AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE

Closed-loop stabilization of propagation delay in fiber-optic links

concept and realization

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Agenda

- ***Introduction***
- ***Unidirectional transfer***
- ***Closed-loop concept and typical aproaches***
  - ***CW***
  - ***modulated carrier***
- ***Architecture with matched electronic variable delay – lines***
- ***Variable delay – line structures***
- ***ASIC design, simulation and layout***
- ***Measurement results of fabricated chip***
- ***Performance of the closed - loop system (I)***
- ***Design shortcomings***
- ***Performance of the closed - loop system (II)***
- ***Conclusions, future plans***

Introduction

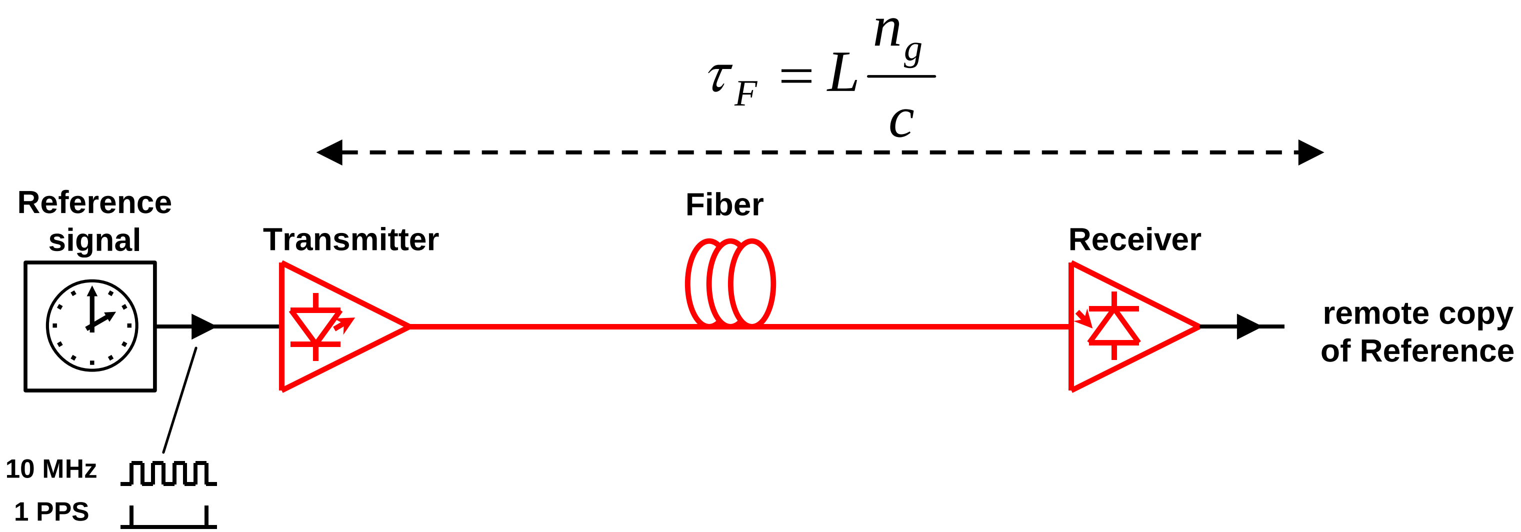
Our goal:

Delivery of precise time/frequency reference signal
to the **remote** laboratory

The problem:

varying propagation delay of the transmission
channel

Unidirectional time/frequency transfer



$$\Delta\tau_F = \frac{L}{c}\frac{\partial n_g}{\partial T}\Delta T_{FIB} + \frac{Ln_g}{c}\frac{\partial L}{L\partial T}\Delta T_{FIB} + \frac{L}{c}\frac{\partial n_g}{\partial \lambda}\Delta\lambda_{LAS}$$

Fundamental accuracy limit: temperature dependence of the fiber propagation delay.

$$\tau_F = f(T) = f(t)$$

Unidirectional time/frequency transfer expected performance

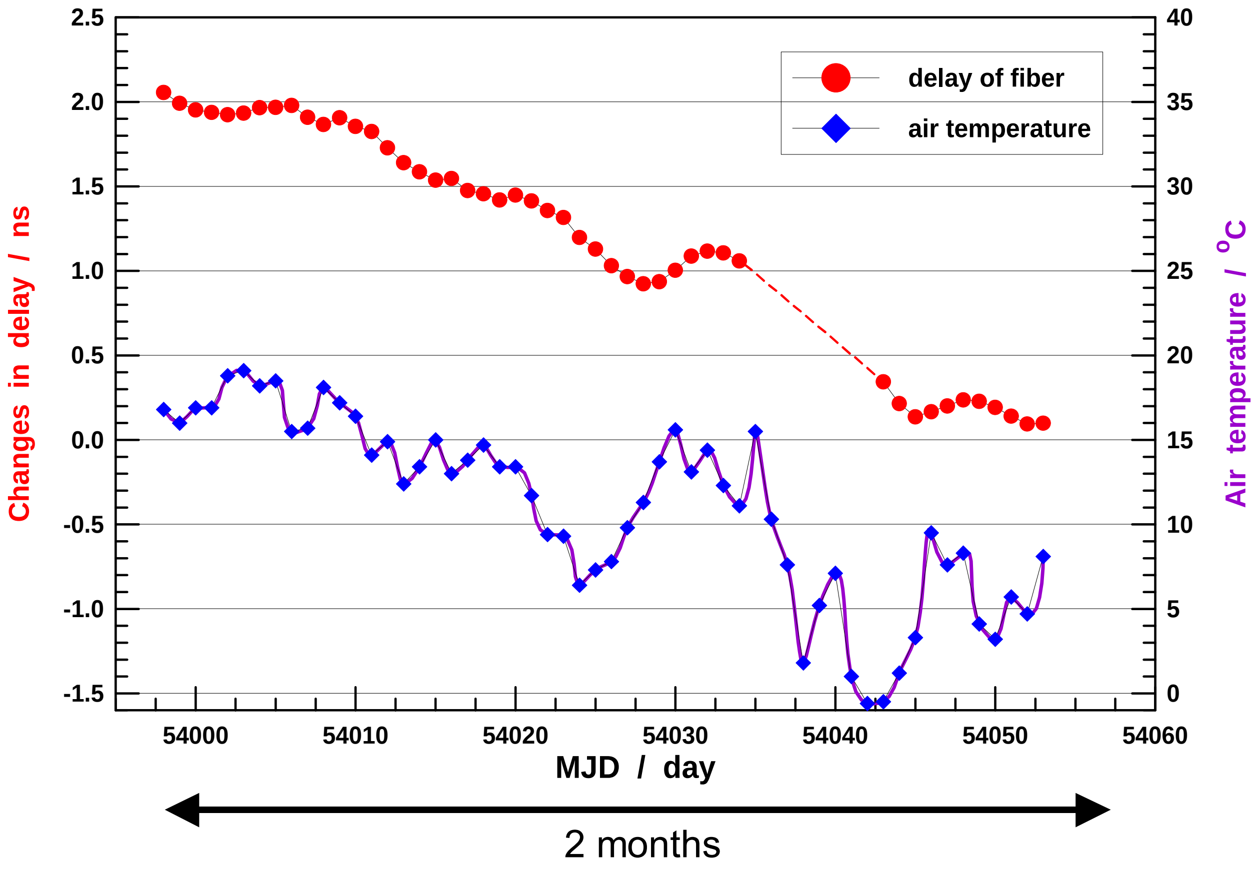
Our measurements results:

Fiber type	Fiber length [km]	λ [nm]	Temperature sensitivity [ps/(K·km)]
SMF-28	12	1550	**36.80**
		1310	**37.97**
SMF-DS	20	1550	**38.67**
LEAF	20	1550	**37.97**

$\Delta\tau_F$ = **39 ps/(K·km)** - worst-case thermal coefficient

For 3 km link:
diurnal temperature variations ~1°C ➡ $\Delta\tau \sim 0.12$ ns ➡ TIE ~ $1\cdot10^{-15}$
seasonal temperature variations ~20°C ➡ $\Delta\tau \sim 2.4$ ns ➡ TIE ~ $7\cdot10^{-17}$

