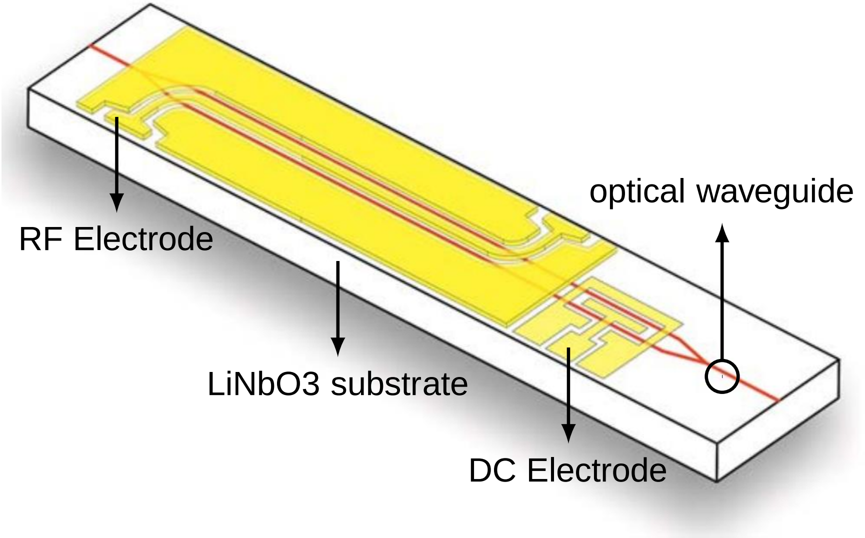




MZM

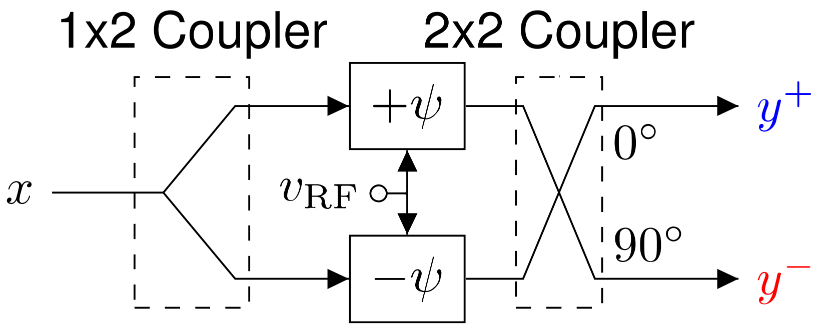
- In MZM optical signal is divided, phase-shifted, and recombined (interferometer).
- Balanced MZM with complementary outputs
- MZM implemented in Lithium-Niobate
→ phase shift proportional to E-field (v_{RF})

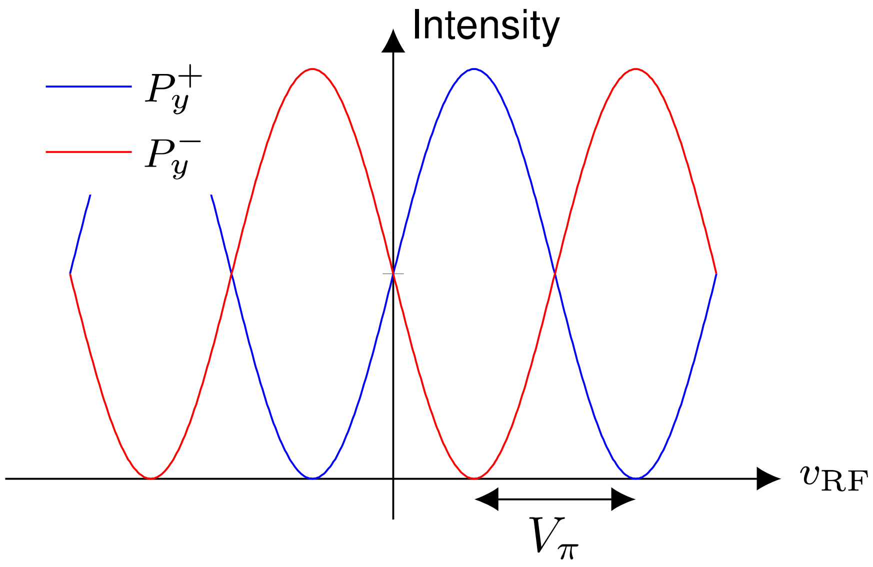




MZM

- Optical phase shift $\psi = \pi v_{RF} / V_{\pi}$
- 2x2 coupler implements interferometer: sinosoidal transfer characteristic for P_y^+ , P_y^- vs. v_{RF}
- $P_y^+ - P_y^- = P_x \sin(\pi \frac{v_{RF}}{V_\pi})$
  and for small ψ : $P_y^+ - P_y^- \approx P_x \times \pi \frac{v_{RF}}{V_\pi}$
- Hence MZM multiplies P_x with v_{RF}
  → MZM represents balanced OE mixer rsp. balanced OE phase detector



