An all-linear-optical technique for intracavity stabilization of CEP drift

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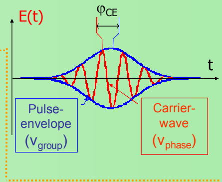
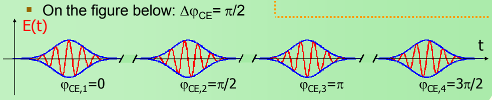
The definition of CEP and its drift

- Phase difference between the carrier wave and the peak of the envelope
- Symbol: φ_{CE}
- The CEP is drifting from pulse to pulse, unless we stabilize it [1]
- In the simplest case the phase increases always by the same amount: $\Delta\varphi_{CE}$
- On the figure below: $\Delta\varphi_{CE} = \pi/2$





Aim

To develop a new method, which is:

- **Linear**
- **Bandwidth independent**
- **Applicable to a wide range of lasers:**
  - **(sub-)picosecond lasers**
  - **Lasers with GHz repetition rates**
  - **UV and far infrared lasers**

Motivation

Use of CEP stabilized pulses

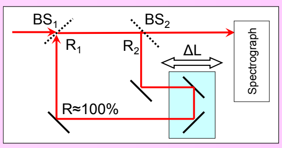
- High precision optical frequency-measurements (by stable "frequency-comb", "frequency-ruler" [1])
- Attosecond physics
- High precision refractive index measurement
- Calibration of astronomical mirrors

Usual methods of CEP drift detection [2]

- octave-spanning spectral bandwidth is essential;
- a nonlinear conversion step is required.

Theory

Dispersion of optical elements can be measured by a Fabry-Perot Interferometer (FPI) [5], from the spectral phase shift of ultrashort laser pulses. → Could be the initial phase, that is, CEP also determined?



- A very long resonant ring instead of FPI.
- Length almost equal to the oscillator cavity
- Spectral interference at the output

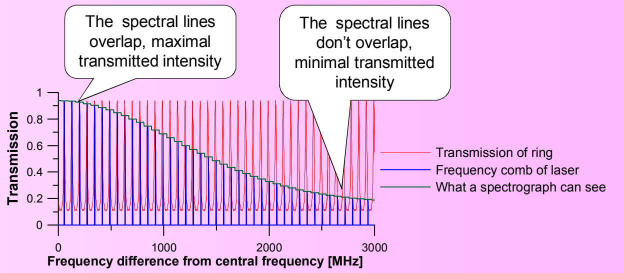
Transmission at a frequency ω

$$T(\omega)=\left[\left(\sqrt{T_1\cdot T_2}\right)\cdot\sum_{a=0}^{N}\left(\sqrt{R_1\cdot R_2}\right)^a\cdot\cos\left(\mathrm{mod}\left(\frac{a\cdot L\cdot\omega}{c}-a\cdot\Delta\varphi_{CE},2\pi\right)\right)\right]^2$$

where: L is the total optical length of the resonant ring at ω; T_1, T_2 transmission of the beamsplitters, R_1, R_2 reflection of beamsplitters, N is the number of round trips, when the pulse intensity goes below 1% of the initial.

Why the spectral transmission of the ring depends on CEP?

(This figure is for demonstration only, in reality one output spectral fringe is more than 10000 comb lines!)

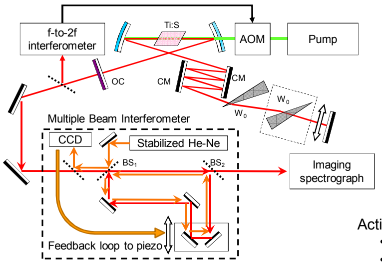


The principle of operation:

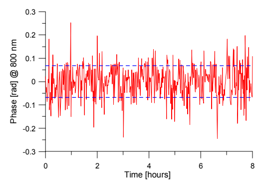
- Oscillator's frequency comb and the resonant ring transmission spectra consists of narrow spectral lines
- An aliasing effect occurs. (the oscillator spectrum is "sampled" at the transmission lines of the ring)
- Using a spectrograph with finite resolution we get a smooth spectral interference pattern
- If CEP shift changes, oscillator's spectral lines move, the spectral pattern moves together
- If repetition rate changes, the spectral pattern density and position changes, but can be compensated

Cross calibration with f-to-2f

Light source: A commercial Ti:S oscillator (10 fs, rep.rate 84.7 MHz, λ=803 nm, Δλ = 70 nm) with CEP stabilization. Cep shift measured by f-to-2f, tuned by an intracavity FS wedge pair



Active stabilization of the interferometer (calculated to phase noise at 800 nm)



Our interferometer

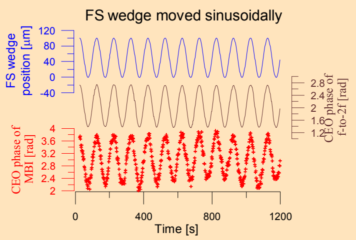
- very long resonant ring
- active length stabilization
- output: spectral interference pattern
  - fringe density ~ ΔL
  - fringe position ~ ΔL and CEP shift
  - evaluation by FFT

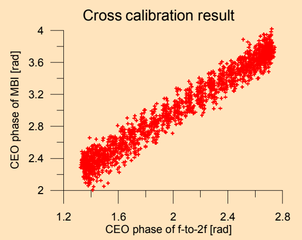
Active length stabilization details

- frequency stabilized He-Ne laser, 2D interference
- firewire CCD camera, 500 frame/second
- acoustic vibration of interferometer analyzed
- thermal expancion compensation by a piezo stage
- limits: ±1°C (sufficient in air conditioned laboratory)

Stability of 8.65 nm over 3.54 m (68 mrad of phase noise at 800 nm)

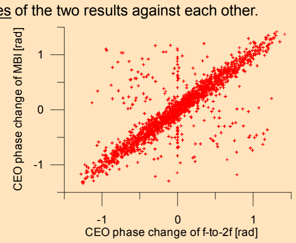
Cross calibration results





Conclusions:
1. The results of the two methods are correlated.
2. Our method can detect CEP shift CHANGES only, that's why the additive constant .
3. The previous limitation is not a problem for stabilization.

To challenge the interferometric method further, and remove all thermal effects, we made a measurement using random wedge positions. Then plotted the CEO phase changes of the two results against each other.



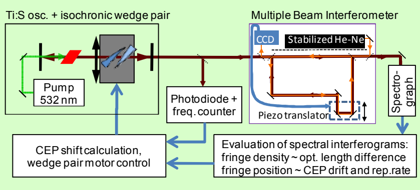
Conclusion: Good 1 to 1 correlation between the two methods

Intracavity stabilization of CEP shift

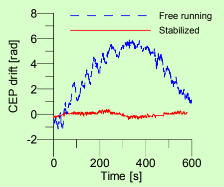
Isochronic wedge pair into a Ti:S oscillator's cavity (rep.rate 70.165 MHz, λ=790 nm, Δλ = 50 nm)

CEP shift tuning: 3.83 rad/mm, unwanted rep.rate tuning 0.68 Hz/mm (negligible)

Experimental setup, block diagram



Experimental results



Conclusion: Succesful CEP shift stabilization of ~ 140 mrad. The method works, but still needs minor revisions.

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