Real – live example

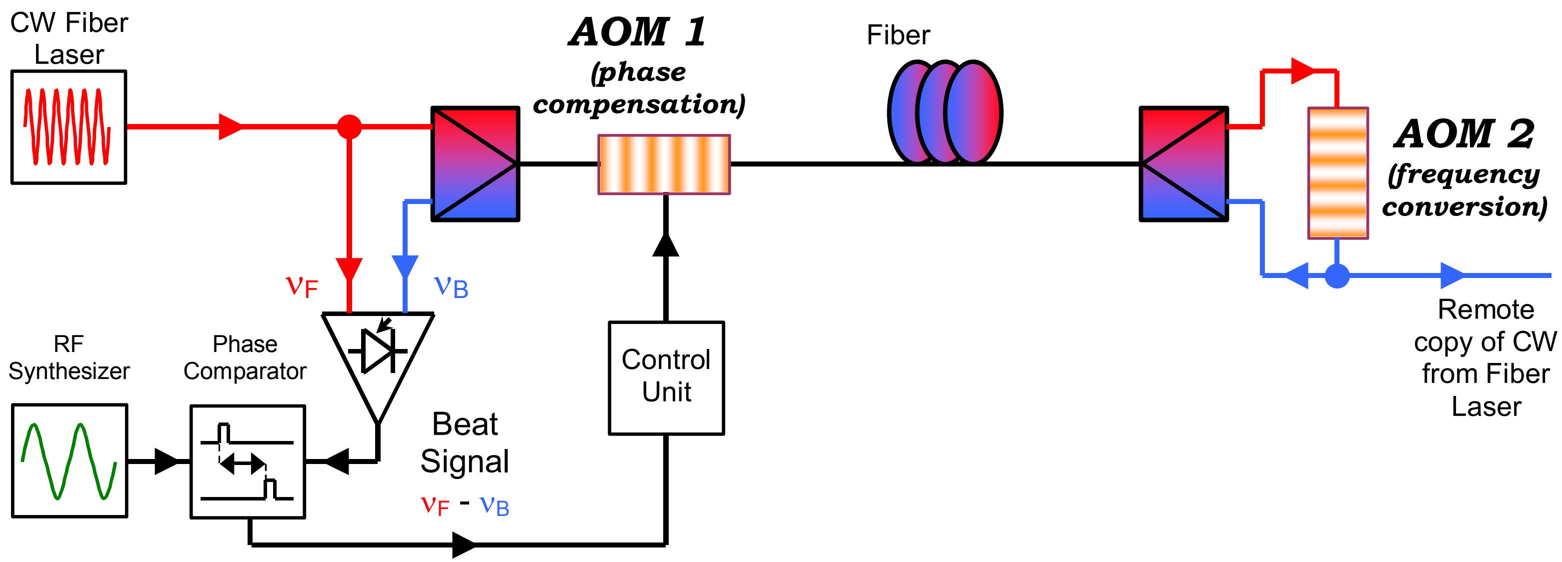


Two-month measurement of 3 km-long fiber propagation delay variation (by Laboratorium Czasu i Częstotliwości, Główny Urząd Miar)

Typical approach to delay stabilization

CW system

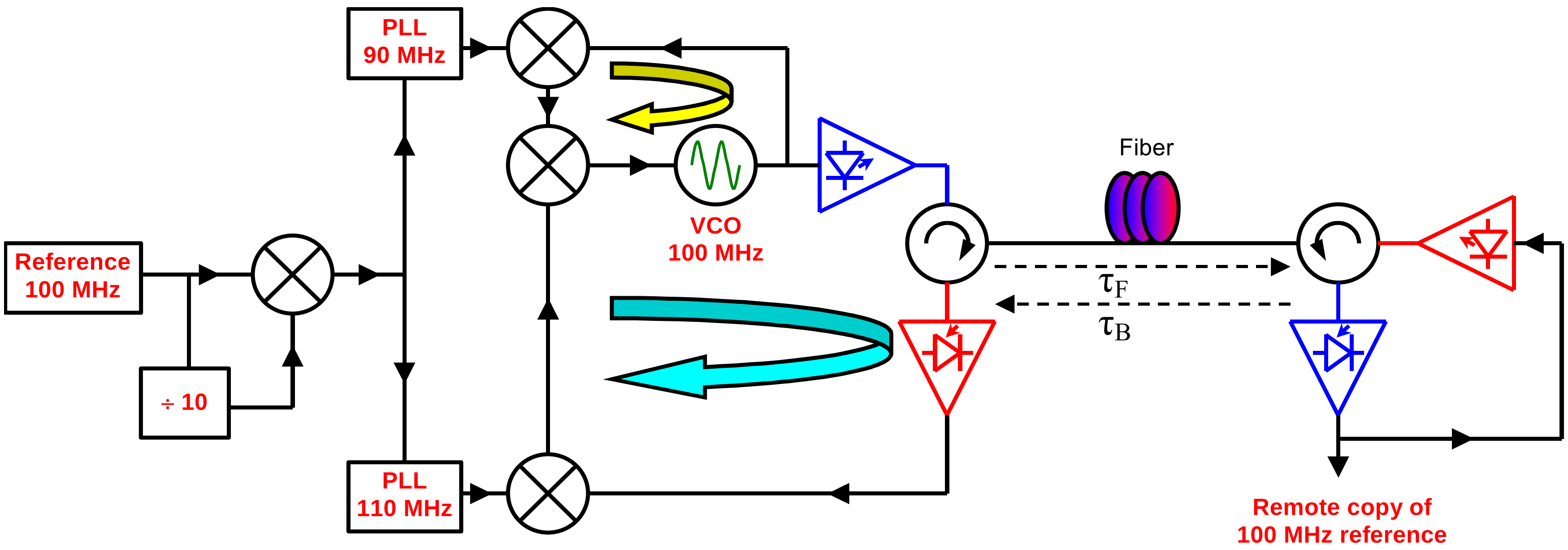
LNE-SYRTE (France), PTB (Germany)



Typical approach to delay stabilization

modulated carrier system

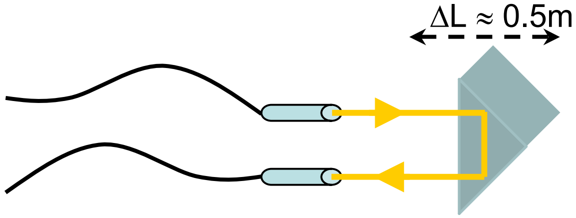
LNE-SYRTE (France)



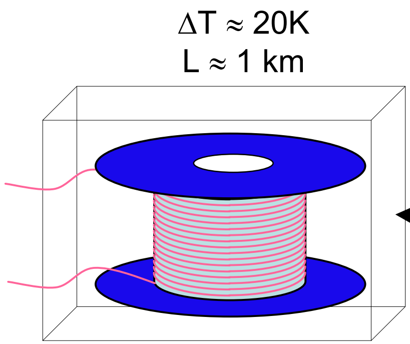
Typical approach to delay stabilization

modulated carrier system

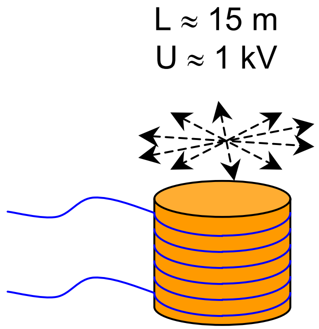
LPL (Paris), NIST (USA)



