Comb-locked frequency-swept synthesizer for ultra-precision long distance ranging

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OSA Optical Sensors and Sensing Congress 21 July 2021 SW4E.3

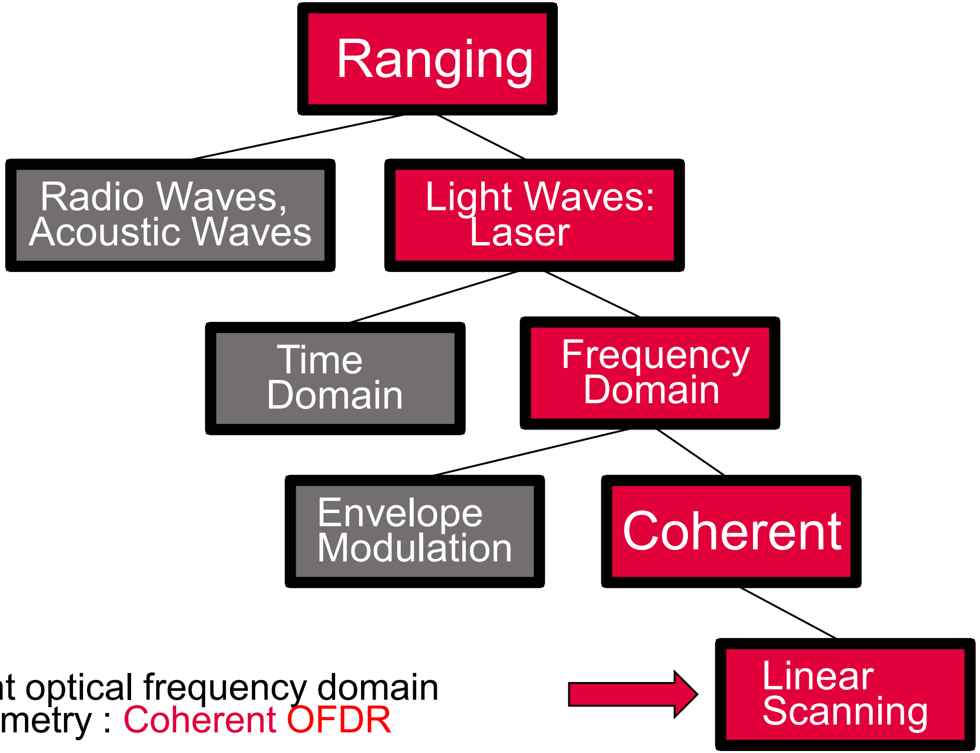
TOPTICA Photonics AG

All Wavelengths.
190 nm - 0.1 THz

Content

- OFDR principle and limitations
- The comb-locked frequency-swept optical synthesizer
- The ranging experiment
- Results and outlook

Ranging techniques



Coherent optical frequency domain Reflectometry : Coherent OFDR

OFDR : principle

confidential

- Linear laser frequency scan
- Building the beat signal from the reference and the measured path
- The beat frequency f is defined by the scan slew rate γ and a delay difference between the reference and the measured path τ :

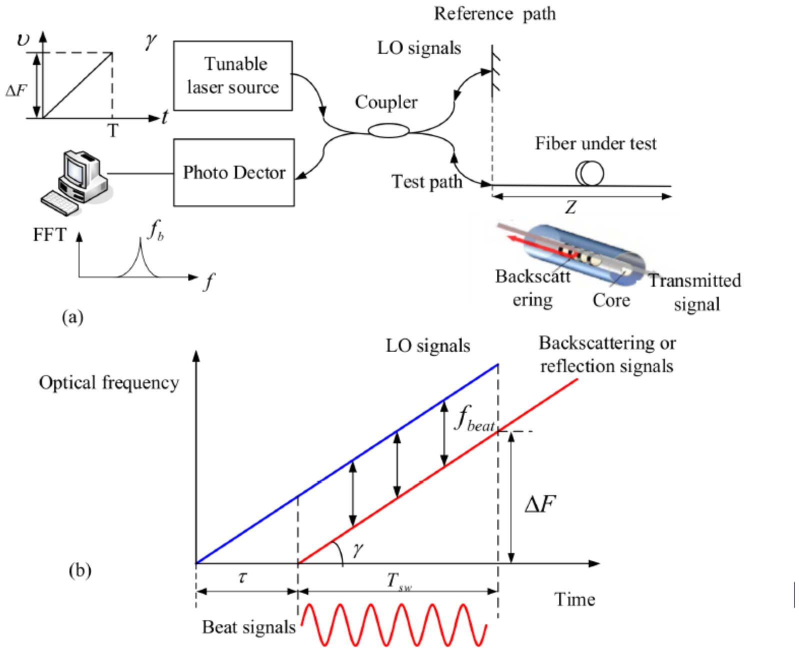
$$f = \gamma * \tau = \gamma * (2x / (c/n)) \qquad (1)$$

