Carrier-envelope phase stabilization

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Outline

- General introduction
  - CEP definitions and representations
  - Stabilization loops theory
  - Noise analysis example
- CEP in oscillators and amplifiers
  - System peculiarities and noise sources
  - CEP detection (f-2f interferometers and others)
  - Feedback mechanisms
  - Some results
- Educationally speaking
  - The noble art of noise frequency analysis

What is the carrier-envelope phase ?

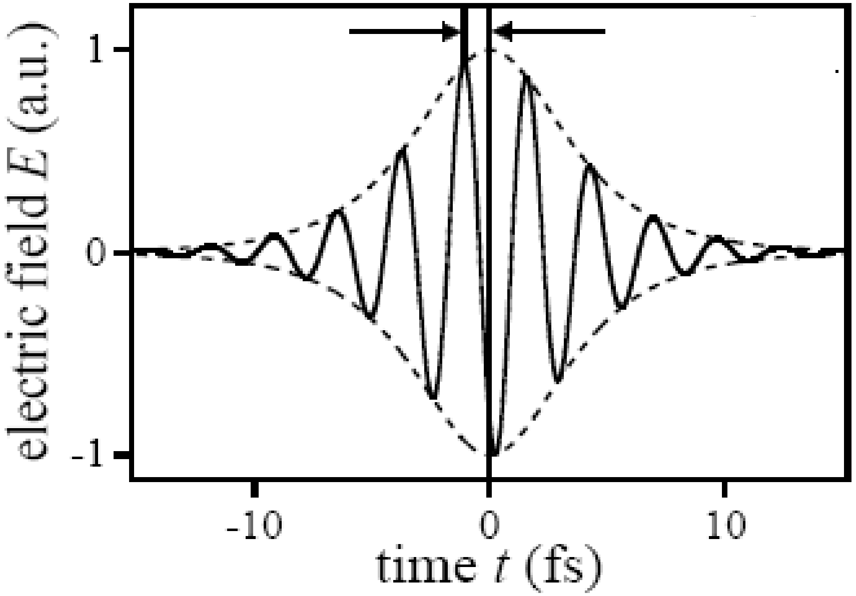
- Electric field description

$$E(t) = A(t).\exp(-i\omega_0 t+i\varphi)$$

Enveloppe

Carrier

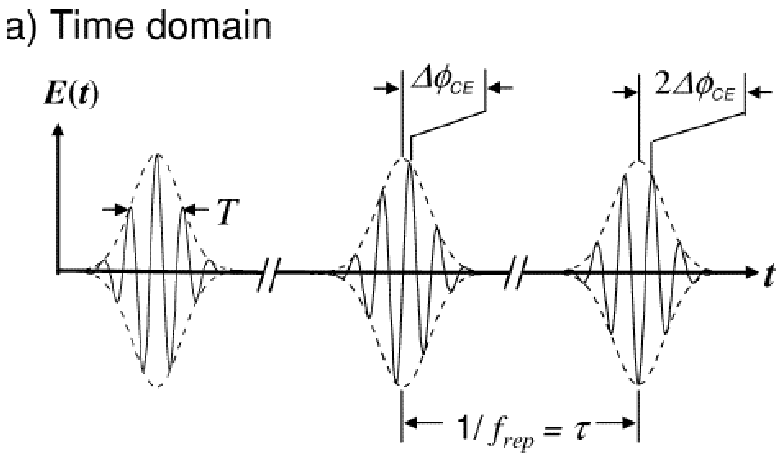
Appl. Phys. B 69, 327–332 (1999)



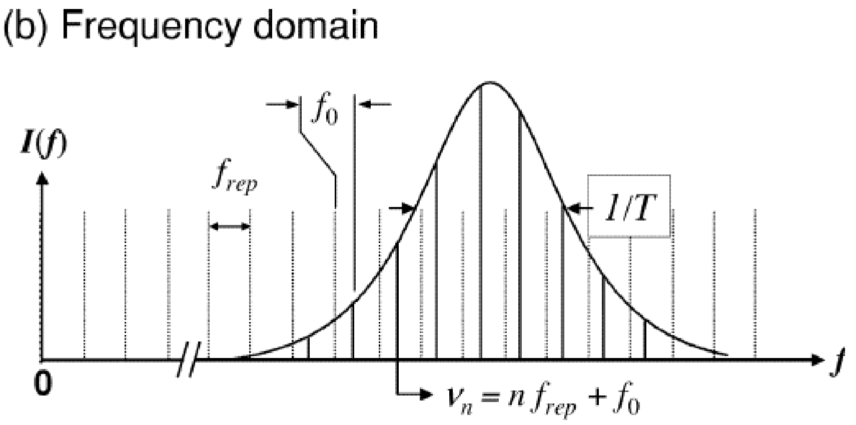
- Definitions
  - Metrology : CE Offset
  - Amplified pulses : CE Phase

CEP representations (I)

- Metrology : frequency ruler with an oscillator



IEEE J. Sel. Top. Quant. Electron. 9,1002 (2003)



$$f_0 = f_{rep} . \Delta\varphi_{CE}/2\pi$$

- Oscillator output
  - ☐ Comb = modes
  - ☐ f_0 = comb frequency offset
  - ☐ $\Delta\varphi_{CE}$ = CE Offset (CEO)

Frequency domain representation

CEP representations (II)

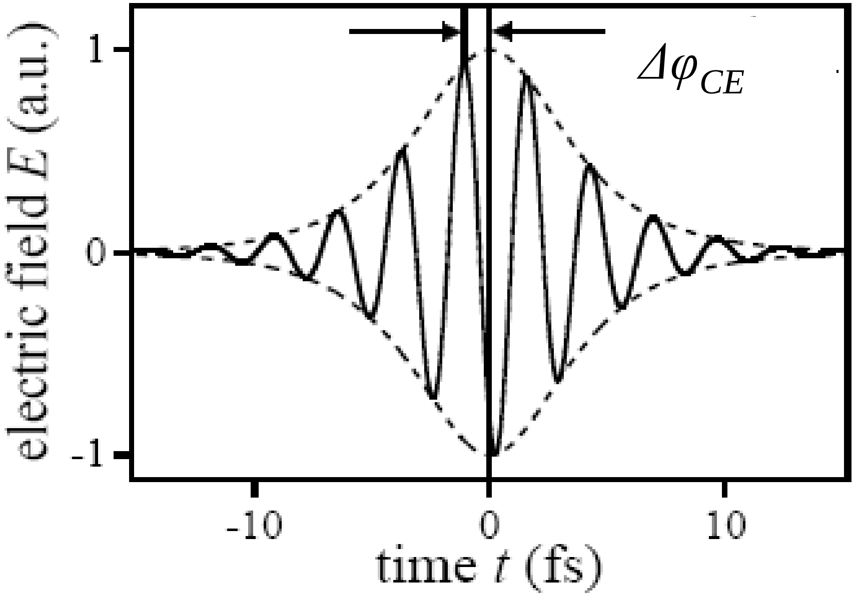
- Single amplified pulses : Electric field oscillation

$$E(t) = A(t).\exp(-i\omega_0 t+i\varphi)$$

$A(t)$: group velocity : $n_G(\omega_0)$
ω_0 : phase velocity : $n(\omega_0)$

- Amplifier output
  - ☐ One single pulse
  - ☐ CE phase (CEP)
  - ☐ Unambiguous definition?