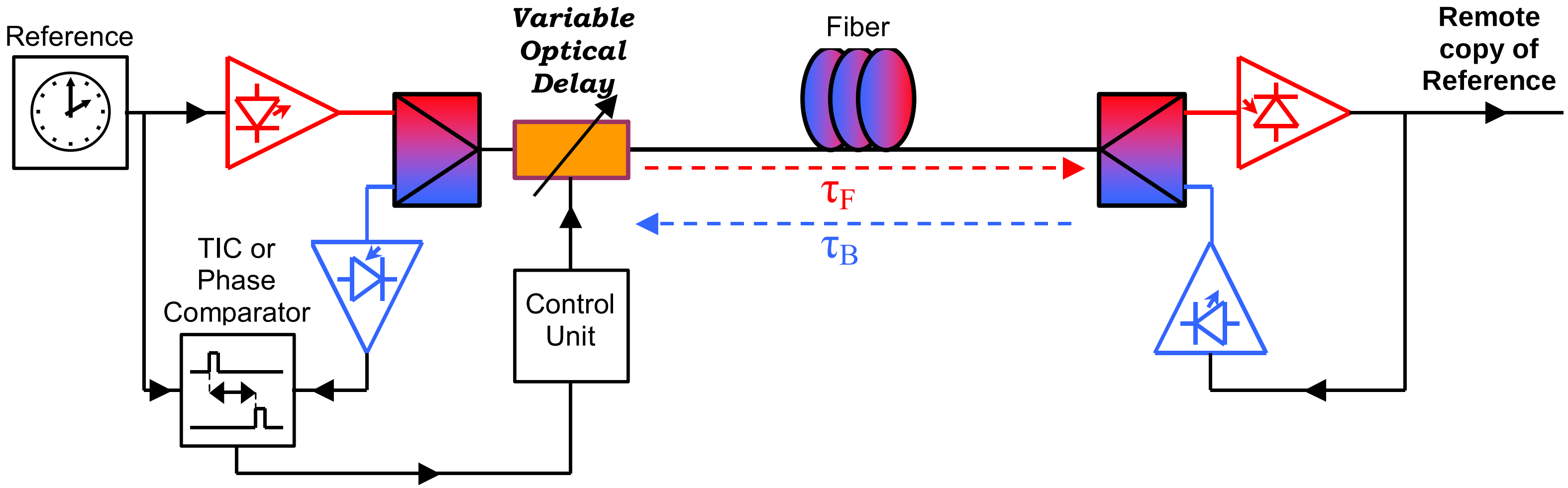
mechanical variable delay line



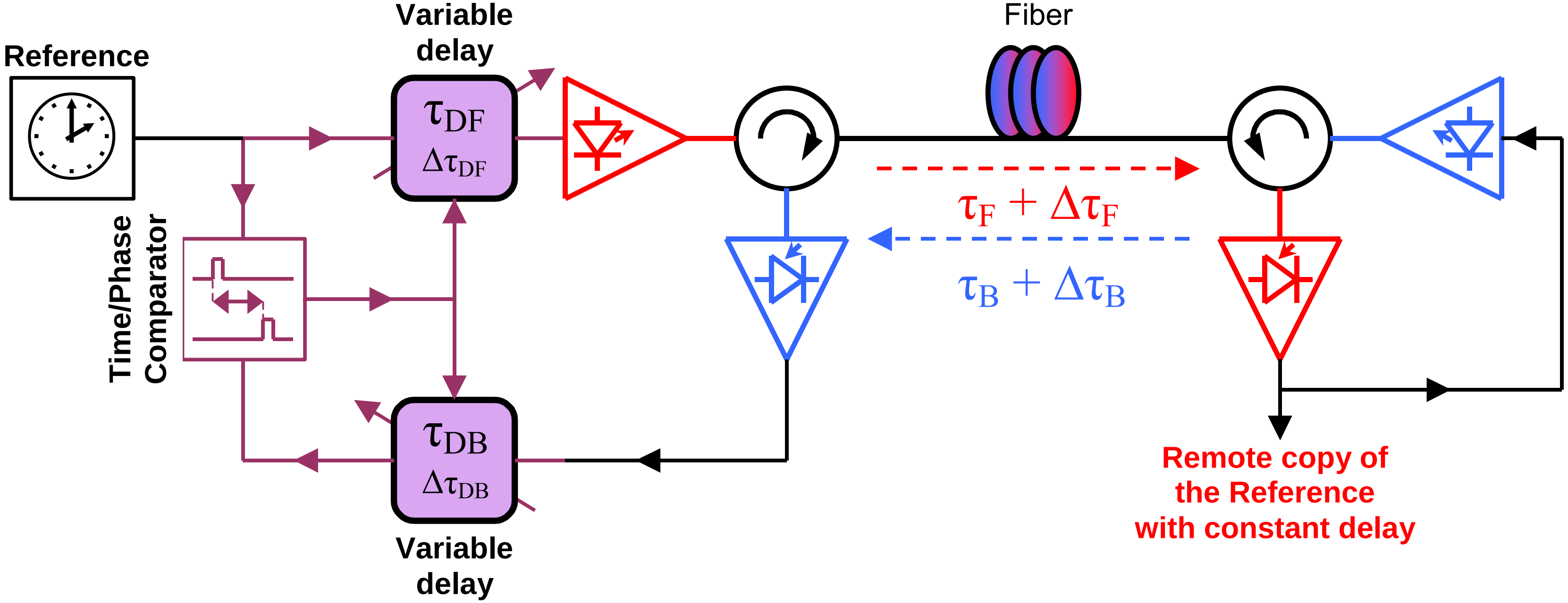
temperature variable delay line



piezo actuator



Our approach: fully-electronic variable delay line



closed-loop conditions (DLL):

$$\tau_{DF} + \tau_F + \tau_B + \tau_{DB} = A_{const}$$

$$\Delta\tau_{DF} + \Delta\tau_F + \Delta\tau_B + \Delta\tau_{DB} = 0$$

constant propagation-delay requirement:

$$\tau_{DF} + \Delta\tau_{DF} + \tau_F + \Delta\tau_F = B_{const}$$

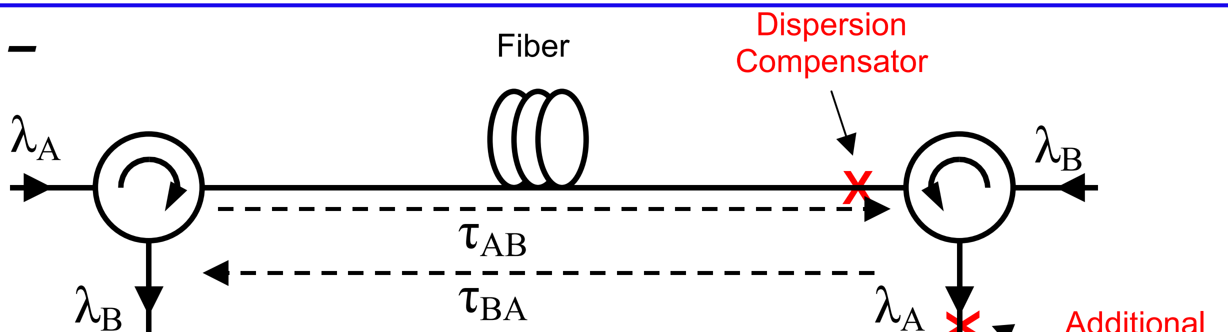
$$\Delta\tau_{DF} + \Delta\tau_F = 0$$

⇒ $\Delta\tau_B + \Delta\tau_{DB} = 0$

$\Delta\tau_F = \Delta\tau_B$ (to a few ps)

⇒ $\Delta\tau_{DF} = \Delta\tau_{DB}$ matched delays

Accuracy limits – chromatic dyspersion

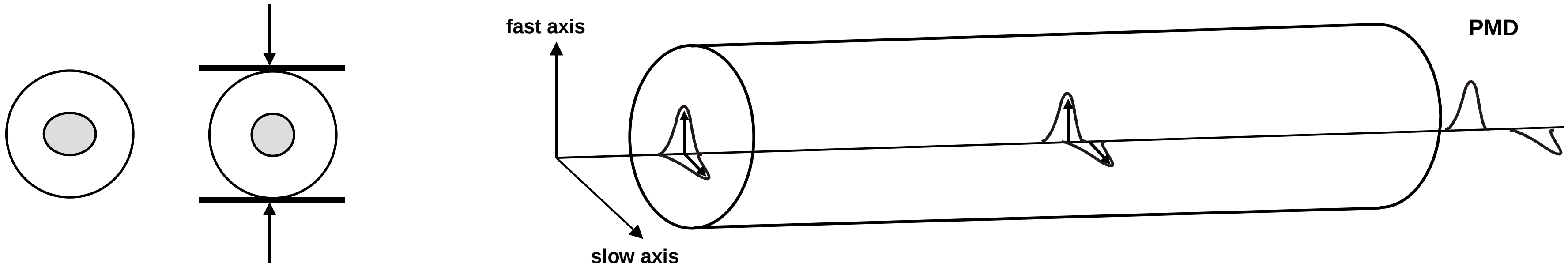


$$\tau_{AB} - \tau_{BA} = LD(\lambda_A - \lambda_B)$$

$$\frac{dD}{dT} \sim -1.5...-4 \cdot 10^{-3}\,\mathrm{ps/(nm \cdot km \cdot C)}$$

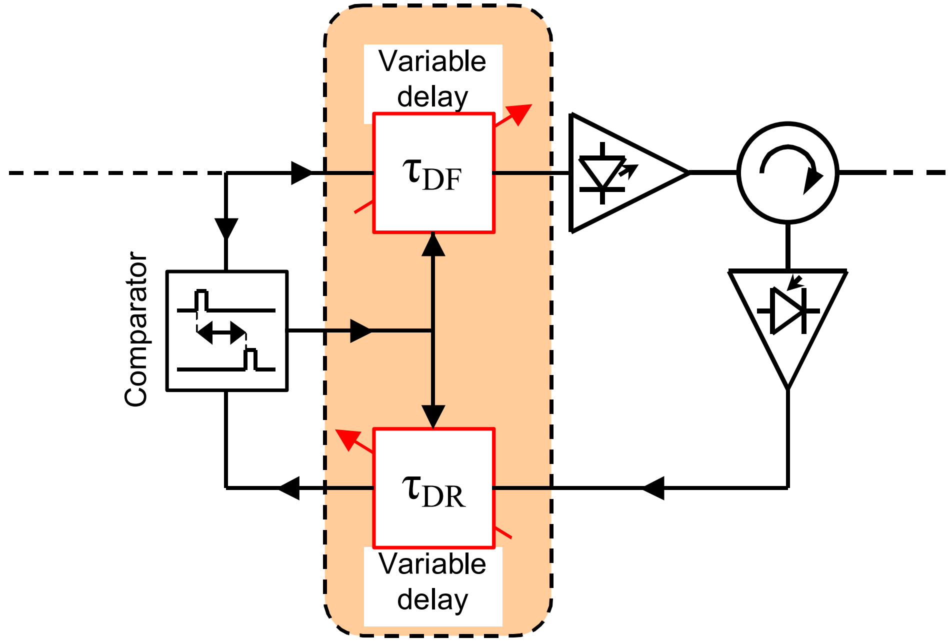
For **100 km long fiber**, Δλ=0.4 nm, ΔT=20°C ➡ **$\Delta(\tau_{AB} - \tau_{BA}) \sim 3$ ps**