where
x – single pass distance, *c* – speed of light,
n – refractive index

- Solving for distance : (2) $x = fc / (2\gamma n)$

Benefits:

- High sensitivity
- High resolution



Distributed Optical Fiber Sensors Based on Optical Frequency Domain Reflectometry: A review

Zhenyang Ding [1,2,3,*], Chenhuan Wang [1,2,3], Kun Liu [1,2,3,*], Junfeng Jiang [1,2,3], Di Yang [1,2,3], Guanyi Pan [1], Zelin Pu [1] and Tiegen Liu [1,2,3]

OFDR : resolution

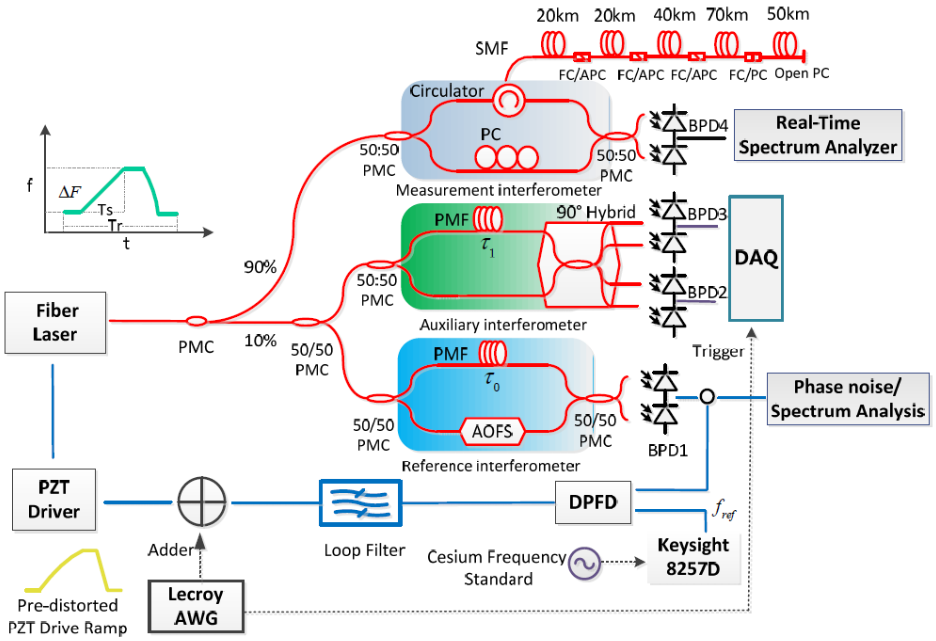
Resolution is the figure of merit for many sensing applications.

- transform limit : laser frequency scan range
- linearity and frequency noise
- dispersion correction

Here we focus on linearity and frequency noise.

OFDR : state of the art

Methods to boost the OFDR resolution using combination of methods.



