OPTICAL FREQUENCY MEASUREMENTS
AND
FIBER-BASED DISSEMINATION OF HIGHLY STABLE
OPTICAL REFERENCE FREQUENCIES

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• Introduction

• Optical frequency measurements using Ti:Sa Laser (Ca, Yb⁺)

• Fiber-based comb generators
  – setup and control
  – Transfer- Oscillator Principle
  – some applications of the Transfer Principle
  – comparison of two combs

• first steps to disseminate optical reference frequencies

• Summary and outlook
Femtosecond Laser as Frequency Comb Generator

Time domain:

Frequency domain:

\[ \nu_{\text{meas}} = \nu_{\text{ceo}} + m \nu_{\text{rep}} + \nu_X \]
Optical frequency measurement: Teamwork at PTB

- **Cs Fountain**
  - 5 MHz
- **H Maser**
  - 100 MHz
- **Wavelength Standards**
  - I$_2^-$ stabilized Laser
    - HeNe, Nd:YAG
  - NIR Laser
- **Microwave Standards**
  - 100 MHz
- **Optical Frequency Combs**
  - $\nu_{opt}$ in SI Hertz
  - 344 THz (871 nm)
  - 200 m Fiber Link
- **Reference Resonator**
- **SHG**
- **Yb$^+$ Trap**
  - 688 THz
  - 435.5 nm
  - Laser Control
  - Time Constant: 10… 30 s
  - 456 THz (657 nm)
  - 200 m Fiber Link
- **Reference Resonator**
  - Laser Control
  - Time Constant: 10… 30 s
- **Clock Laser**
- **HeNe, Nd:YAG**
- **NIR Laser**

**Optical Frequency Standards**
Measurement of the transition frequency of the Ca frequency standard

Ca-Frequency-standard 456 THz

Comparison frequency chain / frequency comb

Primary Standard Cs-fountain 9.2 GHz

ν_{Ca} = 455,986,240,494,000 Hz

\frac{u(\nu_{Ca})}{\nu_{Ca}} = 1.2 \cdot 10^{-14}
Measurement of the transition frequency of the $^{171}$Yb$^+$ single ion frequency standard

new comparison of two traps: uncertainty $<10^{-15}$

$\nu_{\text{Yb}}^+ = 688 \, 358 \, 979 \, 309 \, 311 \, \text{Hz} \pm 6.2 \, \text{Hz}$

$\frac{u(\nu_{\text{Yb}}^+)}{\nu_{\text{Yb}}^+} = 9 \cdot 10^{-15}$
• Continuous operation of a Ti:Sa fs-comb over more than several hours is cumbersome to achieve.

• Several computer controlled servo loops are required for continuous operation over days.
New Results with Er: Fiber Comb

- $f_{\text{rep}} \approx 100$ MHz
- $<P> \approx 8 / 100-200$ mW
- $\Delta t \approx 85$ fs
- $\lambda_{\text{central}} = 1568$ nm


Long term drift of optical resonator

- Absolute frequency measurements are limited by the short time stability of the microwave reference.

\[ \sigma_y(\tau) = 4.5 \cdot 10^{-13}/\tau + 5 \cdot 10^{-16} \cdot \tau \]
Can we do better?

For optical Oscillators with lesser noise than a H- Maser

The Measurement of a Frequency Ratio avoids the „noisy“ unit Hz!
Transfer-Oscillator Principle

\[ \nu_1 = (\nu_{CEO} + \Delta_1) + m_1 \times f_{rep} \]

\[ \Delta_1 \]

\[ \nu_{CEO} \]

\[ \nu_A = \nu_{CEO} + \Delta_1 = \nu_1 - m_1 f_{rep} \]

\[ \nu_B = (\nu_{CEO} + \Delta_2) \times m_1 / m_2 = (\nu_2 - m_2 f_{rep}) \times m_1 / m_2 \]

\[ \nu_2 = (\nu_{CEO} + \Delta_2) + m_2 \times f_{rep} \]

\[ \nu_C = \nu_A - \nu_B = \nu_1 - m_1 f_{rep} - (\nu_2 - m_2 f_{rep}) \times m_1 / m_2 \]

\[ \nu_C = \nu_1 - \nu_2 \times m_1 / m_2 \]

Independent of \( f_{REP} \) and \( \nu_{CEO} \)!