Accuracy limits - polarization-mode dispersion



In nowadays fibers $\mathrm{PMD} \sim 0.1\,\mathrm{ps}/\sqrt{\mathrm{km}}$

For 100 km long fiber ➡ **$\Delta\tau_P \sim 1$ ps**

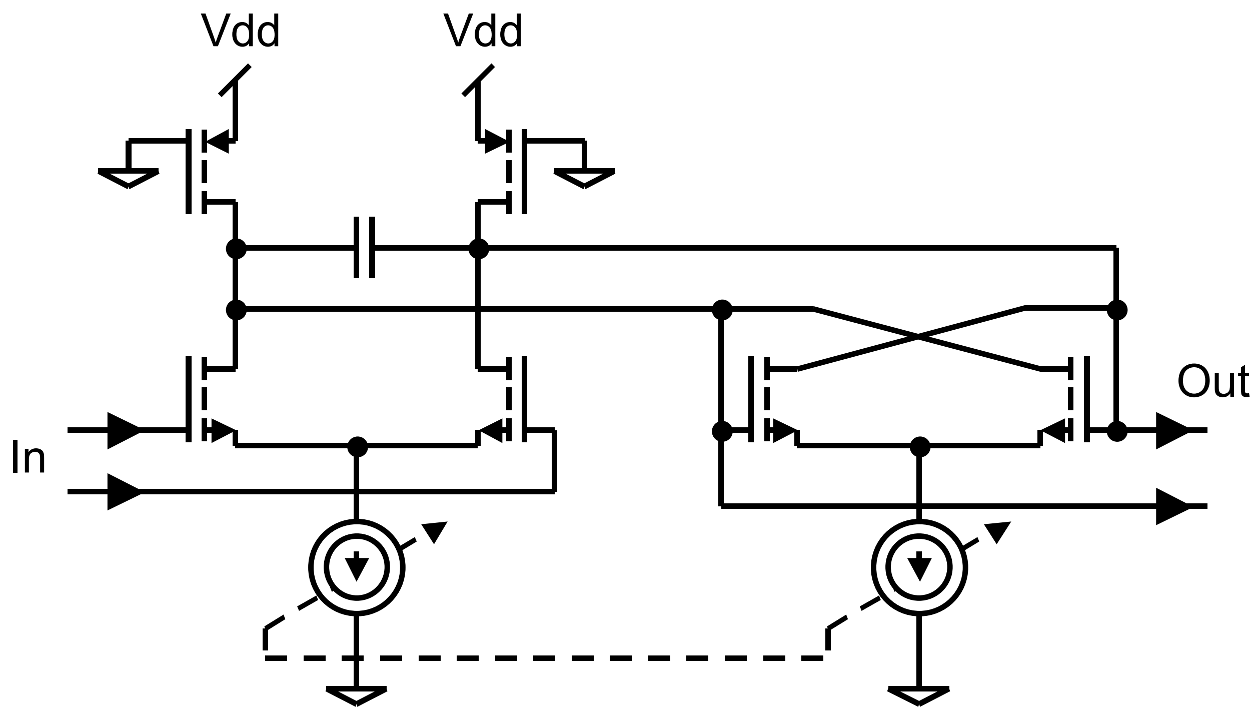


Requirements concerning the variable delay blocks:

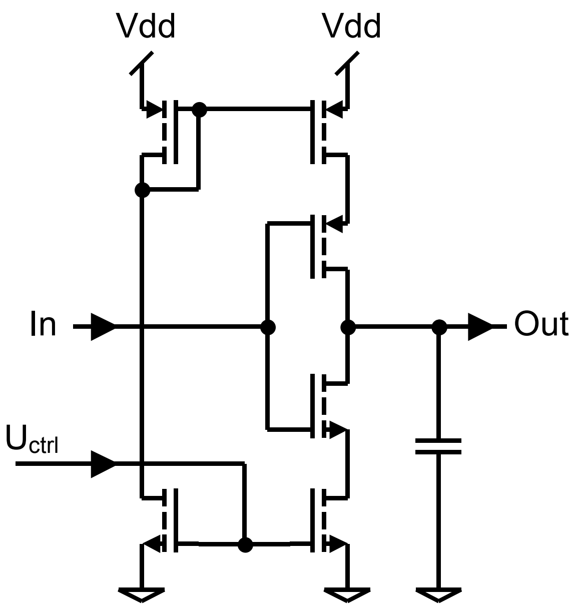
- ***input signal: 1PPS or 10 MHz (binary)***
- ***monotonic tuning***
- ***no glitches***
- ***continuous tuning or small tuning steps; ~ 20 ps***
- ***tuning range ~ 100 ns (for 30 km fiber length)***
- ***excellent matching: $\tau_{DF} - \tau_{DB} < 20$ ps***

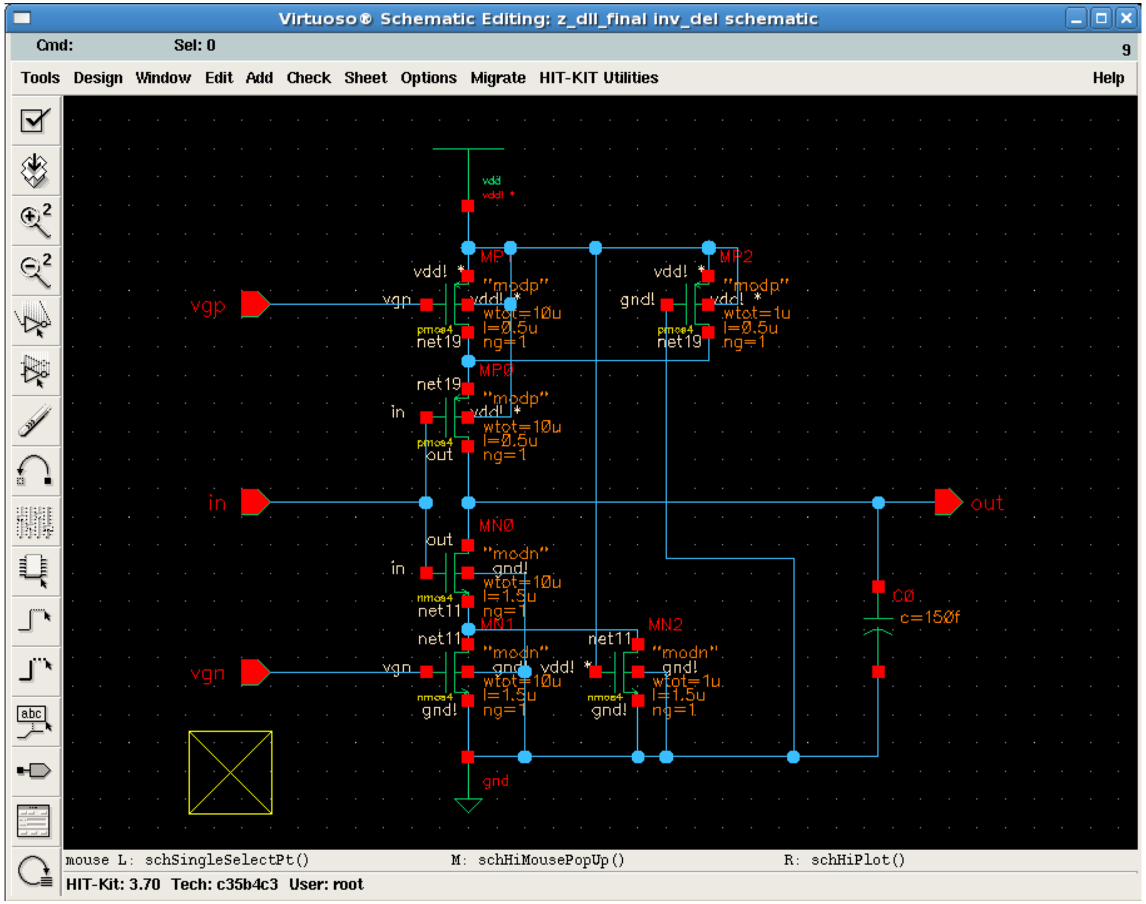
There are no off-the-shelf components fulfilling above requirements

Structures available for the variable delay – line cell with positive feedback (Razavi)