Appl. Phys. B 69, 327–332 (1999)

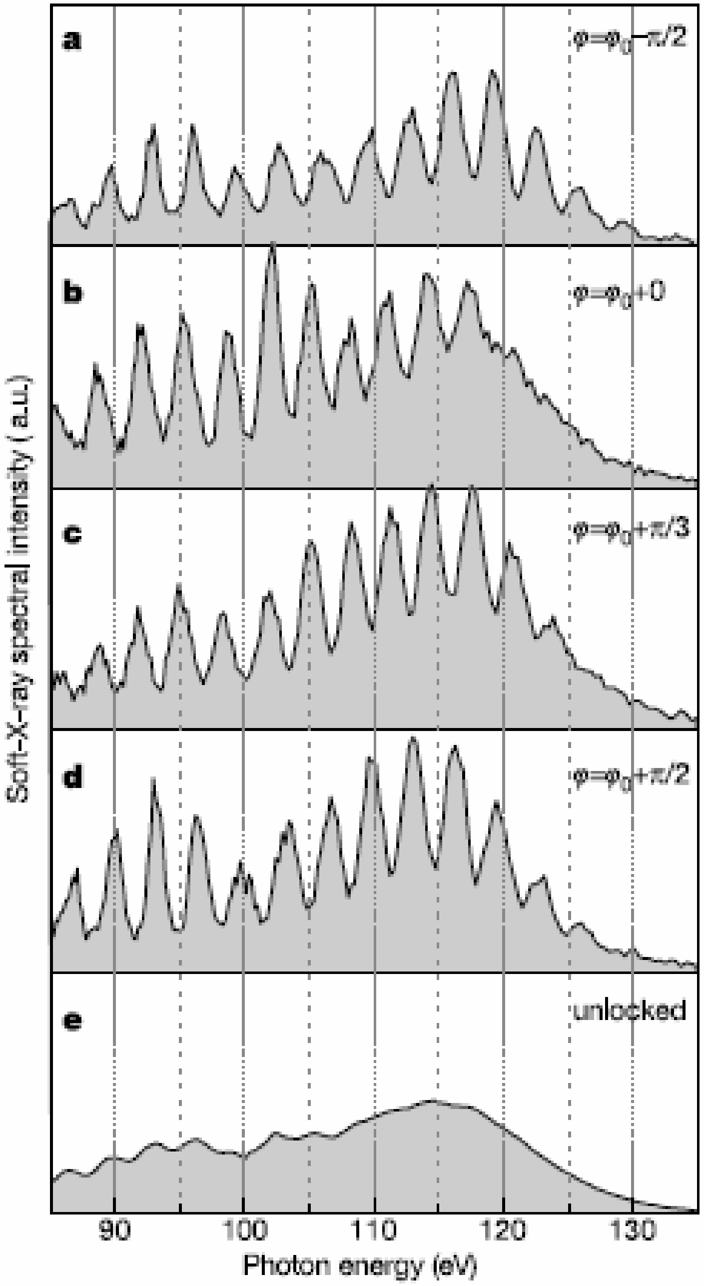


Time domain representation

Why stabilizing?

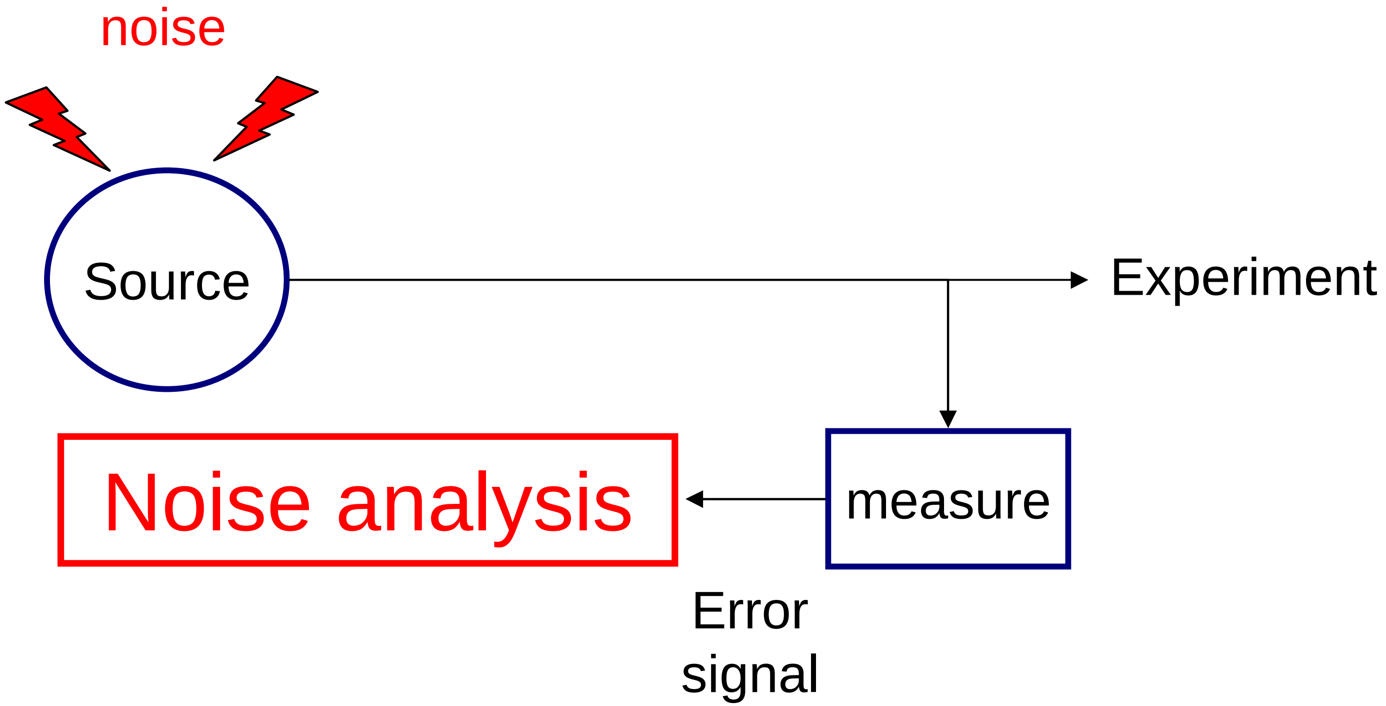
- Example: XUV generation
  - Integration over 500 shots
  - What if no phase lock?
  - Blurred results!

CEP stabilization
=
Reproducible results



Nature 421, 611 (2003)

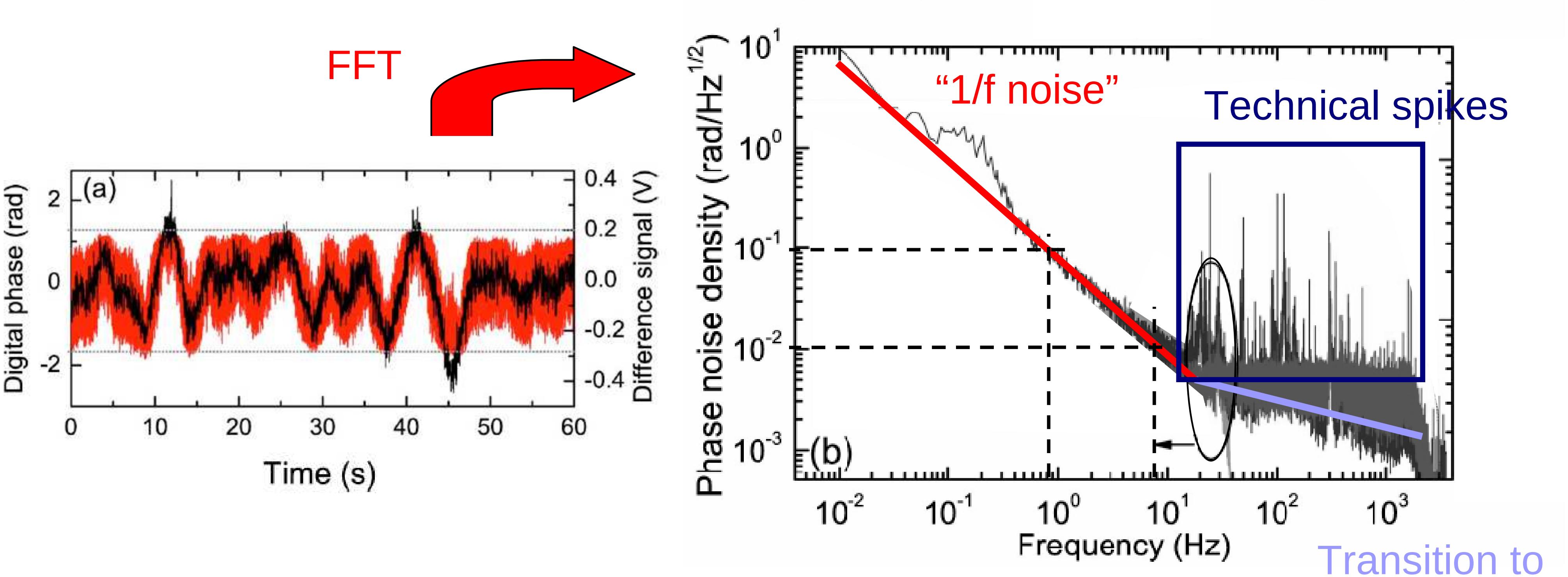
Stabilization loops (I)