Ultra-long range optical frequency domain reflectometry using a coherence-enhanced highly linear frequency-swept fiber laser source

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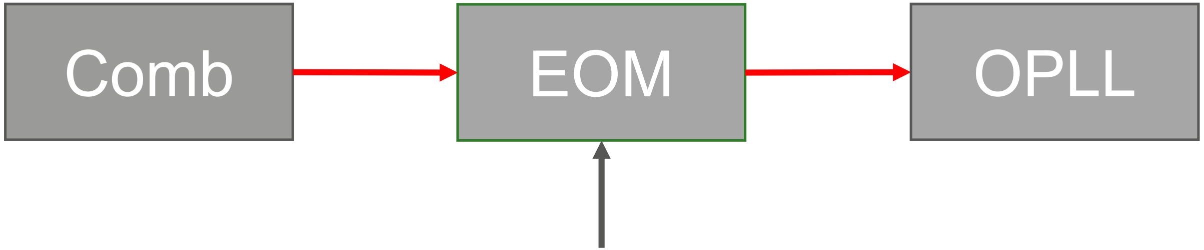
Optical synthesizer : proved applications

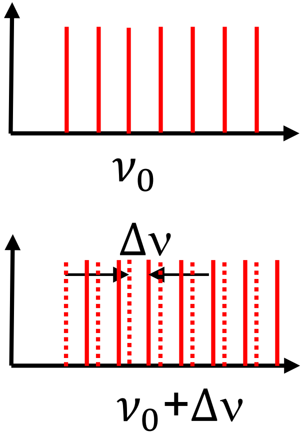
R. Gotti, et al, “Comb-locked frequency-swept synthesizer for high precision broadband spectroscopy,” *Sci. Rep*. 10(1), 2523 (2020).

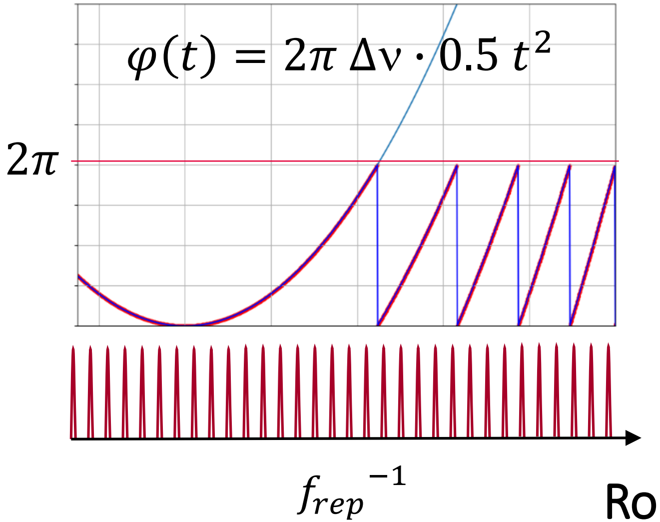
T. A. Puppe, Y. Mayzlin, J. Robinson-Tait and R. Wilk, "Comb-locked Frequency-domain terahertz spectrometer," *2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, Paris, France, 2019, pp. 1-1, doi: 10.1109/IRMMW-THz.2019.8874007.

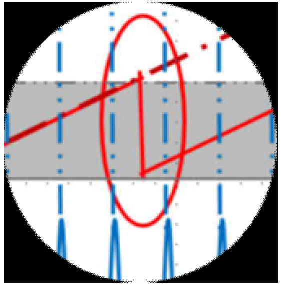
Optical synthesizer : principle



$$\nu = \nu_0 + \underbrace{\frac{1}{2\pi}\frac{\delta\varphi}{\delta t}}_{\Delta\nu}$$

