Integrated photonic beamformer employing continuously tunable ring resonator-based delays in CMOS-compatible LPCVD waveguide technology

Chris Roeloffzen

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TELECOMMUNICATION ENGINEERING

University of Twente
Enschede - The Netherlands

LioniX

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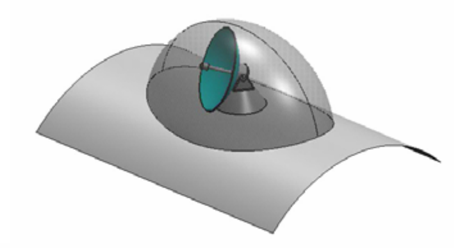
   - System performance.
4. Conclusions

1. Introduction: aim and purpose

Aim:

Development of a novel K_u-band antenna for airborne reception of satellite signals, using a broadband conformal phased array

Purpose:



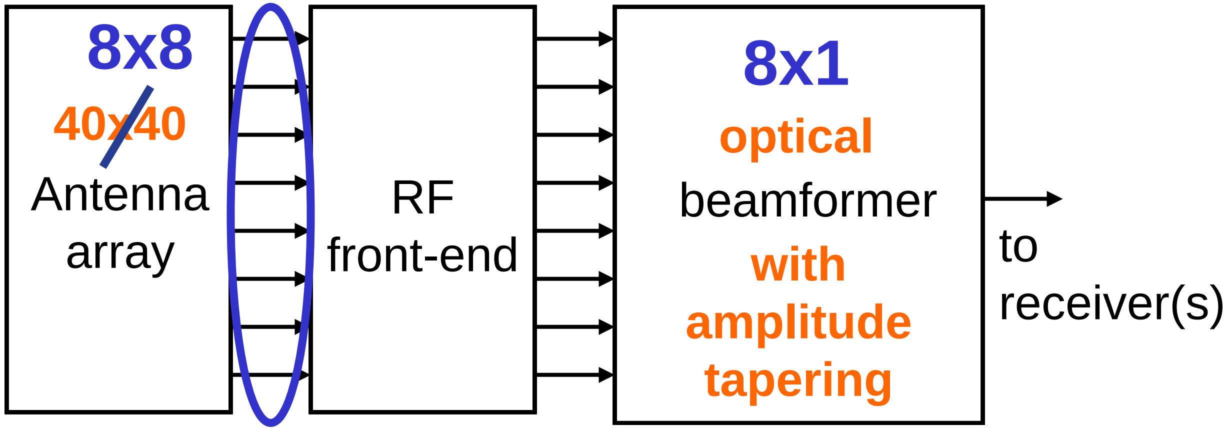
- Live weather reports;
- High-speed Internet access;
- Live television through Digital Video Broadcasting via satellite (DVB-s)

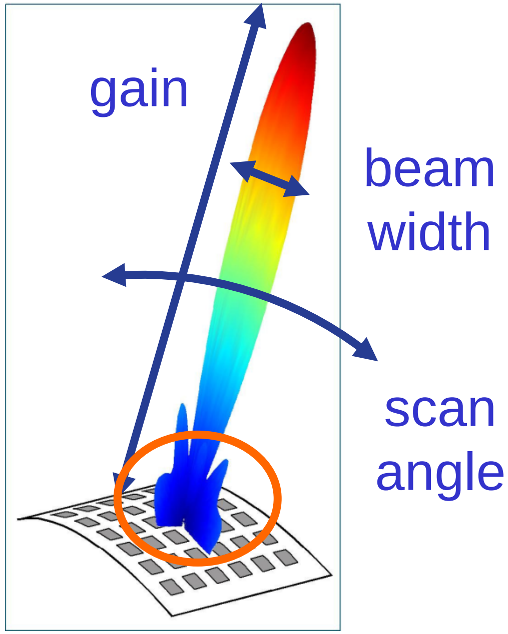
1. Introduction: specific targets

Specific targets:

- Conformal phased array structure definition;
- Broadband stacked patch antenna elements;
- Broadband integrated optical beamformer based on optical ring resonators in CMOS-compatible waveguide technology;
- Experimental demonstrator.