Noise analysis (I)

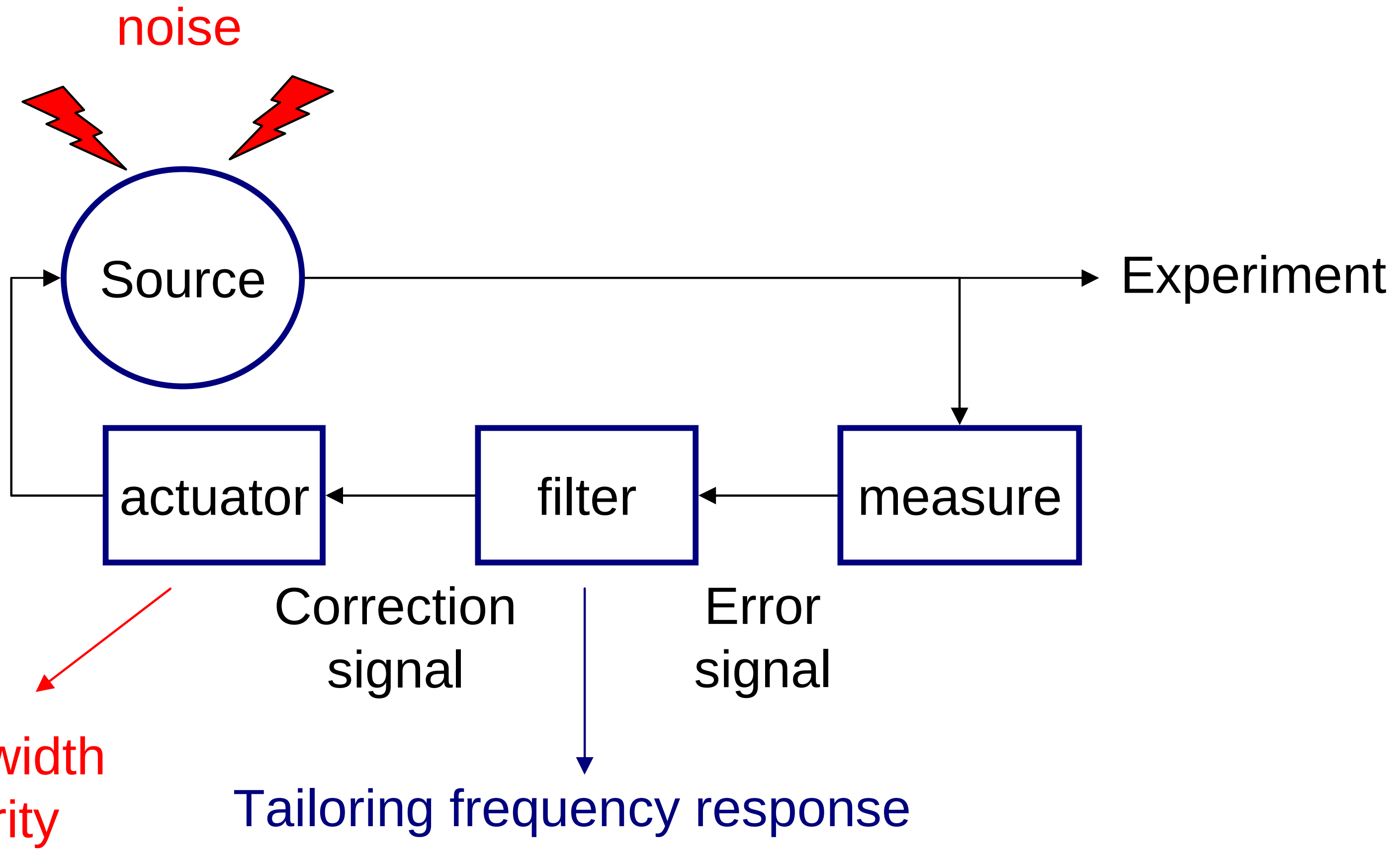
- Noise power spectral density : $\mathrm{rad}^2/\mathrm{Hz}$ vs Hz (or in $\mathrm{rad}/\mathrm{Hz}^{1/2}$ vs Hz)
    - Frequency analysis of an error signal e(t)

      $\mathrm{FFT}(|e(t)|^2)$
    - Example: 3 kHz multipass amplifier Opt. Lett. 33, 2545 (2008)



Transition to "white noise"

Stabilization loops (II)


noise

Source

Experiment

actuator

filter

measure

Correction signal

Error signal

Bandwidth
Linearity

Tailoring frequency response

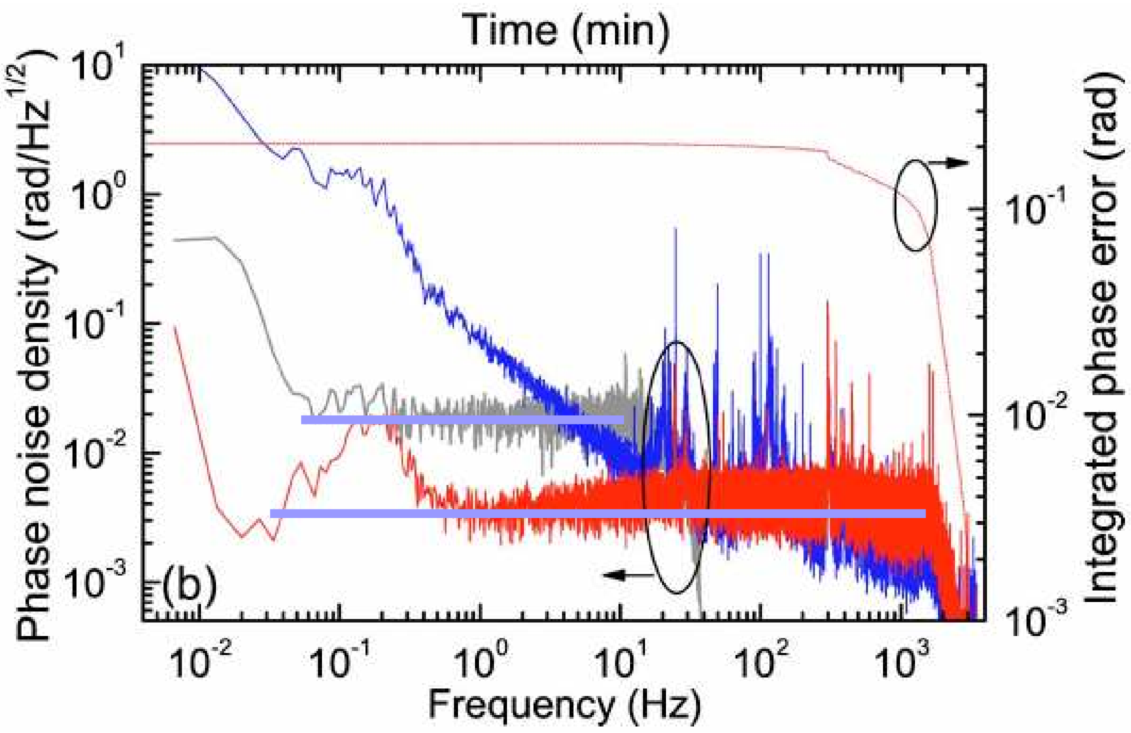
Opt. Express 14, 2497 (2006)

Noise spectrum analysis (II)

- Noise power spectral density : rad^2/Hz vs Hz (or in rad/Hz$^{1/2}$ vs Hz)
  - Example: 3 kHz multipass amplifier Opt. Lett. 33, 2545 (2008)