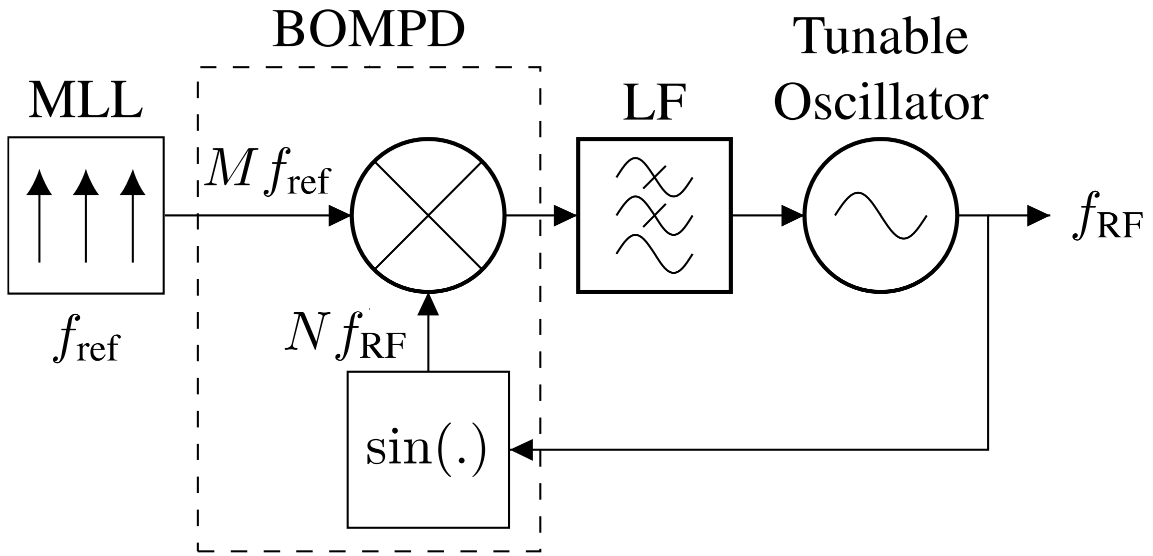


OEPLL model, harmonic locking

- Detailed nonlinear mathematical model of OEPLL with BOMPD[1]

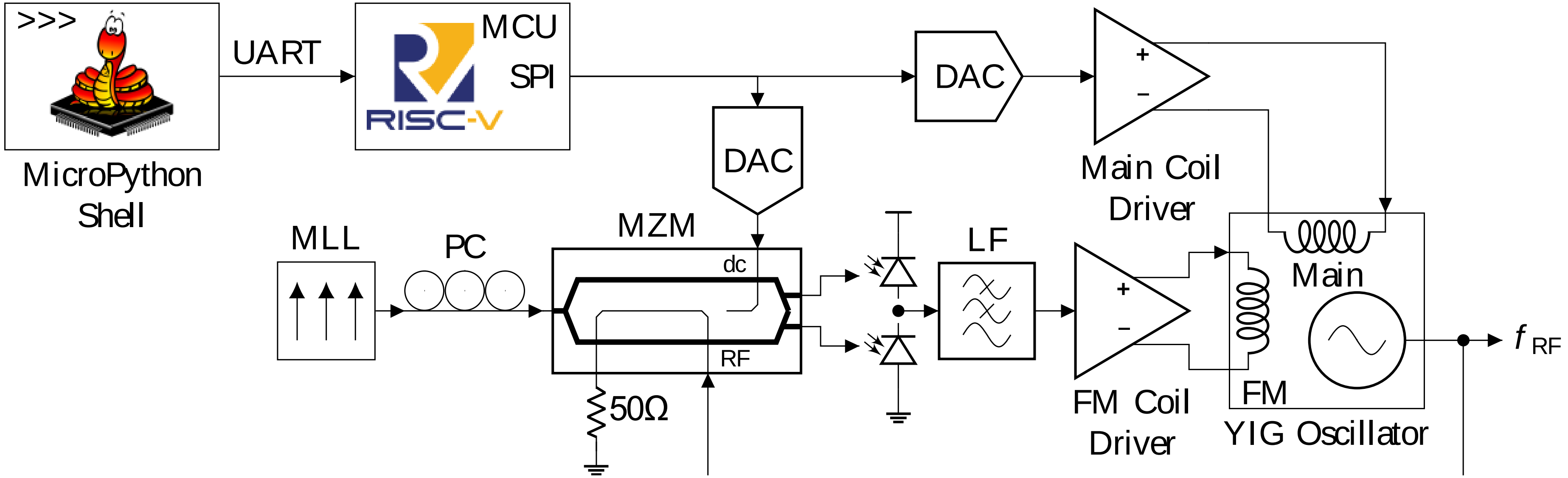
- For low RF amplitude BOMPD is operated approx. linear (N=1) OEPLL locks on $f_{RF} = M f_{ref}$
  → Integer-N PLL