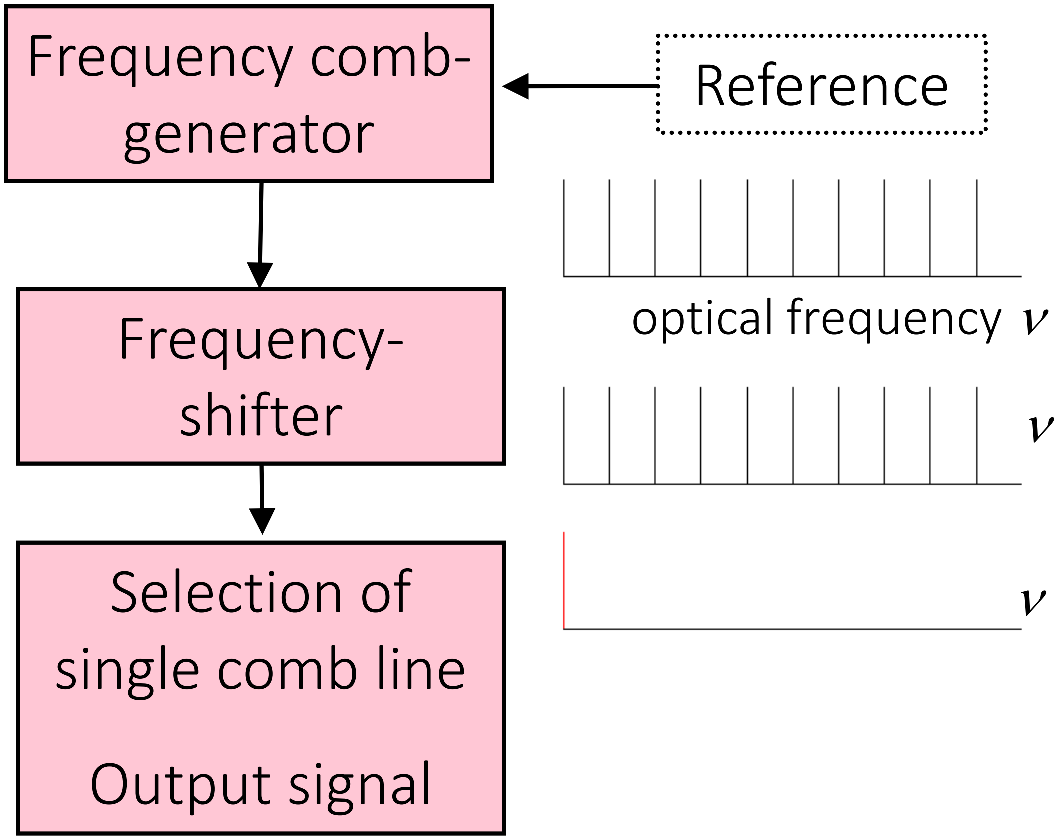






Rohde et al. Opt. Lett.,39, 4080 (2014)

Optical synthesizer : principle



- Precision
- Fixed phase relation to reference

- Precision
- Tunability
- Agility

- Single frequency output signal

DE102010022585 (B4)

Optical synthesizer : advantage

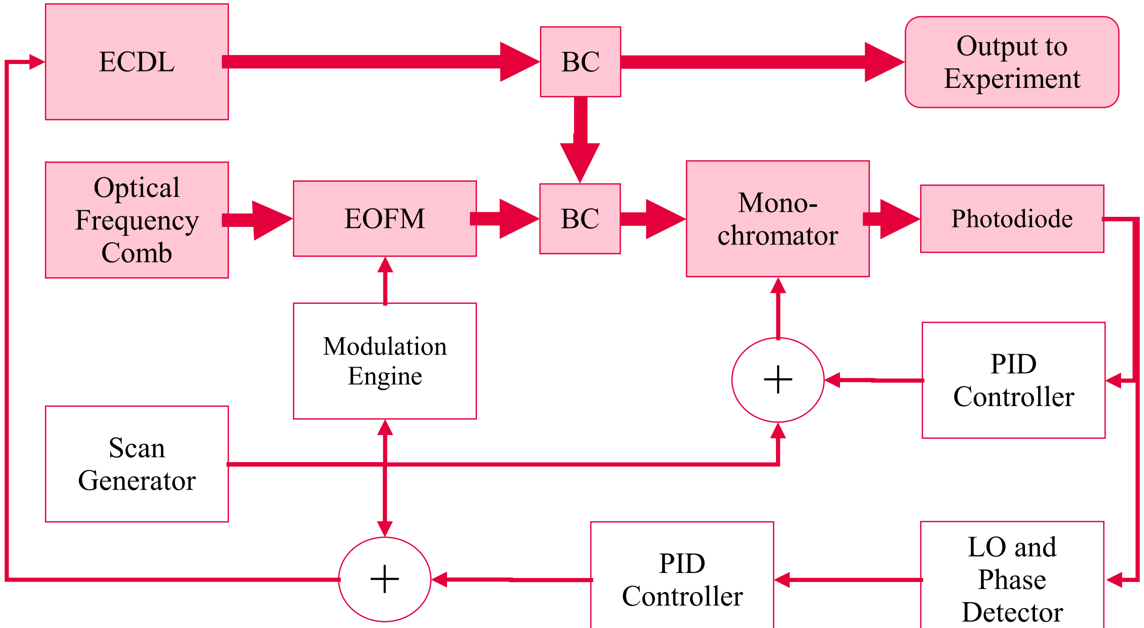
- the scanning cw laser is permanently phase-locked to the frequency comb and inherits its low phase noise and precision