- Free running : blue
- Slow loop : grey
  - 5 ms integration
  - 115 mrad (10min)
- Fast loop : red
  - Single shot
  - 210 mrad (10min)
- Phase integration

$$\varphi_{CEP} = \sqrt{2\int_{f_{\min}}^{f_{\max}} PSD(f)df}$$

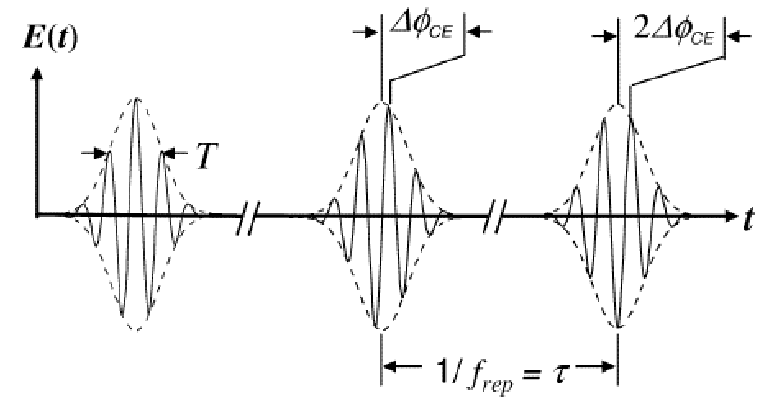


“white noise”
Along the whole BW

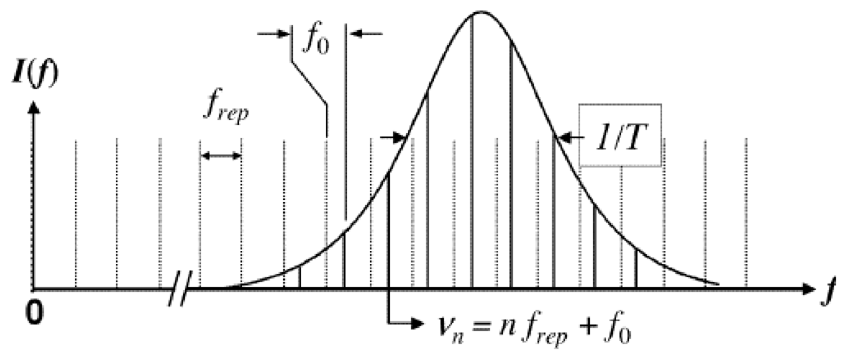
CEP in oscillators

CEP in oscillators

a) Time domain



(b) Frequency domain



IEEE J. Sel. Top. Quant. Electron. 9,1002 (2003)

$$f_0 = f_{rep}.\Delta\varphi_{CE}/2\pi$$

- Basic notions
  - $n(\omega_0)$ to $n_G(\omega_0)$ variations
  - f_0 is the pulse-to-pulse CEP slip rate
  - Pulse-to-pulse shifts are small

- When locked
  - f_0 constant $\rightarrow \Delta\varphi_{CE}$ constant slip rate, but absolute value?
  - Usually $f_0 = f_{rep}/\mathrm{N}$

Oscillators peculiarities

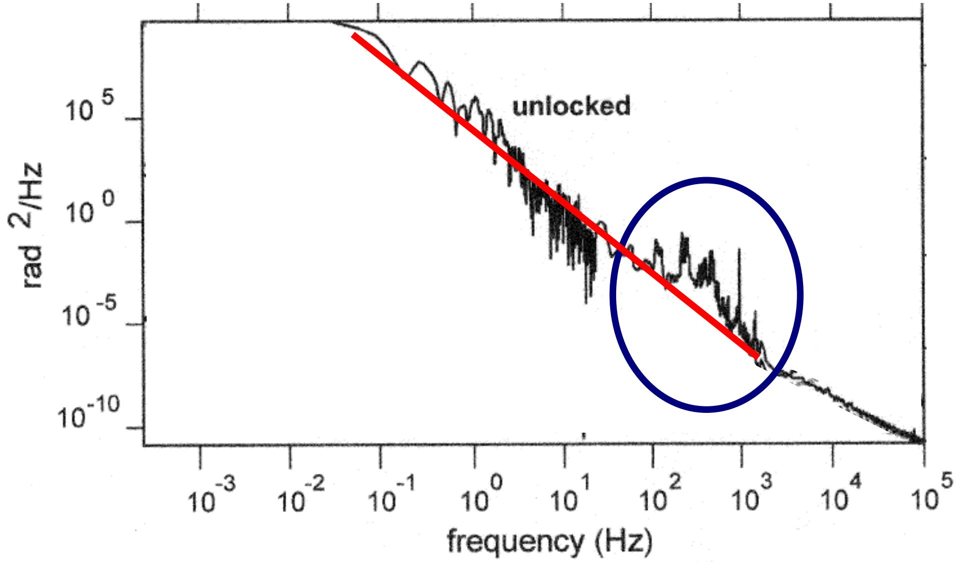
- Architecture
  - Cavity length
    - 6 m ↔ 25 MHz
    - 15 cm ↔ 1 GHz
  - Gain medium / Pump
  - Dispersion control
    - Prism
    - Chirp mirrors

- Experiments
  - Metrology
    - Frequency combs
    - Frequency synthesis
    - Octave spanning prismless cavities
  - Amplification seeding
    - 100 MHz - sub20fs

CEP noise sources in oscillators

- Common noise sources
  - Mechanical vibrations
  - Air pressure changes
  - Temperature changes

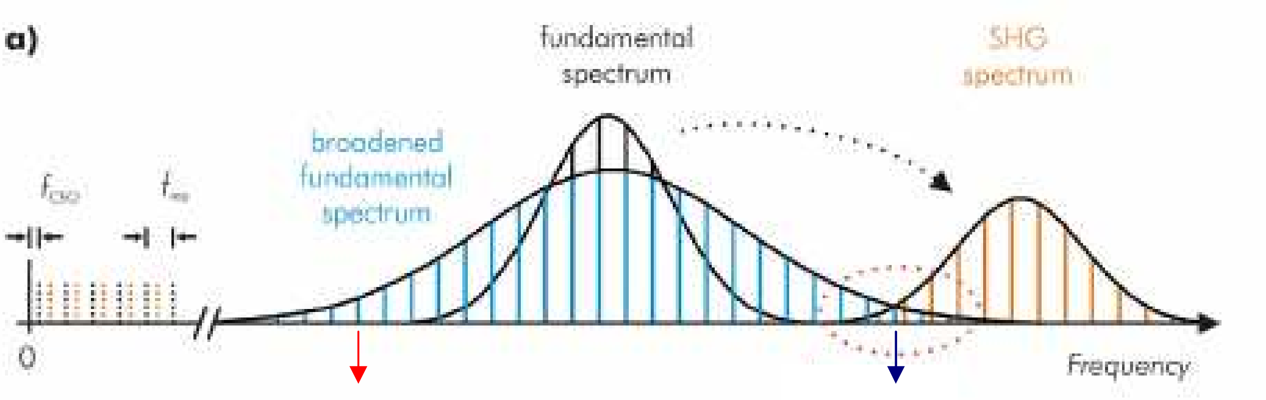
- Gain medium with Kerr Lens Mode locking
  - Amplitude-phase coupling Opt. Lett. 28, 851 (2003)



IEEE J. Sel. Top. Quant. Electron. 9, 1002 (2003)

CEP detection (I)

- f-2f interferometer
  - ☐ Spectral broadening
    - ν_n and ν_{2n}
    - CEP preserving?



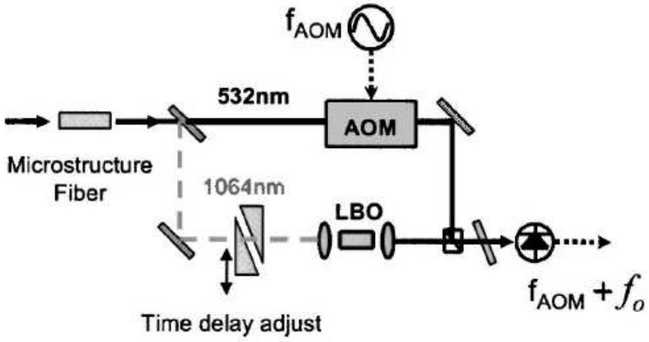
  - ☐ Frequency doubling of "red" part

    $\nu_n = n.f_{rep} + f_0 \rightarrow 2\nu_n = 2(n.f_{rep} + f_0)$

  - ☐ Beat note with "blue" part

    $2\nu_n - \nu_{2n} = 2(n.f_{rep} + f_0) - (2n.f_{rep} + f_0) = f_0$

    - Mach-Zehnder interferometer
    - Single point detection



J. Opt. Soc. Am. B 21, 1098 (2004)

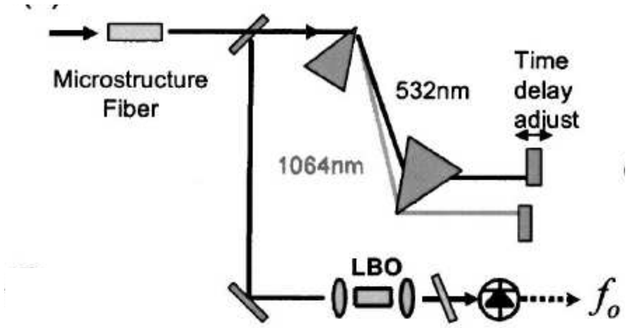
  - ☐ Self referencing: loss of absolute phase value