\( \nu_C \) corresponds to a beat signal between arbitrary reference frequencies \( \nu_1 \) and \( \nu_2 \).

Applications of the Transfer Principle

• **Determination of sources of technical / phase noise**

• **Direct stabilization of NIR laser**
  - to H-maser reference
  - to optical reference
  allows to transfer the stability of an optical reference to an other laser
    - Optical Synthesizer
    - Spectroscopy of atomic transitions with microwave precision
    - The Ultimate Master Laser!!

• **Direct comparison of optical oscillators without additional noise due to fs comb**

• **Dissemination of optical reference frequencies via fiber network (Telecom)**
Determination of technical noise/ phase noise contributions

\[ \nu_{\text{meas}} = \nu_{\text{f rep}} + \nu_{\text{CEO}} + \nu_X \]

\[ \nu_{\text{transfer}} = b * \frac{\nu_{\text{CEO}} + \nu_X}{c} / \nu_{\text{HMaser}} \]

A/D converter (soundcard)

\[ \nu_{\text{meas}} / \nu_{\text{HMaser}} = (\nu_x) / c \]

Synth. 11.4GHz

PLL

predivider

DDS

a beatnote of \(~3\) kHz

@ \(\nu_{\text{virtual}}\) of 1.4THz
Beat note between H maser and ECDL @ 1,4 THz

Measurement of the frequency RATIO Ca/ H Maser

Noise of H Maser at 1,4 THz
Direct Stabilization of NIR Fiber-Laser to H-Maser Reference

\( v_1 = 194 \text{ THz} \)

\[ \sigma_y(2, \tau) = 2.5 \cdot 10^{-13}/\tau \]

\( v_2 = 456 \text{ THz} \)

\[ \sigma_y(2, \tau) = 9 \cdot 10^{-15}/\tau \]

Digital PLL

 PLL

DDS: \( / (m_2/m_1) \)

PLL

 \( \nu_{\text{C}} \)

Digital PLL

HMaser

100 MHz

Synth. 11,4GHz

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Applications of the Transfer Principle

- Determination of sources of technical / phase noise
- Direct stabilization of NIR laser to H-maser reference
  - Optical Synthesizer
  - Spectroscopy of atomic transitions with microwave precision
- Direct stabilization of NIR laser to optical reference
  - All Optical Synthesizer
- Transfer of the stability of one optical reference to an other laser
  - The Ultimate Master Laser!!
- Direct comparison of optical oscillators without additional noise due to fs comb
  - Collaboration between MPQ Garching, Univ. Konstanz & PTB
  - Where are the limits of the comb?
Comparison of two independent fiber combs

\[ \nu_1 = \nu_c + \nu_2 \times \frac{m_1}{m_2} \]

PTB Comb

RF-Reference H-Maser

10m SMF28

MPQ Comb

Transfer beat \( \nu_c \)

cw-Fiber Laser

\[ \nu_1 = 194 \text{ THz} \]

\[ \nu_2 = 456 \text{ THz} \]
Comparison of two independent fiber combs

\(<\text{PTB}\rangle = (4462194,769 \pm 0,40) \text{ Hz}\)

\(<\text{MPQ}\rangle = (4462194,772 \pm 0,46) \text{ Hz}\)

\(<\text{Difference}\rangle = (-0,0052 \pm 0,001) \text{ Hz}\)

2.5 \times 10^{-16}
Comparison of two independent fiber combs

Drift: $-5.28(68) \, \mu\text{Hz/s}$

$3 \times 10^{-20} / \text{s}$
Some possible sources of frequency error

**temperature drift**
- fiber @1.5 mm
- mixer (phase comparator)
- cable @100 MHz

**VoltageStandingWaveRatio**

**relative frequency offset**
- ≈1*10^{-20} @ 0.1 K / h
- < 1*10^{-15}
- < 1*10^{-20}
- < 4*10^{-16}

**rate of temp change**: 0.5 K / d

**absolute delay PTFE**: 250m*4ns /m

**relative change PTFE**: 6*10^{-5} / K
## Applications of the Transfer Principle

- Determination of sources of technical / phase noise
- Direct stabilization of NIR laser to H-maser reference
  - Optical Synthesizer
  - Spectroscopy of atomic transitions with microwave precision
- Direct stabilization of NIR laser to optical reference
  - All Optical Synthesizer
- Transfer of the stability of one optical reference to an other laser
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- Direct comparison of optical oscillators without additional noise due to fs comb
- **Dissemination of optical reference frequencies via fiber network (Telecom)**
Dissemination of optical reference frequencies by fiber