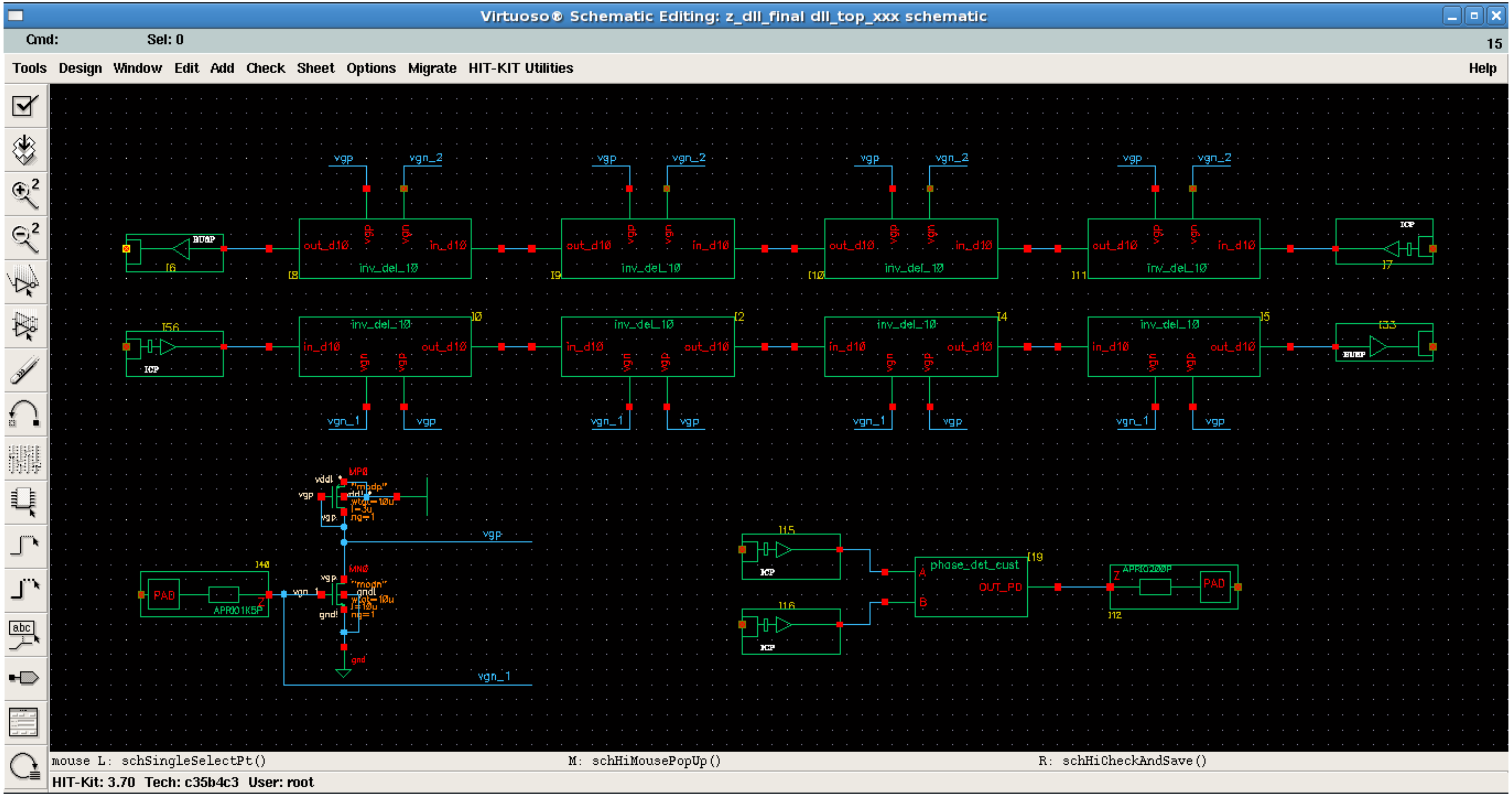


Structures available for the variable delay – line inverter-based cell

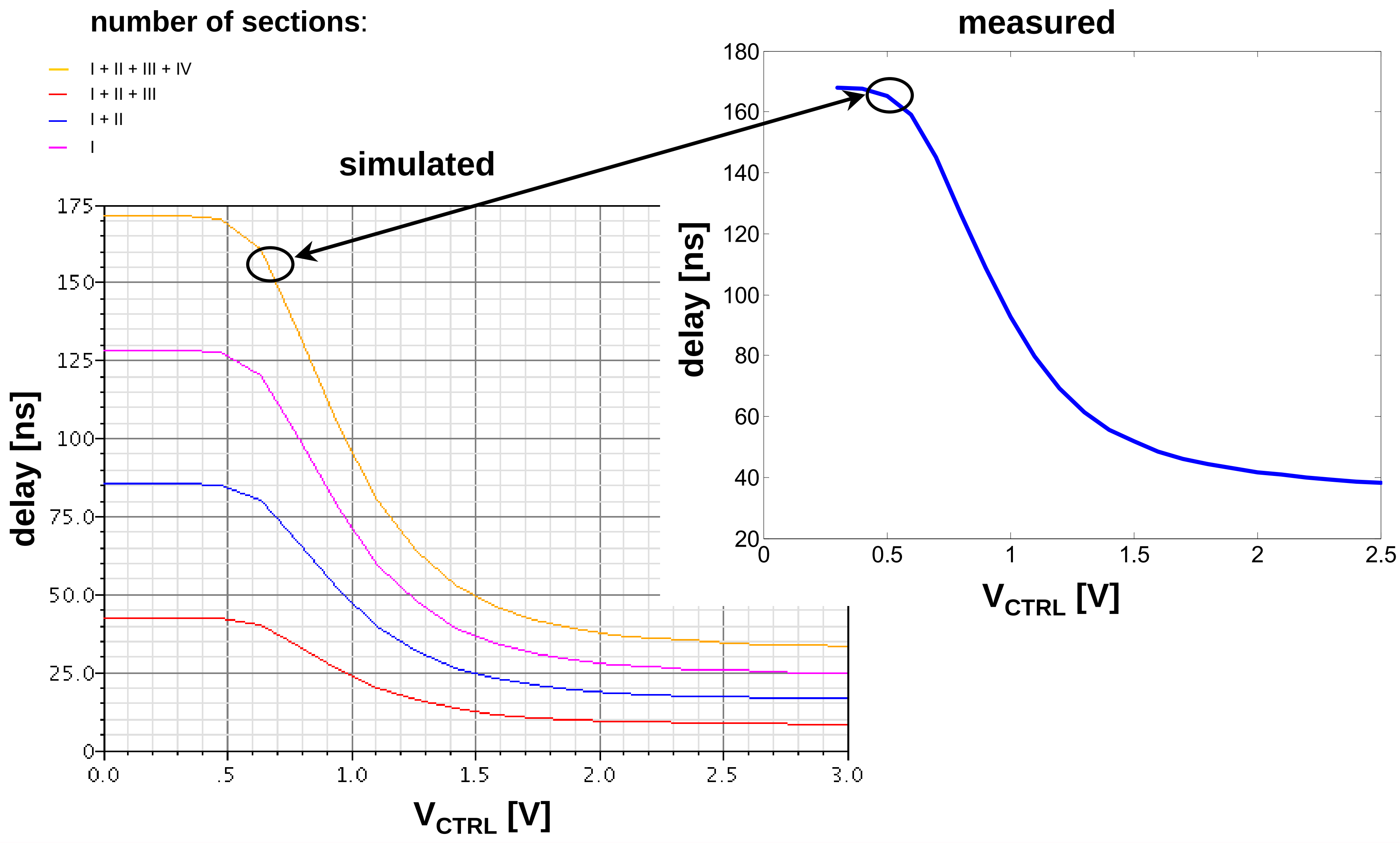




ASIC structure



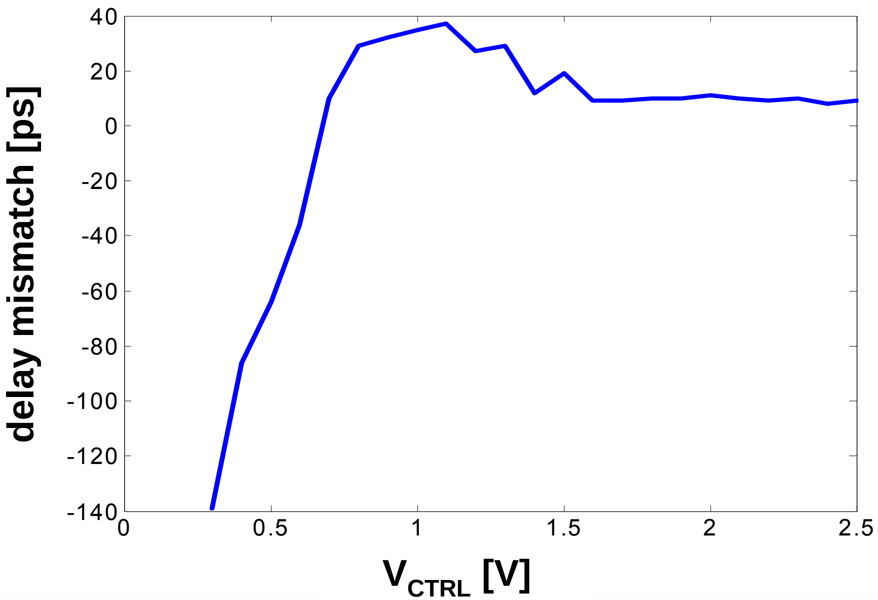
Simulations results – delay vs control voltage