- Mathematical model allows for careful optimization of PLL paramters for min. PN



[1]M. Bahmanian and J. C. Scheytt, "A 2–20-GHz Ultralow Phase Noise Signal Source Using a Microwave Oscillator Locked to a Mode-Locked Laser," in *IEEE T-MTT*, vol. 69, no. 3, pp. 1635-1645, March 2021

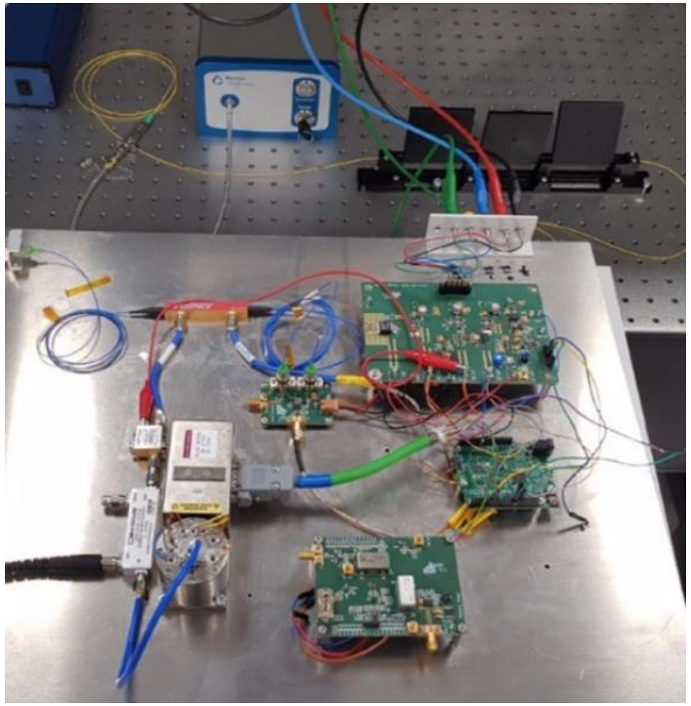
2-20 GHz OEPLL Frequency Synthesizer[1]