- the comb's intrinsic constant mode spacing allows a strictly linear scan

- locking the comb allows absolute measurement that is traceable to the frequency standard

- the scan can be on the fly adopted for various measurement conditions

Optical synthesizer : diagram



Optical synthesizer : components

components from Toptica Photonics AG:

- continuously tunable laser CTL1550

- mode locked oscillator : the heart of the DFC CORE

- Some dedicated optics,

  electronics,

  and software

Optical synthesizer : Features

- central wavelength ~ 1570 nm

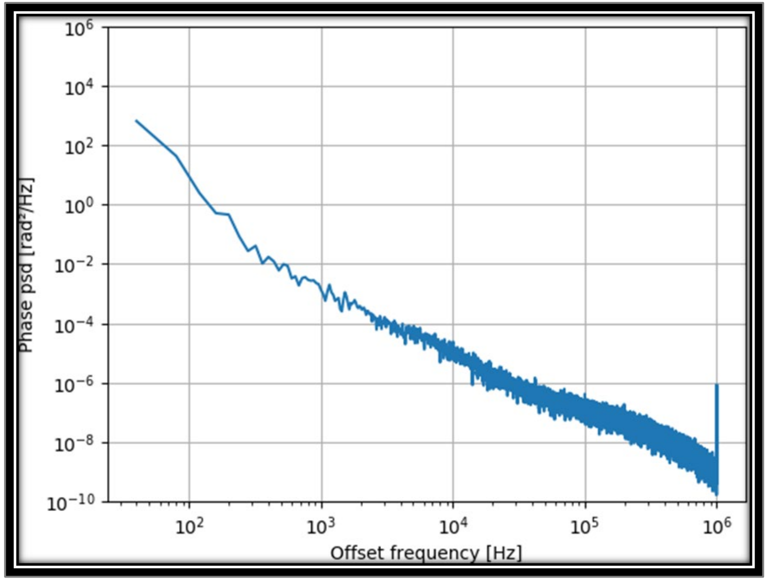
- frequency range ~ 10 THz : mode hop free