CEP detection (II)

- Broadening in PCF
  - AM/PM in fiber Opt. Lett. 27, 445 (2002)
  - Octave spanning oscillators

- MZ stability
  - Michelson Opt. Lett. 31, 1011 (2006)
    - Still bulky
  - Common path interferometer J. Opt. Soc. Am. B 21, 1098 (2004)
    - Small group delay compensation range
  - Wollaston prisms Opt. Lett. 35, 1209 (2010)
  - Stabilization Opt. Express 14, 9758 (2006)

- 2 steps in 1
  - Broadening + SHG in ZnO layers Opt. Lett. 27, 2127 (2002)
  - Broadening + DFG in PPLN Opt. Lett. 30, 332 (2005)
    - No fiber, no interferometer
    - Useful spectrum
    - <7fs pulses



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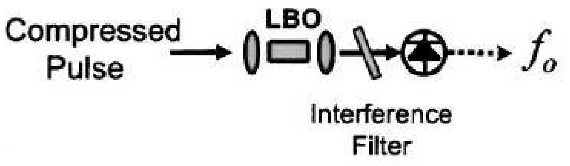


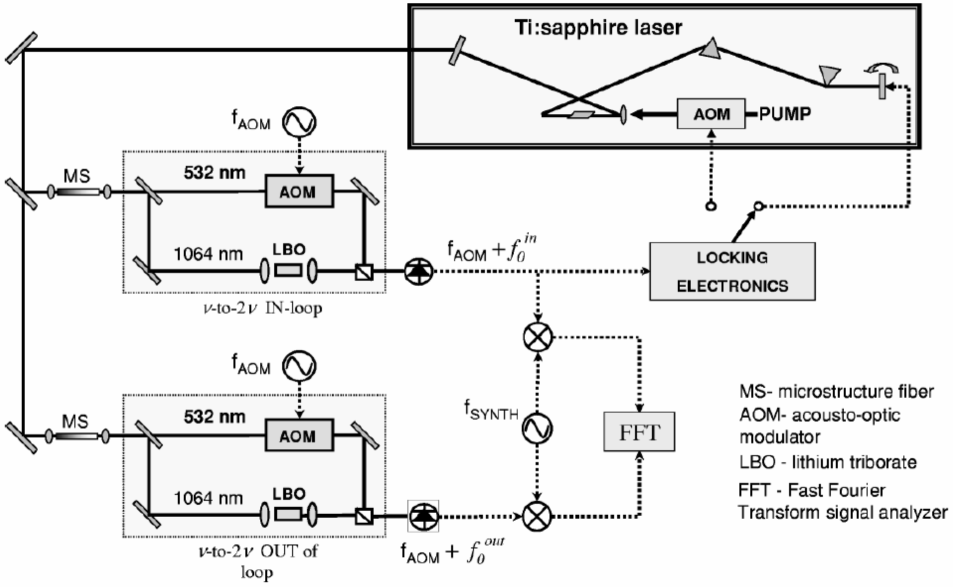
CEP detection (III)

- Quantum interference in semi conductors Opt. Lett. 30, 735 (2005)
    - Photocurrent detection (single- and two-photon absorption interferences)
    - Amplitude and direction proportional to relative phases
    - No amplitude/phase correlation
    - Low contrast

- Spectrally – spatially resolved interferometry Opt. Lett. 32, 3095 (2007)
    - Linear method
    - Low optical bandwidth and power
    - Long processing
    - Accuracy

Feedback

- Prisms
  - End mirror piezo tilting
  - Pros
    - Quiescent pump
  - Cons
    - Beam pointing
    - Feedback BW ~ 25 kHz
- Pump power
  - AO/EO modulation
    - Noise eater configuration
  - Pros
    - No dispersive elements
    - Feedback BW ~100 kHz
  - Cons
    - AM/PM coupling



IEEE J. Sel. Top. Quant. Electron. 9, 1002 (2003)

Some feedback results

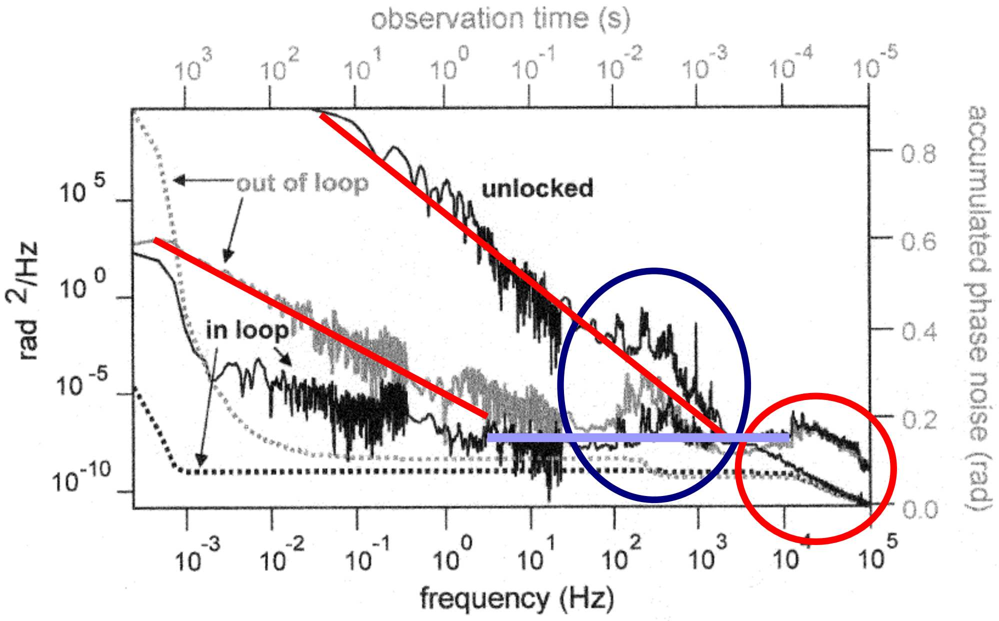
- Standard f-2f + prism feedback
  - ☐ 1 mHz – 100 kHz

    → 120 mrad
  - ☐ Out of loop analysis

    → 720 mrad
- PPLN + pump feedback
  - ☐ Out of loop analysis
  - ☐ 0.2 mHz - 35 MHz

    → 99 mrad
  - ☐ 1 mHz - 100 kHz

    → 72 mrad



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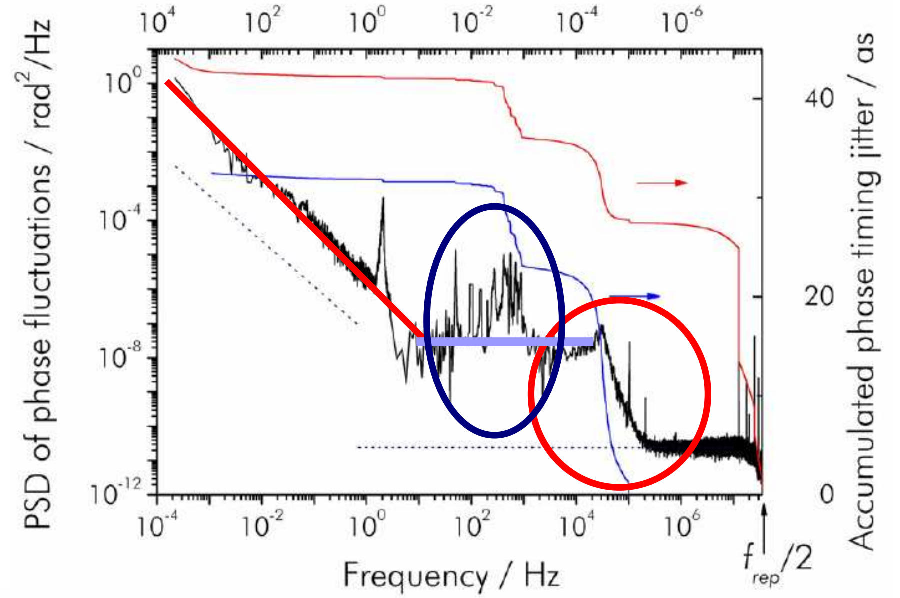
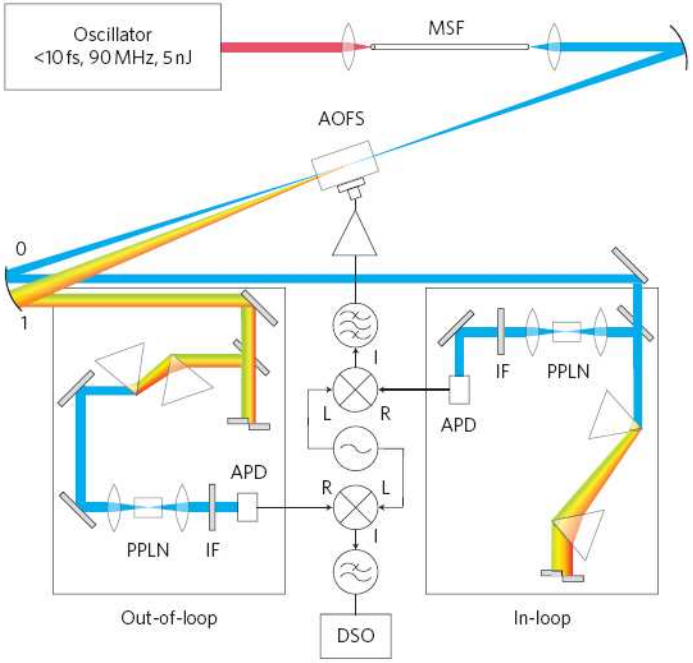