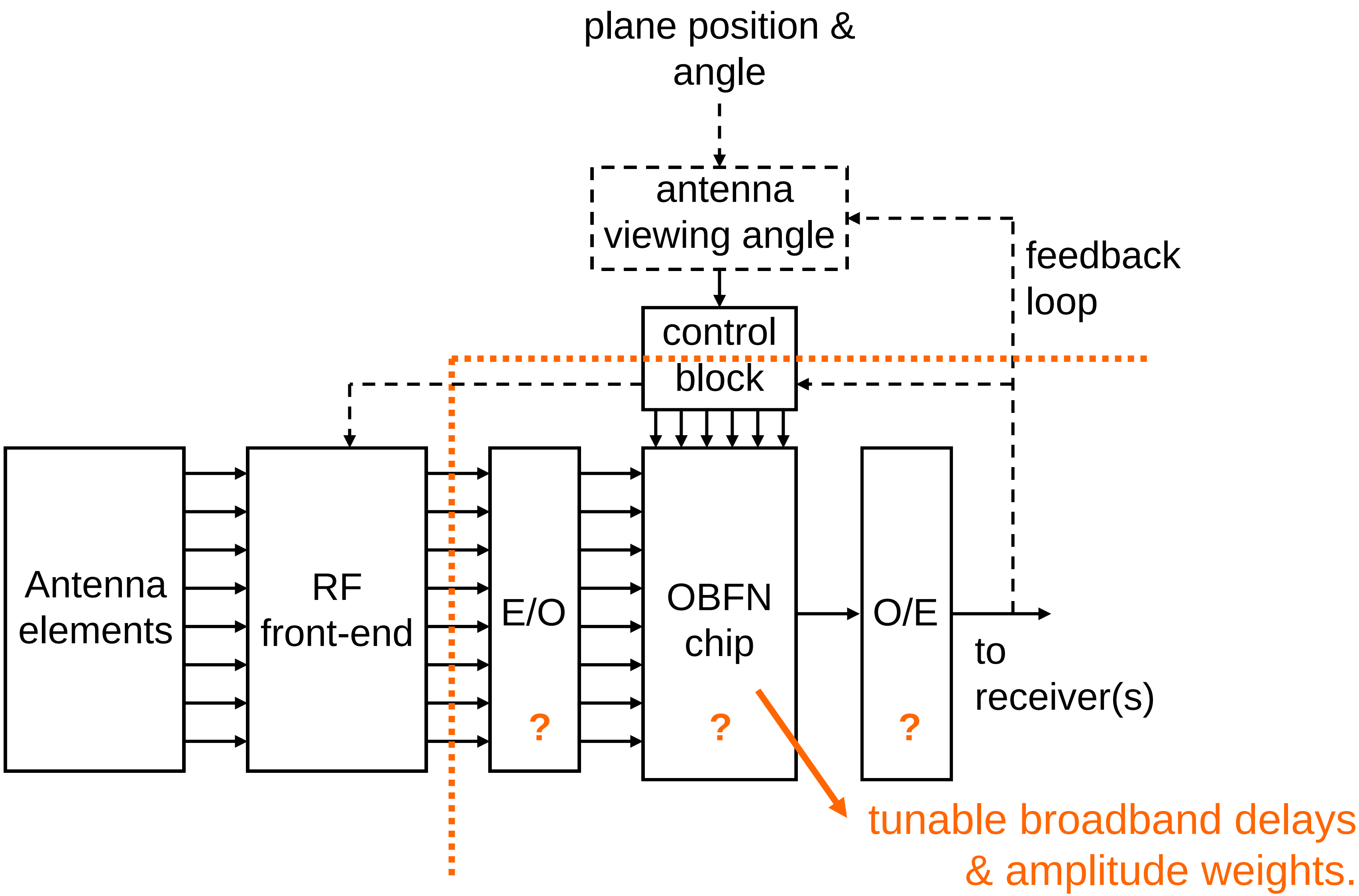
2. System overview & requirements



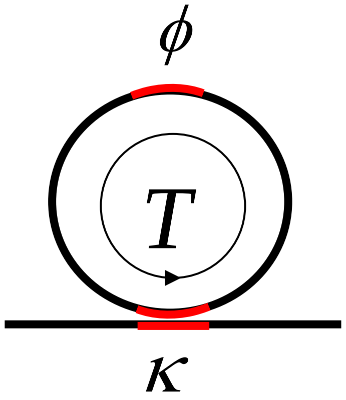


Frequency range: 10.7 – 12.75 GHz (K_u band)
Polarization: 1 ~~2~~ linear (H/V)
Scan angle: -60 to +60 degrees
Gain: > 32 dB
Selectivity: << 2 degrees → Continuous delay tuning required !
No. elements: ~1600
Element spacing: $\sim\lambda/2$ (~1.5 cm, or ~50 ps)
Maximum delay: ~2 ns
Delay compensation by phase shifters? → beam squint at outer frequencies!
→ (Broadband) time delay compensation required !