- frequency resolution   < 0.1 Hz

- scanning speed 100 kHz/s … 1 THz/s

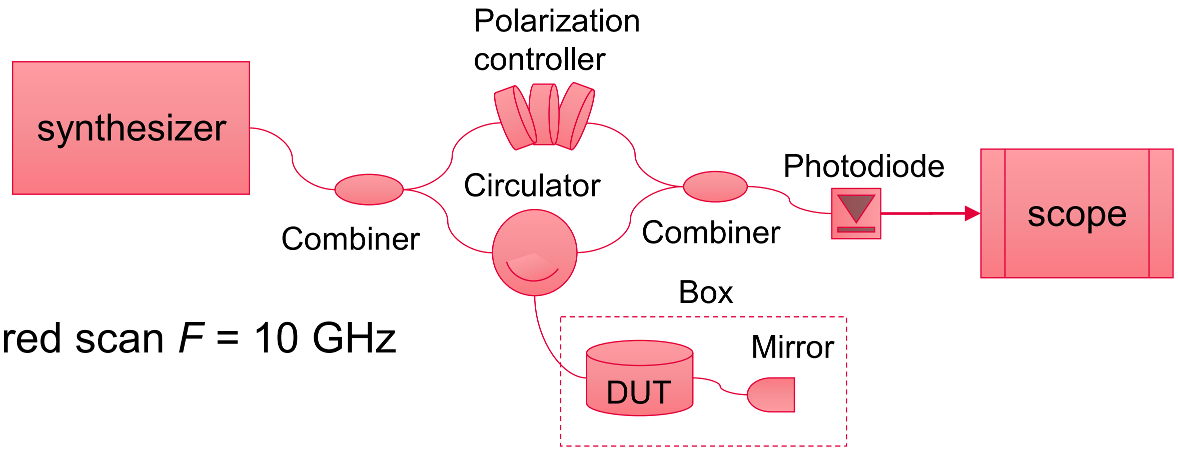
- scanning form : saw tooth, triangle

- slew rate modulation for dispersion correction



phase noise density by free running mode locked laser

Experiment : setup and parameters



Slew rate γ ~ 0.5 THz/s

Capture time T = 20 ms - > captured scan F = 10 GHz

Transform limit:

$dx0 = c/(2Fn)$ = 0.3e9/(2 * 10e9 * 1.5) = **10 mm**

Dispersion limit (@ fiber dispersion k = 30e-9 (1/GHz):

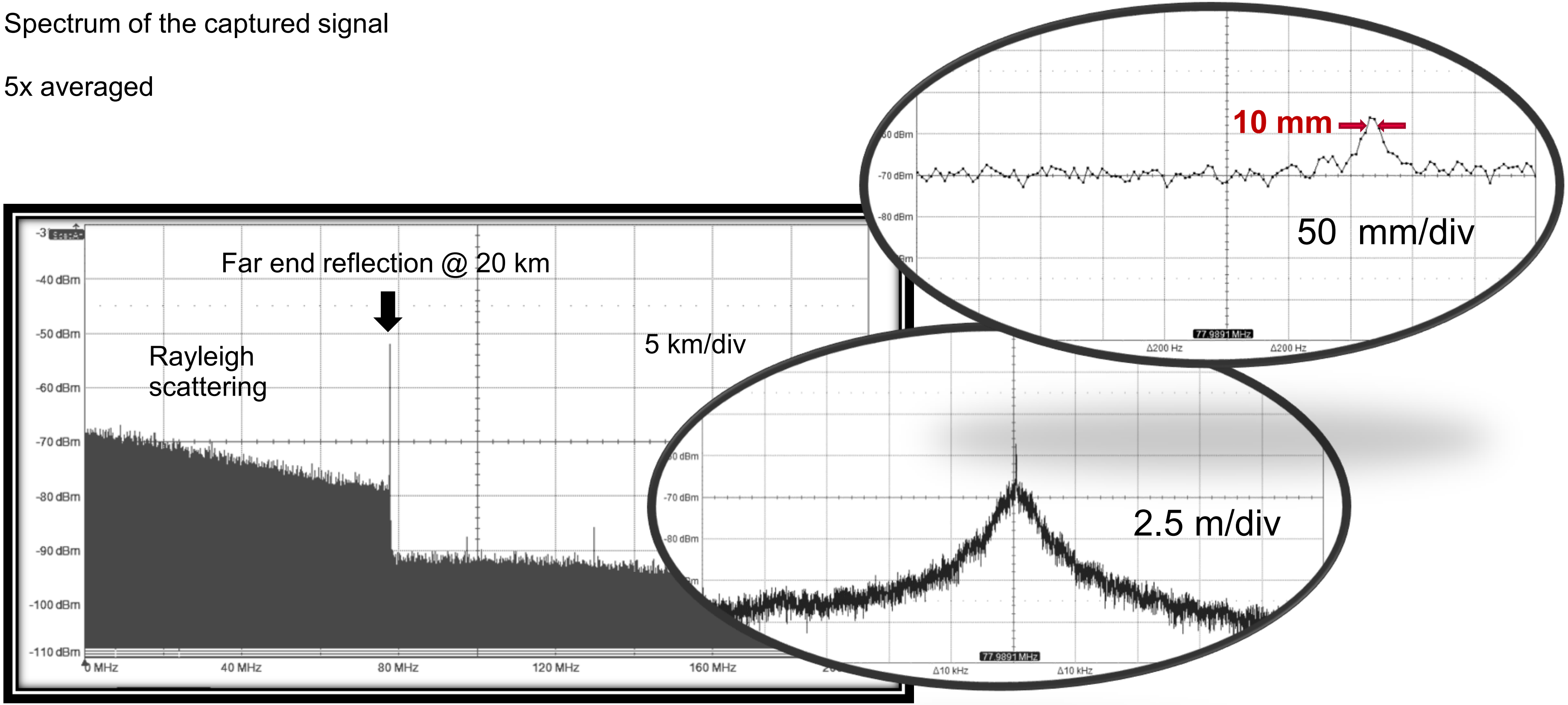
$dx1 = 2xkF$ = 2 * 20e3 * 30e-9 * 10 = **12 mm**