Laser Phys. Lett. 3, 37 (2006)

Feedforward

- Acousto-optical frequency shifter
  - Transmitted: f_0
  - Diffracted: $f_{AOFS} + f_0$
- “Feedforward” scheme
  - External stabilization
  - BW > MHz
  - Angular dispersion



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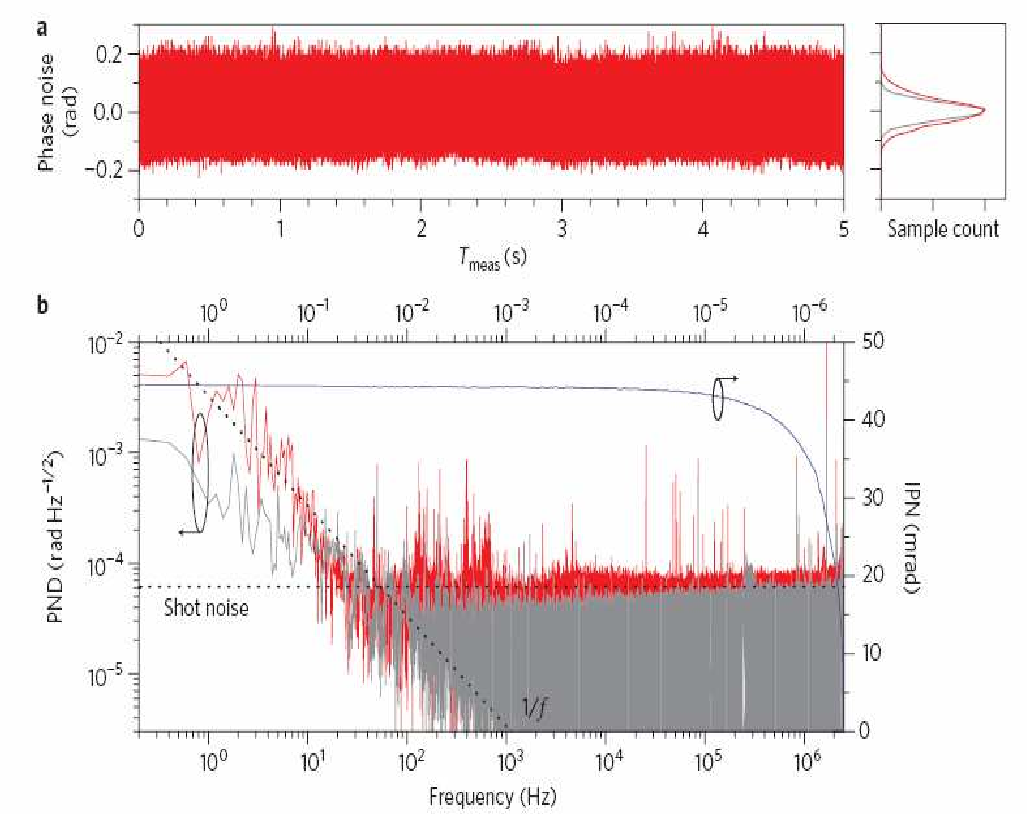


Nature Photon. 4, 462 (2010)

Conclusion on oscillators

- State of the art
  - You’d better use
    - Good mechanical and thermal isolation
    - No prism
    - Low noise single mode pump
  - Feedback on AOM / PPLN
    - 100 mrad rms
    - 0.2 mHz – 35 MHz
  - Feedforward
    - 45 mrad rms
    - 0.5 Hz – 2 MHz

2005
Nobel Prize

- Teams
  - Germany
    - Max Planck Institute (Garching)
    - Max Born Institute (Berlin)
  - USA
    - MIT
    - JILA
  - Companies
    - Femtolasers
    - Menlo Systems
    - Idesta QE

CEP in amplifiers

Amplifiers peculiarities

- Pulse picking
  - Aliasing
- Stretching
  - Bulk
  - Gratings
- Amplification
  - Regenerative cavity
  - Multiple passages
- Compression
  - Gratings
  - Chirp mirrors
  - Grisms
- Spectral broadening

- From the source
  - kHz – 20fs – >mJ

- To the experiment
  - kHz – sub10fs – <mJ

CEP noise sources in amplifiers (I)

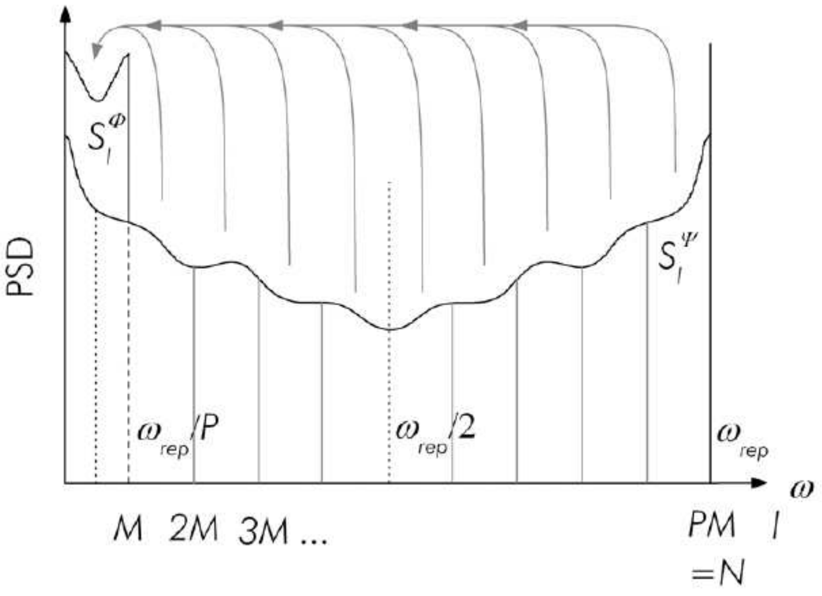
- Aliasing : sampling rate f_s: analysis up to $f_s/2$ (Nyquist)
  - In oscillators $f_s = f_{rep}$
  - In amplifiers $f_s = f_{rep}/P$
    - kHz → P = 80.000

- Where does the oscillator high frequency noise go?

→ Stacks in the amplifier Nyquist band

- Need for low noise CEP stable oscillators!