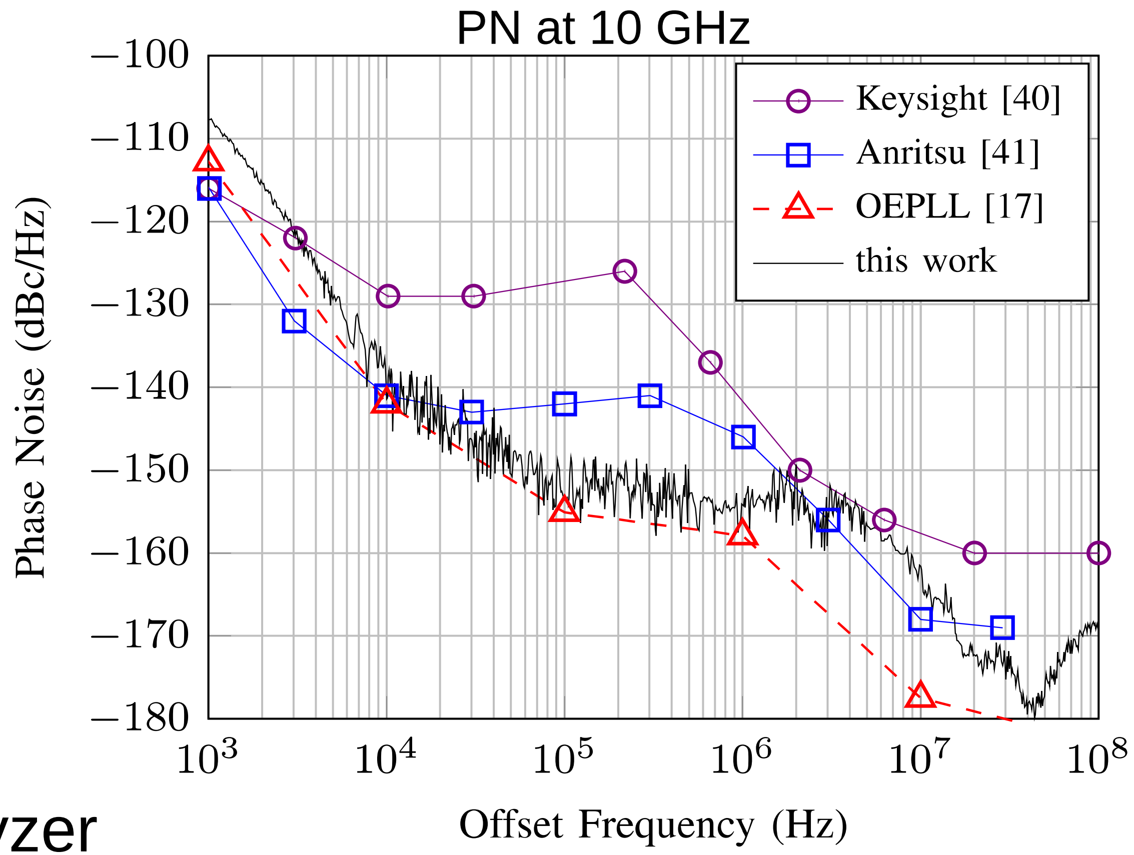


- MLL with repetition rate of 250 MHz
- Polarization controller
- Bias point of MZM is set via a DAC
- Low noise YIG oscillator as VCO
- YIG Main coil controlled by DAC
- YIG VCO locks on N*250MHz within 2-20 GHz
- RISC-V MCU, MicroPython shell

[1]M. Bahmanian, S. Fard, B. Koppelmann, J. C. Scheytt, "Wide-Band Frequency Synthesizer with Ultra-Low Phase Noise Using an Optical Clock Source," *2020 International Microwave Symposium (IMS)*, 2020

2-20 GHz OEPLL Frequency Synthesizer

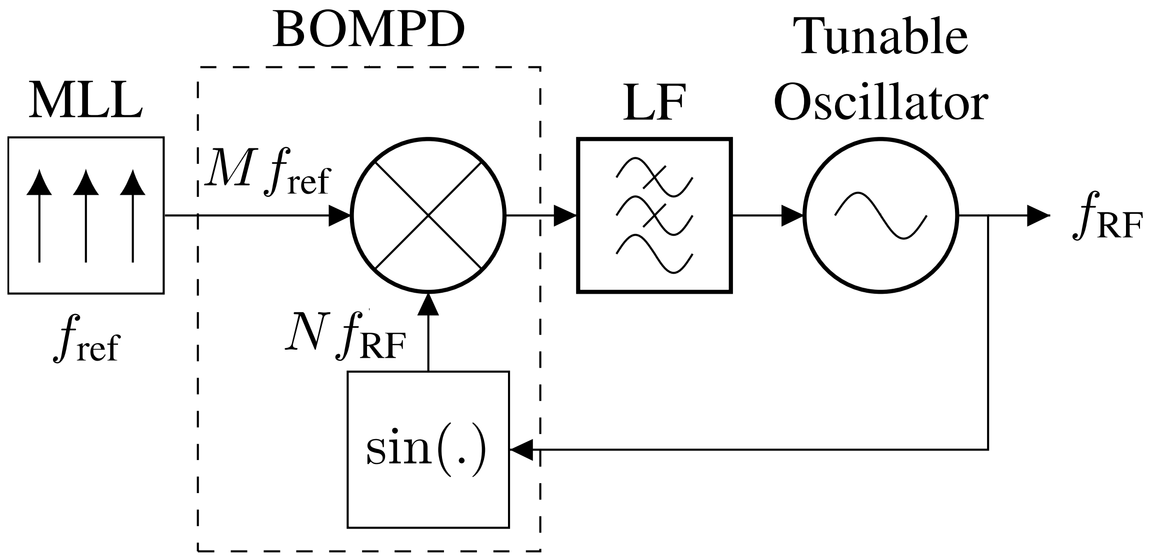




- Measurement with Anapico PN analyzer
- Jitter below 3 fs rms from 3-20 GHz
- PN better than any electronic RF signal generators