Simulations results – delay mismatch

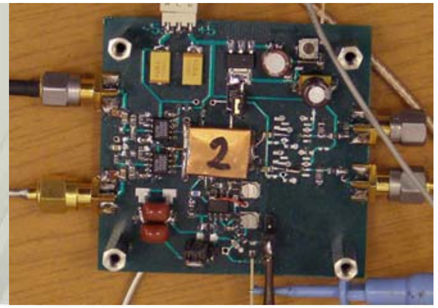
simulated

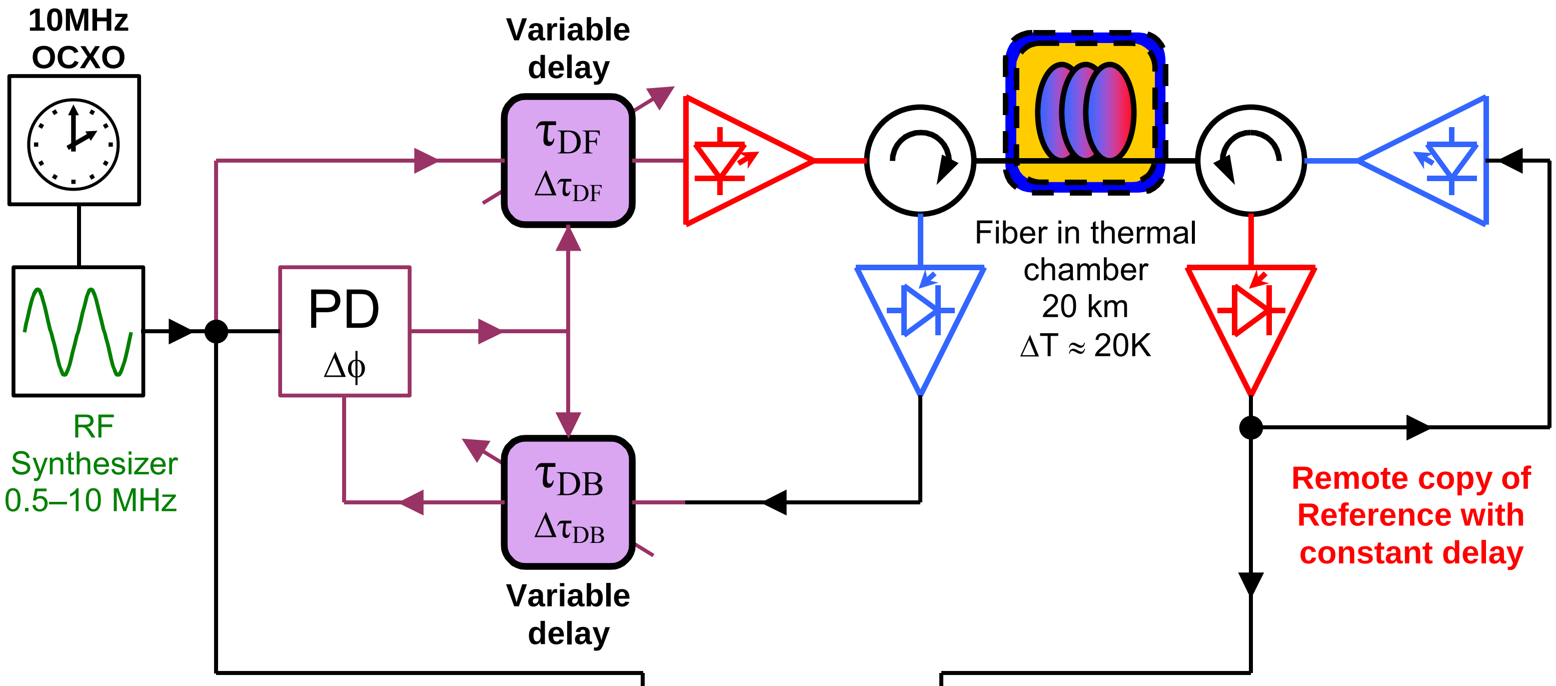
	I + II + III + IV		I + II + III		I + II		I	
V_{CTRL}	τ_m	σ_τ	τ_m	σ_τ	τ_m	σ_τ	τ_m	σ_τ
0.5	169.2	183.6	126.5	164.6	84.3	129.2	42.1	90.5
0.7	149.6	268.8	111.8	214.9	74.5	154.7	37.3	94.0
1.2	69.0	132.0	51.4	101.9	34.4	72.9	17.4	41.7
1.5	48.9	63.1	36.3	48.6	24.3	35.3	12.3	20.4
V	ns	ps	ns	ps	ns	ps	ns	ps