Opt. Lett. 30, 2487 (2005)



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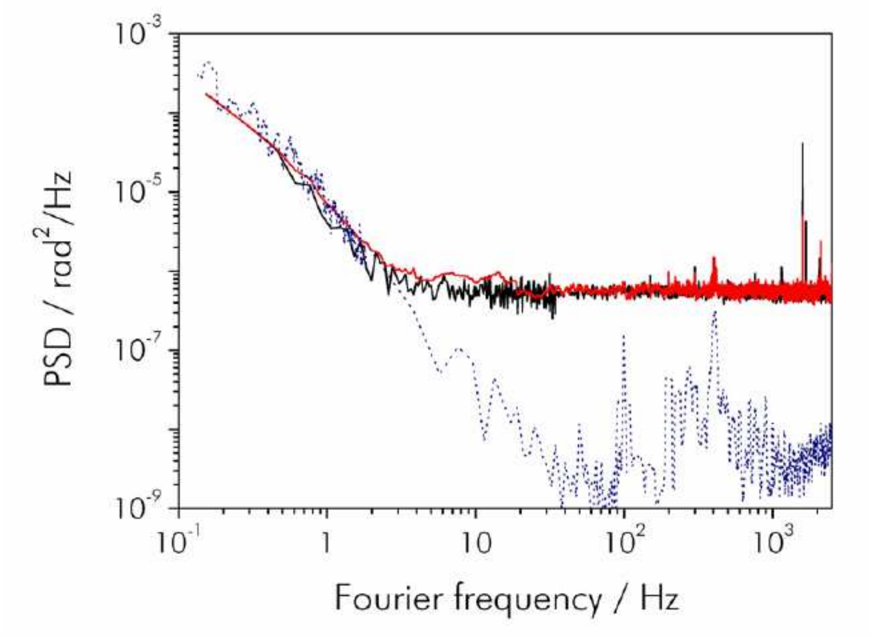


Blue : noise measured at f_{rep}
Black : noise measured at 5 kHz
Red : blue curve with aliasing effect

CEP noise sources in amplifiers (II)

- Dispersion management Appl. Opt. 45, 8350 (2006)
  - Mechanical stability
  - Beam pointing
  - Rather bulk systems than large devices with gratings
  - Low stretching/compression

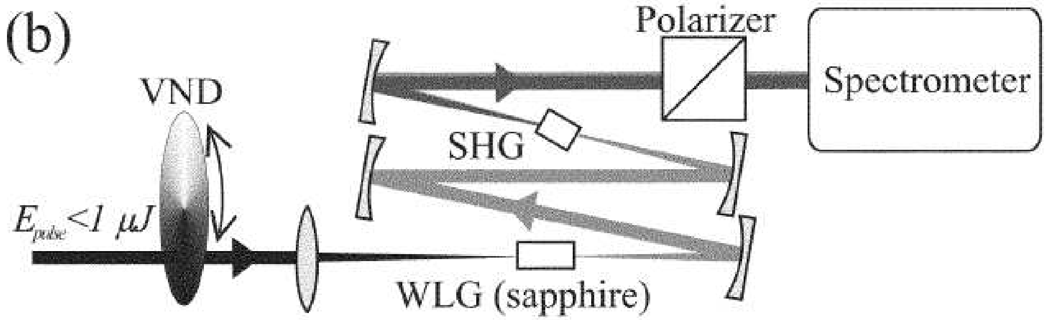
- Amplifier
  - Pump timing jitter
  - Thermal load – (cryo-)cooling
  - Repetition rate : potential bandwidth
  - Rather kHz rate DPSS pumps

CEP detection (I)

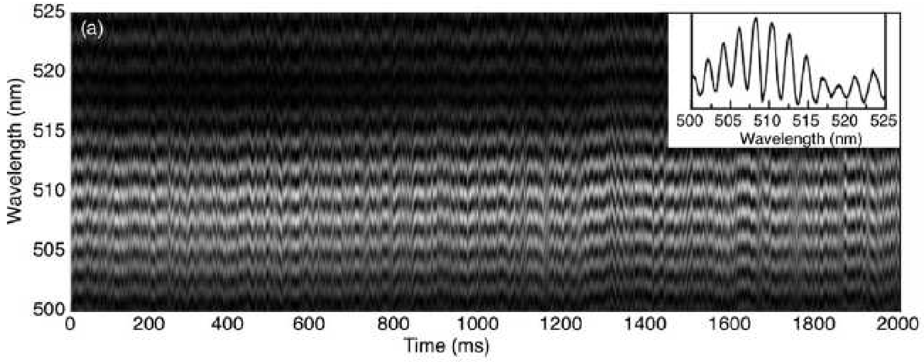
- Self-reference : f-2f Opt. Lett. 26,1436 (2001)
  - ☐ Spectral broadening
    - Sapphire or BaF_2 plate
  - ☐ Frequency doubling
  - ☐ FTSI

  - ☐ Low energy needed
  - ☐ Compact system

  - ☐ No absolute phase control
  - ☐ Continuum stability
  - ☐ Bandwidth issue Opt. Lett. 33, 2545 (2008)
    - Spectrometer integration time
    - Computer processing



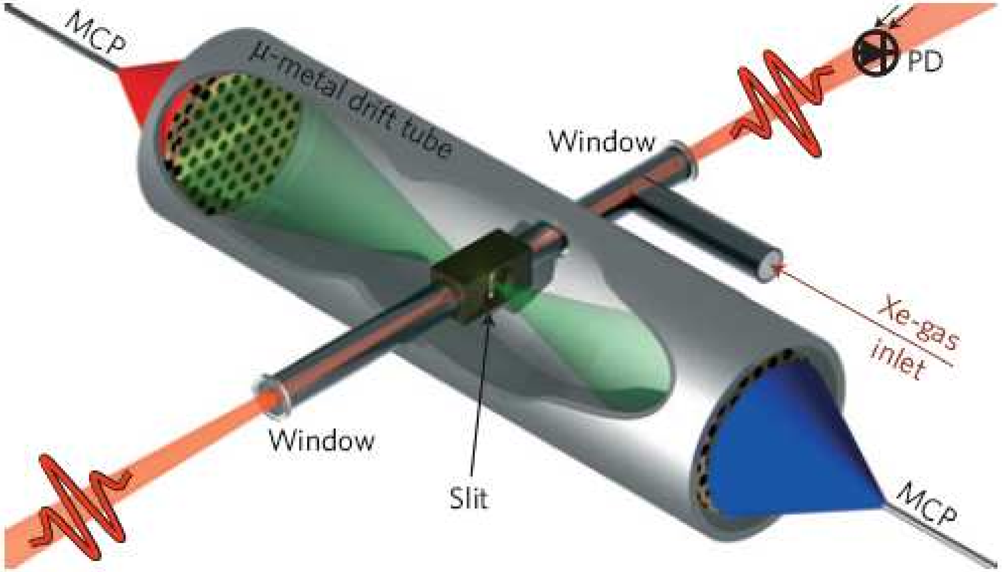
J. Sel. Top. Quant. Electron. 9, 972 (2003)



Opt. Lett. 34, 1333 (2009)

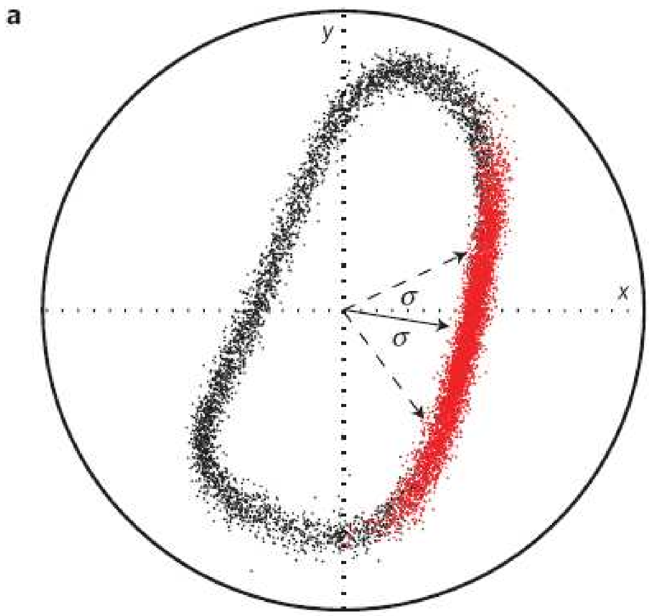
CEP detection (II)

- Above Threshold Ionization Nature 414, 182 (2001)
  - ☐ Photo-ionization + stereo time of flight measurement
  - ☐ Absolute phase
  - ☐ Non-intrusive measurement



CEP detection (II)

- Above Threshold Ionization Nature 414, 182 (2001)
  - Photo-ionization + stereo time of flight measurement
  - Absolute phase
  - Non-intrusive measurement
- Dual stereo-ATI Nature Phys. 5, 357 (2009)
  - True single shot
  - High precision (mrad)