OEPLL model, interharmonic locking[1]

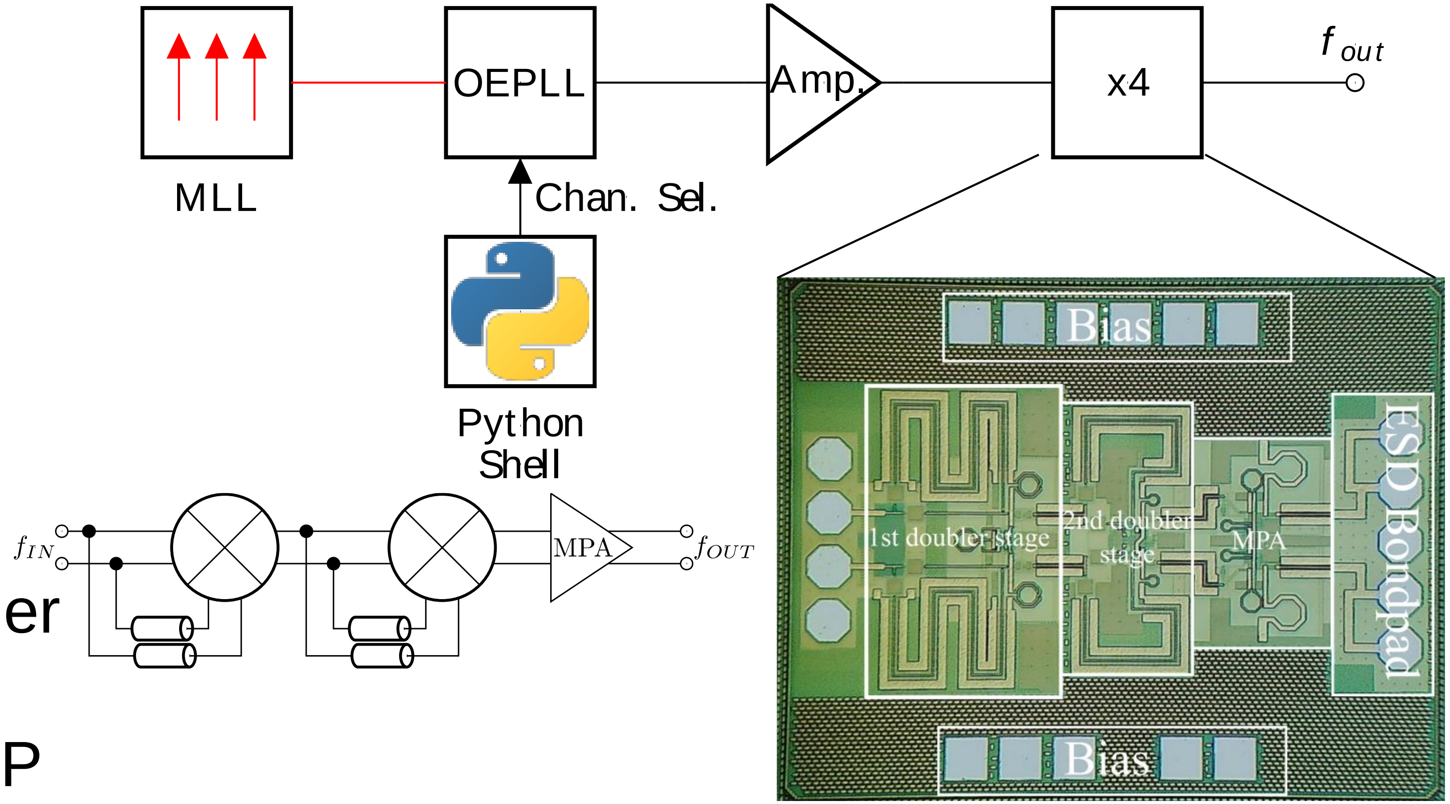
- For high RF amplitude BOMPD is in nonlinear fashion (N=1, 2, 4)
- OEPLL locks on $f_{RF} = \frac{M}{N} f_{ref}$
  → Interharmonic locking of PLL
- Typically not seen in electronic PLLs
- BOMPD gain changes, loop dynamics changes slightly, still reliable lock