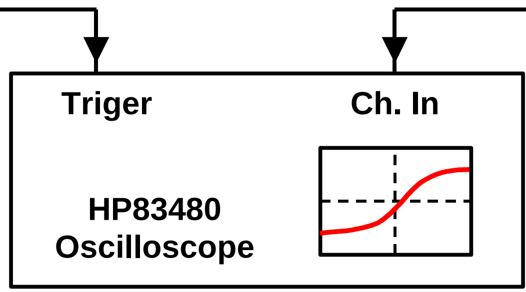


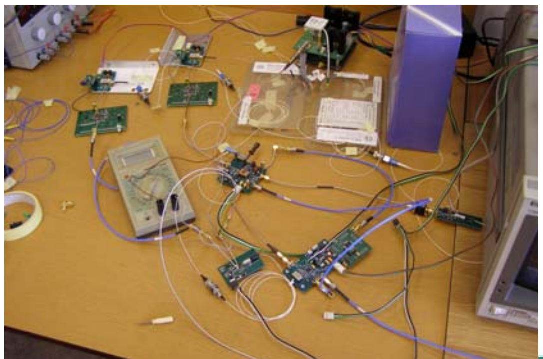
measured

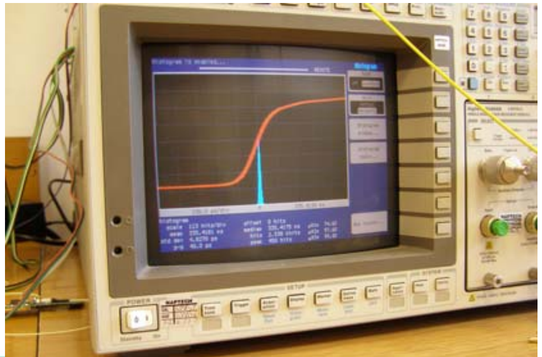
Measurement setup



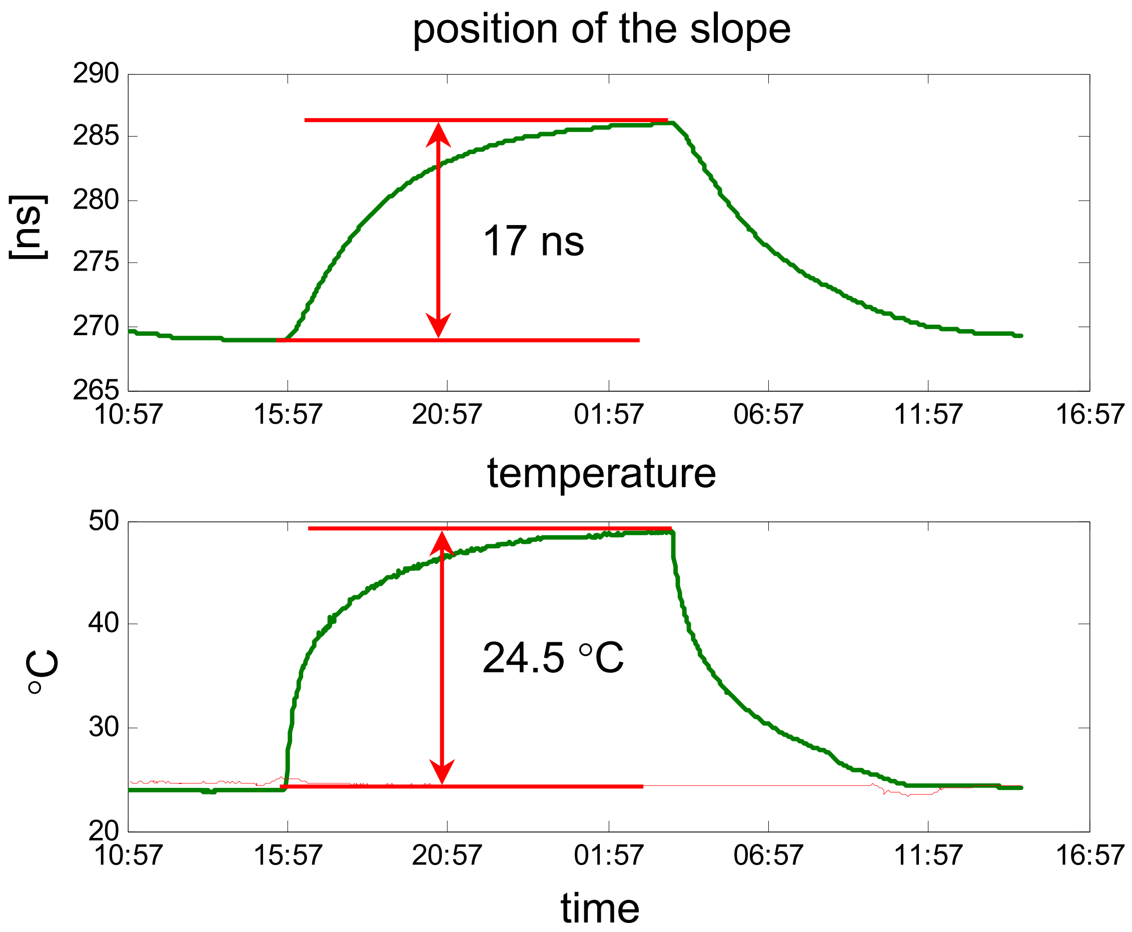




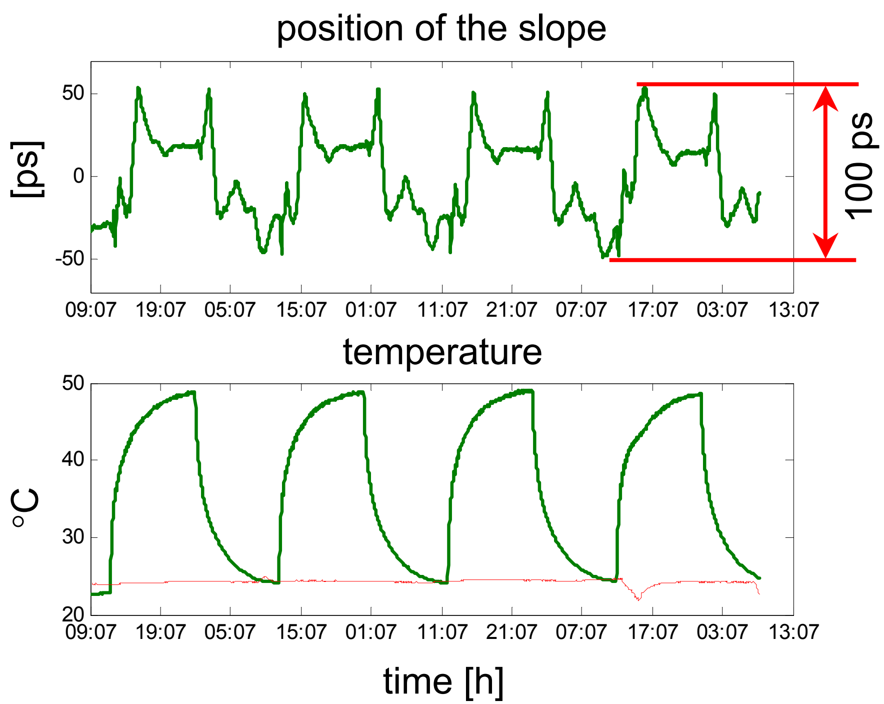


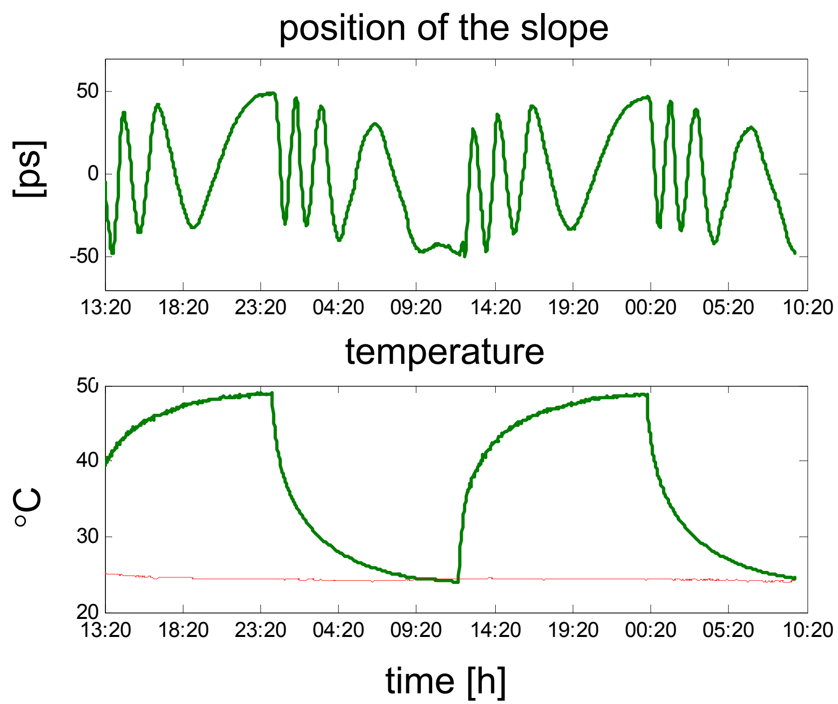


Open-loop performance



Closed-loop performance (I)

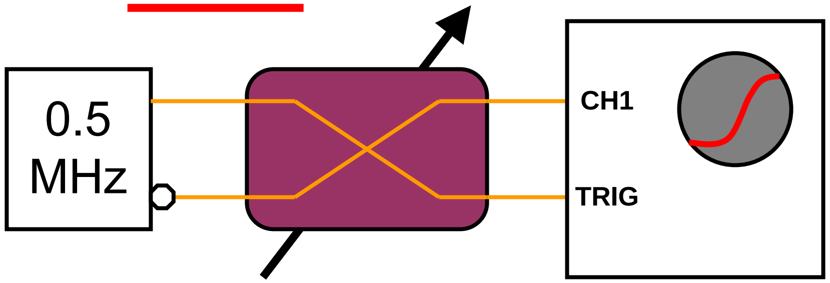


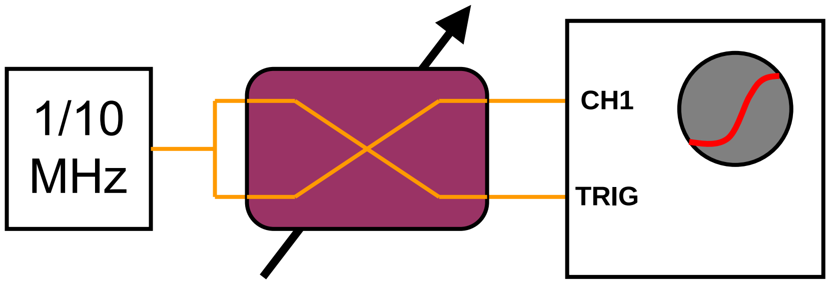


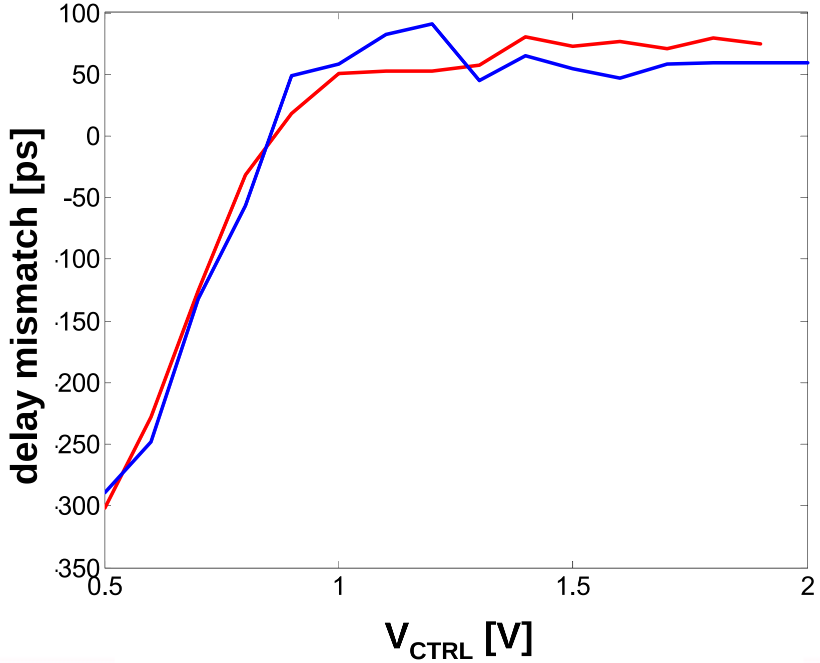
achieved reduction: **170x (17 ns → 100 ps)**
~ 200 fs/km·K @ 20km, 25K

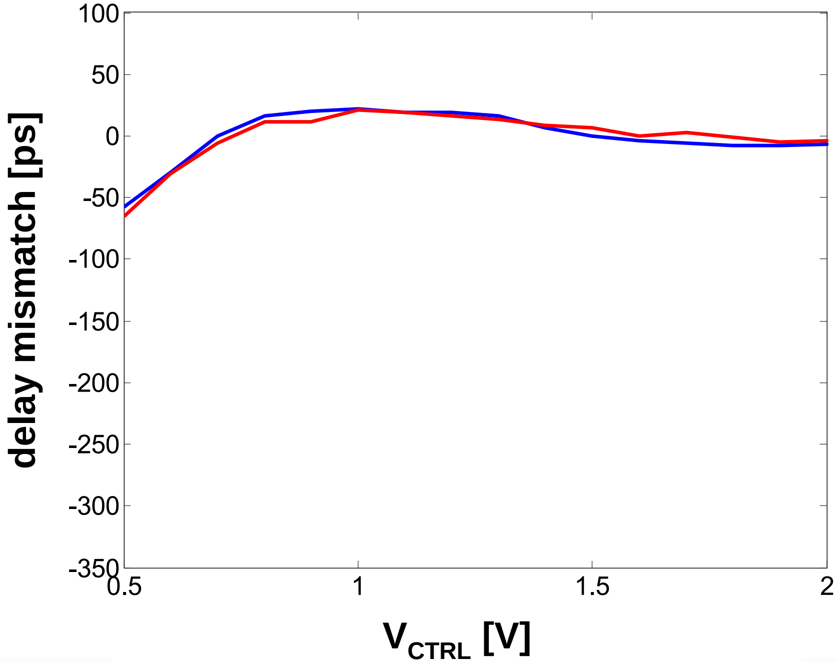
literature reports: **~ 110 fs/km·K @ 2.5 km, 4K (Narbonneau 2006)**