- Microwave Link
  - Microwave-over-fiber
    - Information is contained in modulation frequency of optical carrier ( @ 1,5µm )

- Optical Link
  - frequency-standard-over-fiber
  - fs-laser-over-fiber
    - Transfer of the repetition rate of a modelocked laser @ 1,5 µm
  - cw laser @ 1,5µm
    - Information is contained in carrier frequency

- LPTF/ SYRTE -->LPL
  - 2 x 43 km Telecom Fiber
  - 100 MHz AM 1,55µm Laser
  - $\sigma_y$: few $10^{-14}@ 1s$
    - $4•10^{-17}@ 5•10^4s$

- JILA / NIST 6,9 km BRAN
  - JILA / NIST
    - $\sigma_y$: $4•10^{-14}@ 1s$
    - $2 x 3,5 km BRAN$
    - 100 MHz AM 1,55µm Laser
    - $\sigma_y$: $2,4•10^{-13}@ 1s$
      - $<1•10^{-14}@ 10^4s$
Comparison of two independent optical frequency standards by optical fiber link

\[ \Delta \nu_{cw} = \nu_2 \times \frac{m_1}{m_2} - \nu_4 \times \frac{m_3}{m_4} + (\nu_{c1} - \nu_{c3}) + \delta \nu_{\text{link}} \]

\( \nu_1 = \nu_{c1} + \nu_2 \times \frac{m_1}{m_2} \)

\( \nu_3 = \nu_{c3} + \nu_4 \times \frac{m_3}{m_4} \)

\( \nu_2 = 456 \text{ THz} \)

\( \nu_4 = 688 \text{ THz} \)

Comb 1

Yb

Transfer beat \( \nu_{c1} \)

cw-Fiber Laser

\( \nu_1 = 194 \text{ THz} \)

Comb 2

Transfer beat \( \nu_{c3} \)

cw-Fiber Laser

\( \nu_3 = 194 \text{ THz} \)

Fiber Link

\( \Delta \nu_{cw} = \nu_1 - \nu_3 \)
Dissemination of an optical frequency beat signal with fiber comb after propagation in 25 km fiber reel

- Preliminary
- No significant broadening
- No significant degradation of signal to noise ratio
Standard SMF28: Thermal-induced delay change: 7 ppm / °C

Relative frequency change for a 25 km Fiber Reel

-3.4°C

Time constant = (- 3.1 ± 0.3) h
Summary

• Femtosecond lasers are universal tools for optical frequency measurements and allow a phase coherent link to the primary standards of time and frequency.
  – the results of an optical frequency measured with two combs agree within $<3 \times 10^{-16}$ in a period of 10h.
  – long term stability is limited by thermal drifts (solvable technical problems).
  – continuous operation is demonstrated over 84 h.

• Using the transfer concept
  – optical frequency standards in different spectral regions can be compared without additional noise due to the comb.
  – precise optical frequencies can be disseminated by optical fiber network.
plans for the near future

• new long term measurements (Ca, Yb⁺) < absolute and ratio using fiber combs>
• extend the transmission line from 25 to 100 km
• establish a phase stabilization of the fiber link
• exploring our approach at a real telecom fiber network (fiber test bed)
• explore the possibility of a link between Braunschweig and Hannover
• and finally between Paris and Braunschweig
Optical frequency measurement: Teamwork at PTB

- Microwave Standards
  - A. Bauch
  - S. Weyers
  - R. Wynands

- Optical Frequency Standards
  - Yb⁺ Trap
    - Chr. Tamm
    - T. Schneider
    - E. Peik
  - Ca Trap
    - U. Sterr
    - C. Degenhardt
    - G. Wilpers

- Optical Frequency Combs
  - G. Grosche
  - B. Lipphardt
  - fs Frequency-Combs