The DUT is a standard single mode fiber spool with the length about x = 20 km.

Experiment : discussion

Spectrum of the captured signal

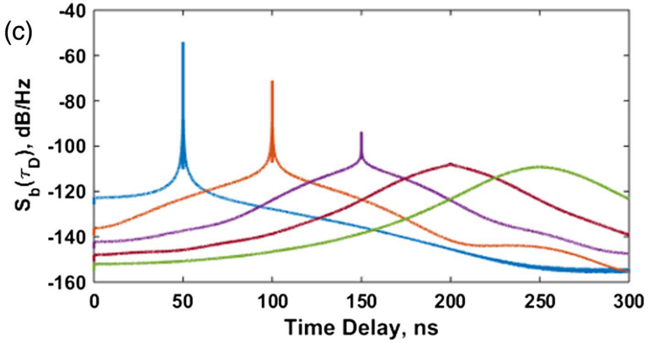
5x averaged



Experiment : discussion

At large distances the low frequency phase noise is the limiting factor.

Solution : comb stabilization



Phase-noise model for actively linearized frequency-modulated continuous-wave ladar

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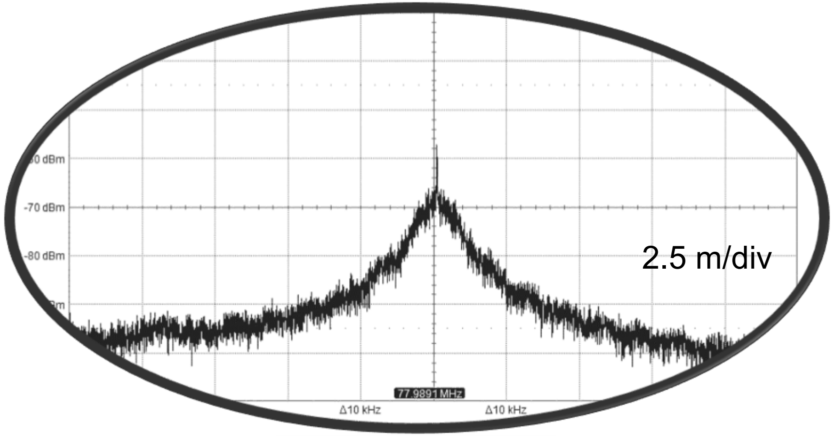

Experiment : conclusion and outlook

The optical synthesizer is suitable for OFDR
resolution of 10 mm at 20 km distance in fiber
to our knowledge, it is 14 times better as the best reported up-to-date.

In current experiment only 0.1 % of available synthesizer scan range is utilized.
At the given oscillator noise, the large possible scan range is advantageous for shorter distances.

Locking the comb to a frequency standard allows for traceable absolute distance measurement.

Wide scan could allow for atmosphere dispersion correction as in dual band systems.

The main challenge for product development is to identify features for certain application.

Experiment : conclusion and outlook

We are looking forward to feedback
on possible application challenges.

Thank you for your attention!