3. Optical beamformer: overview



Single ring resonator:



T : Round trip time;

κ : Power coupling coefficient;

ϕ : Additional phase.

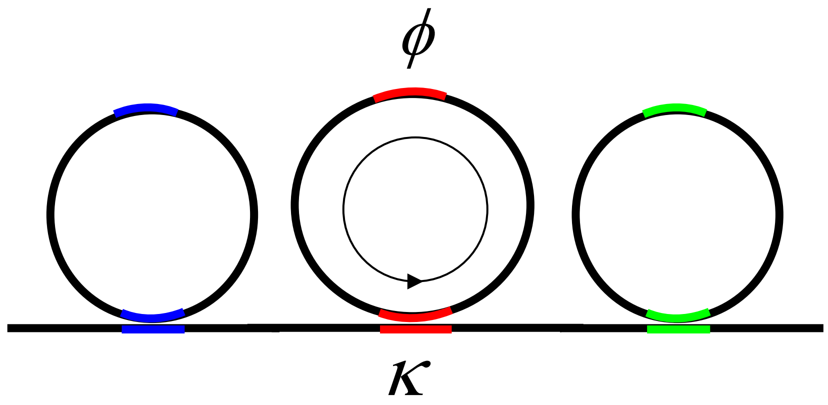
$-\frac{1}{2T}$ $-\frac{1}{4T}$ 0 $\frac{1}{4T}$ $\frac{1}{2T}$

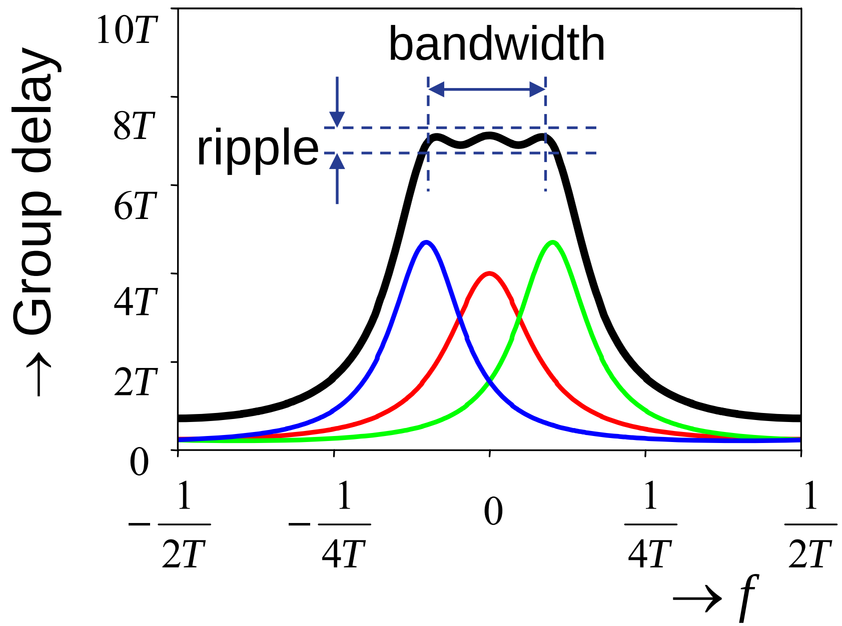
$\rightarrow f$

- Periodic transfer function;
- Flat magnitude response.
- Phase transition around resonance frequency;
- Bell-shaped group delay response;
- Trade-off: <u>delay vs. bandwidth</u>