Design shortcomings

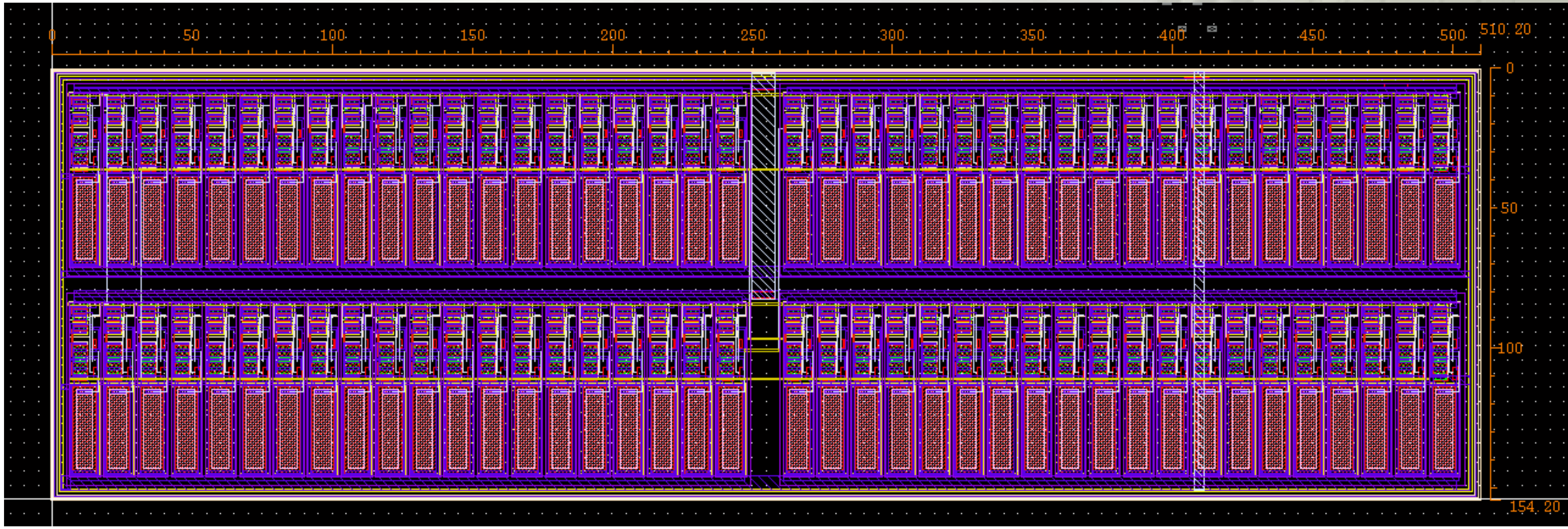


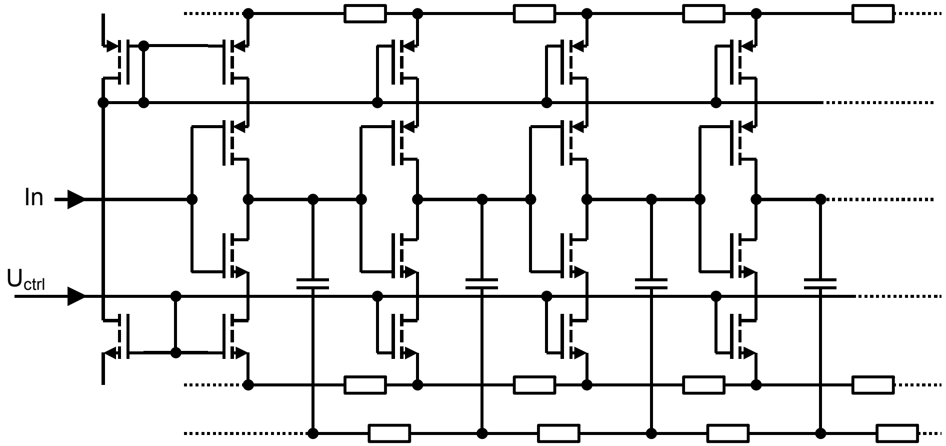




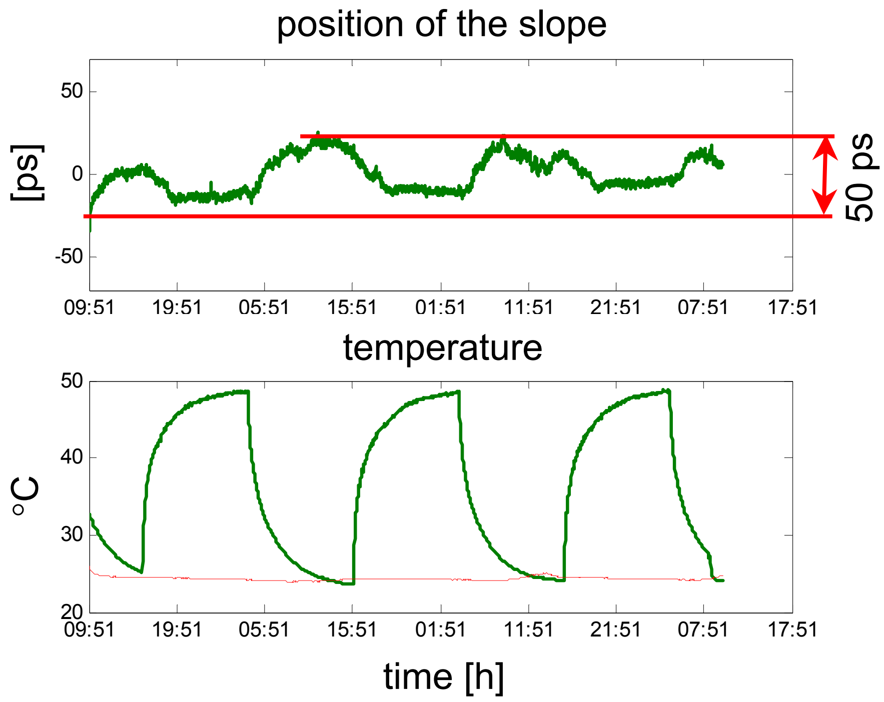


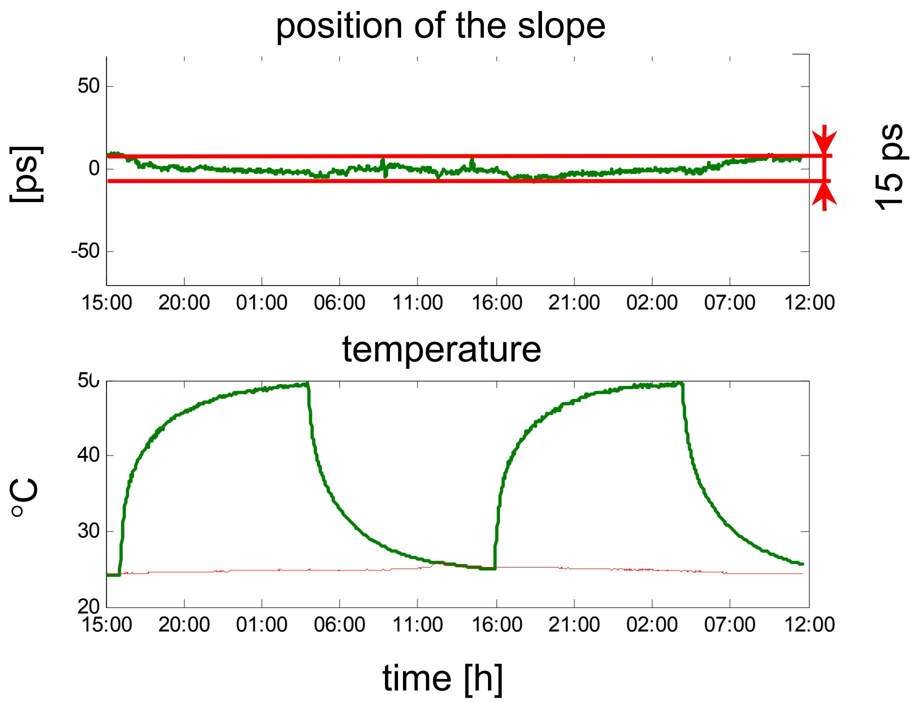
Design shortcomings





Closed-loop performance (II)





achieved reduction: **1100x (17 ns → 15 ps)**

~ 30 fs/km·K @ 20km, 25K

literature reports: **~ 110 fs/km·K @ 2.5 km, 4K (Narbonneau 2006)**

Conclusions

- Fiber optic transfer of time/frequency reference in closed loop exploiting electronically variable matched delay lines offers substantially reduced fluctuations of propagation delay of the link.
- Designed chip is functional, however some problems still awaits for solving:
  - noise coupling through the power supply rails,
  - crosstalk between channels,
- These deficiencies could be probably greatly reduced by improving the layout.
- Inaccurate matching could be improved applying compensation of the tuning chatracteristics.