[1]Meysam Bahmanian, Christian Kress, and J. Christoph Scheytt, "Locking of microwave oscillators on the interharmonics of mode-locked laser signals," Opt. Express 30, 7763-7771 (2022)

77 GHz OEPLL frequency synthesizer for long-range radar[1]

- Combination of OEPLL with SiGe frequency quadrupler
- Output frequency of OEPLL at 19.25 GHz is upconverted to 77 GHz
- Frequency quadrupler made from 2 Gilbert cell doubler
- 130nm SiGe BiCMOS from IHP

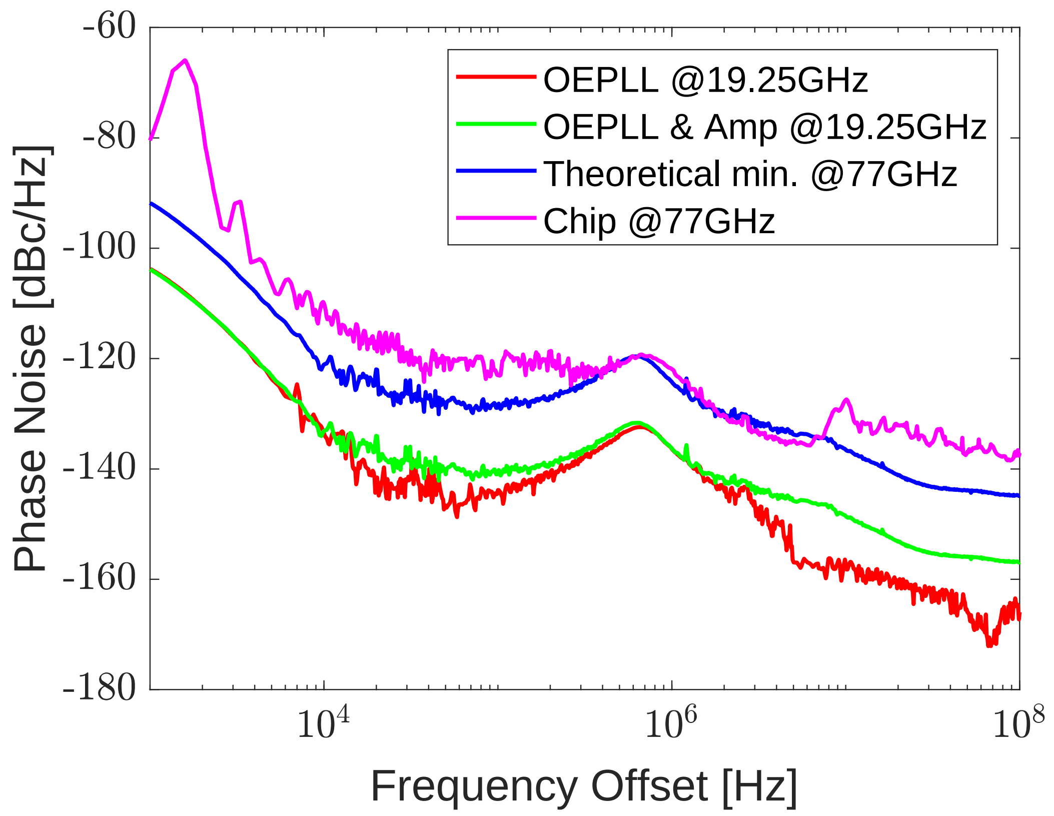


[1]S. Kruse, M. Bahmanian, S. Fard, M. M. Meinecke, H. G. Kurz, and J. Christoph Scheytt, "A Low Phase Noise 77 GHz Frequency Synthesizer for Long Range Radar“, European Radar Conference, 2022, accepted

77 GHz OEPLL frequency synthesizer for long-range radar

- Excellent PN for offset frequencies above 10kHz.

- High PN at 1kHz probably due to measurent setup (insufficient isolation of signal sources in PN crosscorrelation measurements)



Conclusions & Outlook

- Optical oscillators (MLLs, OFC) have potential for extreme low PN and jitter, around 4 orders of magnitude better than electronic oscillators.
- OEPLL using MLL as optical reference was analyzed → nonlinear model
- 2-20 GHz OEPLL implemented with record low phase noise.
- Future work will concentrate on further PN improvements (amplifier phase noise) and extension into THz frequency range

Acknowledgement

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