CEP detection (III)

- Experimental derivations
  - Surface photoelectron emission Phys. Rev. Lett. 92, 073902 (2004)
  - THz emission spectroscopy Nat. Phys. 2, 327 (2006)
  - Half cycle cutoffs Nat. Phys. 3, 52 (2007)
  - …

- Usefulness?
  - Absolute phase
  - Single shot
  - Compactness (vacuum)
  - Pulses requirements (duration, energy)
  - Long processing

Good candidates for CEP characterization…

but not for feedback

CEP feedback

f-2f detection

- Oscillator pump power Nature 421, 611 (2003) / J. Sel. Top. Quant. Electron. 9, 972 (2003)
  - Crosstalk with fast loop

- Moving parts
  - Wedges
  - Stretcher Opt. Lett. 31, 3113 (2006)
  - Compressor Appl. Phys. B 96, 287 (2009)
  - Piezo actuation: slow, non-linear
  - Dispersion side effects

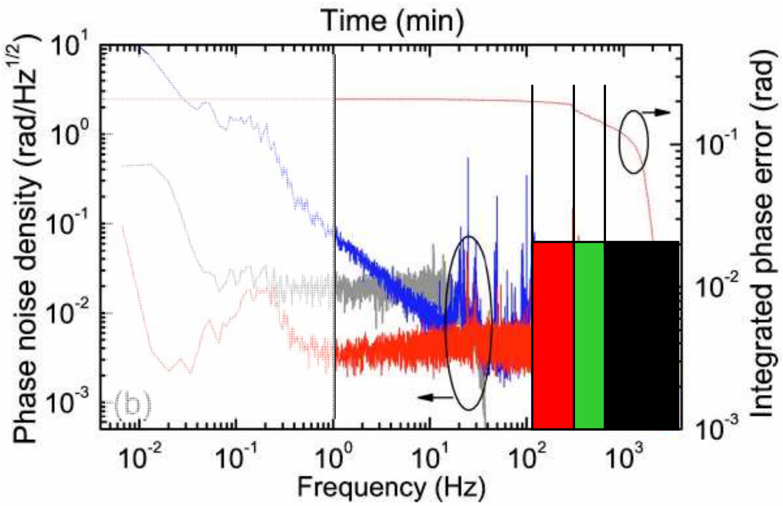
<250 mrad (20 Hz BW)

- AOPDF (Dazzler)
  - Longitudinal Acousto-optical pulse shaping Appl. Phys. B 99, 149 (2010)
  - Phase modulation

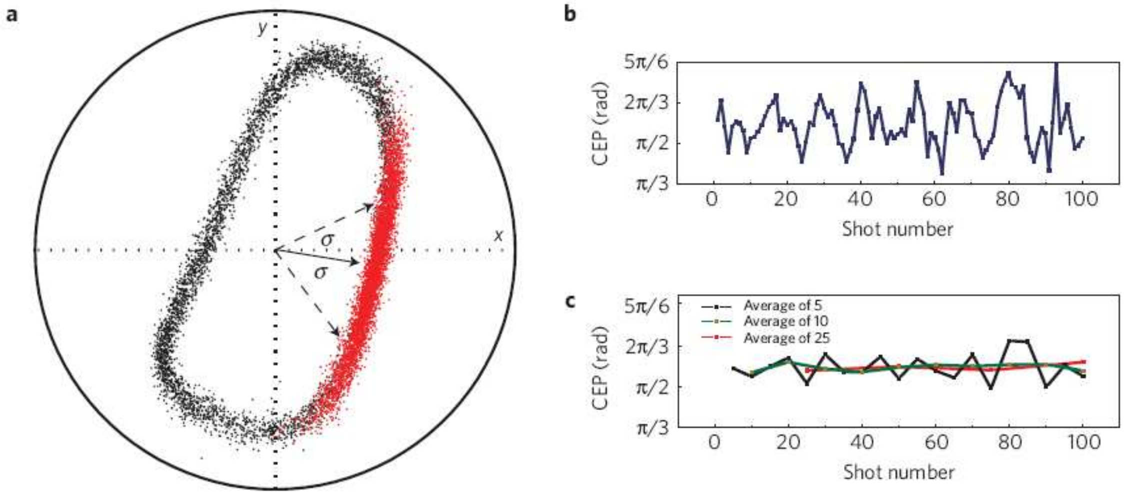
- Electro-optic modulation Opt. Express 19, 5410 (2011)

Results

- With the same laser…
  - Multipass config – 3 kHz – 25 fs – mJ



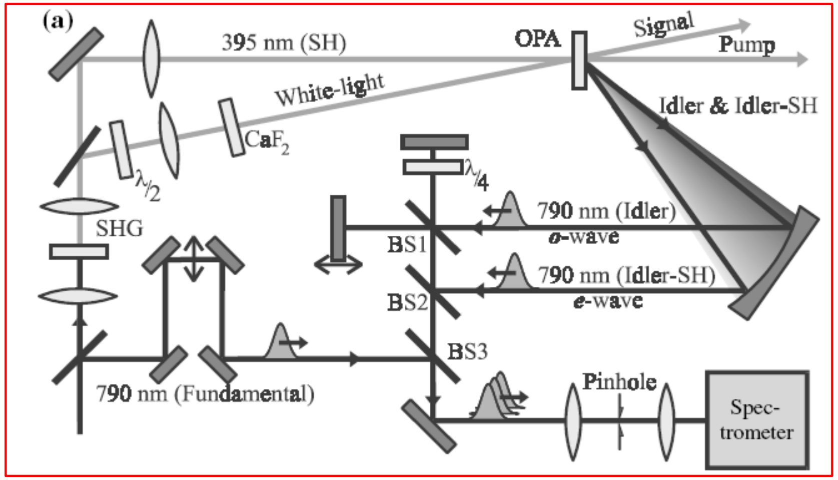
Red: single shot detection : 210 mrad (10 min)
Grey: CCD 5 ms integration : 115 mrad (10 min)



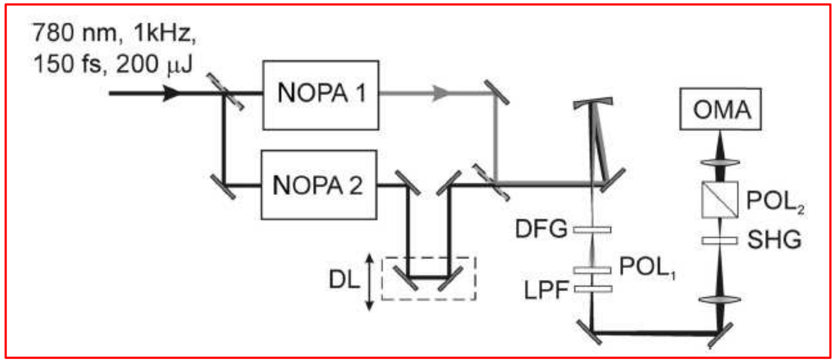
Red: single shot detection: 280 mrad (1.5 s)
Av 5: 195 mrad
Av 10: 140 mrad
Av 25: 110 mrad

CEP in OPAs

- Why (N)OPAs?
  - All optical
  - IR pulses generation for HHG
- Self stabilization with idler
  - Same source
    - $\varphi_I = \varphi_P - \varphi_S - \pi/2$
    - Idler angular chirp
  - DFG: inter pulse
    - Delay line stability
  - DFG: intra pulse
    - Ultrabroad band
  - Further amplification



Phys. Rev. Lett. 88, 133901 (2002)



Opt. Lett. 29, 2668 (2004)

few cycles @1.5-2 μm

~mJ

<250 mrad (few shot BW)

Conclusion

- Many sources, many experiments, many teams
  - (highly) CEP-stable oscillators needed
  - Detection
    - f-2f for feedback
    - more complicated apparatus for accurate detection
  - Feedback
    - Low bandwidth (<10 Hz) because of the detection
    - Actuators?
  - Be careful on what you see
    - 100-300 mrad @ what bandwidth?

Perspectives

Conclusion & perspectives

- Young science yet already astonishing performances
  - Many labs and companies involved
  - More turnkey systems
- Oscillators
  - Feedforward…
  - …SNR / detection / BW…
  - …down to <10 mrad over MHz BW
- Amplifiers
  - Detection schemes
  - Feedback BW

Thank you for your attention