3. Optical beamformer: ORR-based delays

Cascaded ring resonators:





- Rippled group delay response;
- Enhanced bandwidth;
- Trade-off: delay vs. bandwidth vs. delay ripple vs. no. rings;

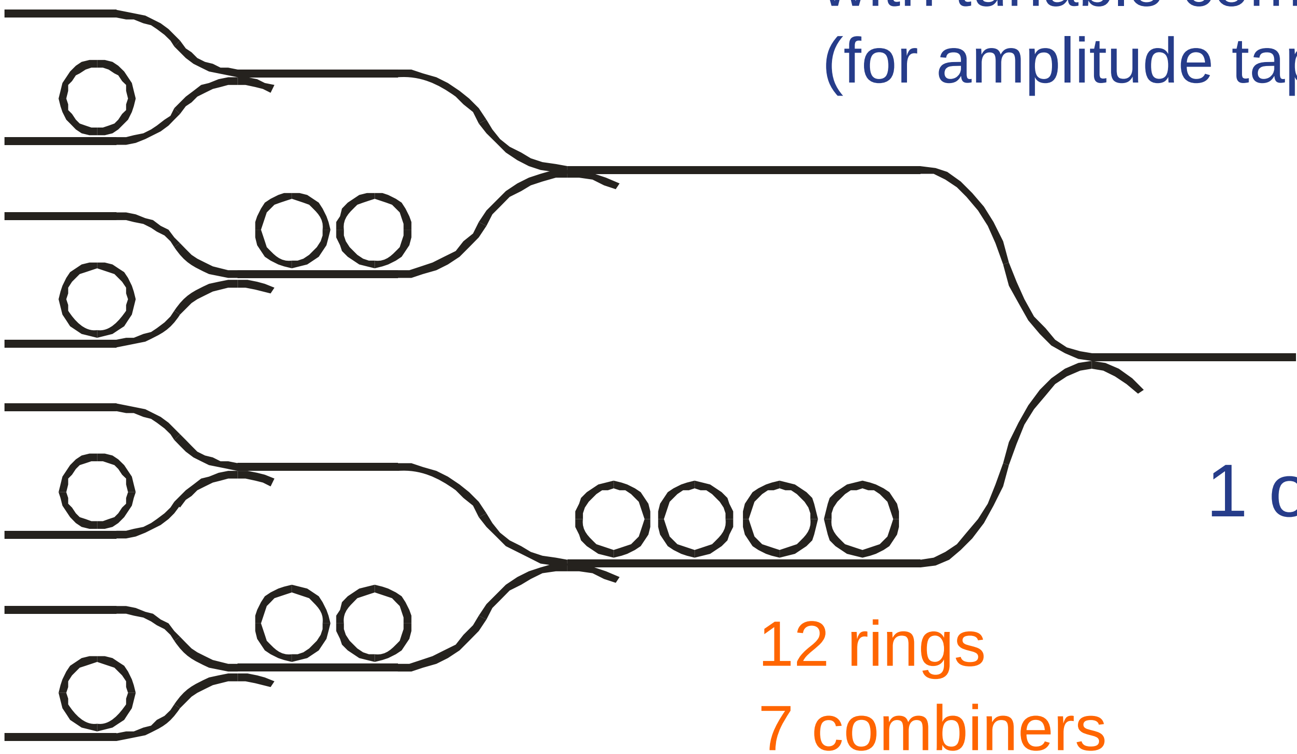
Or in other words: for given delay ripple requirements:

Required no. rings is roughly proportional to product of required optical bandwidth and maximum delay

8x1 Optical beam forming network (OBFN)

combining network
with tunable combiners
(for amplitude tapering)

8 inputs
with
tunable
delays

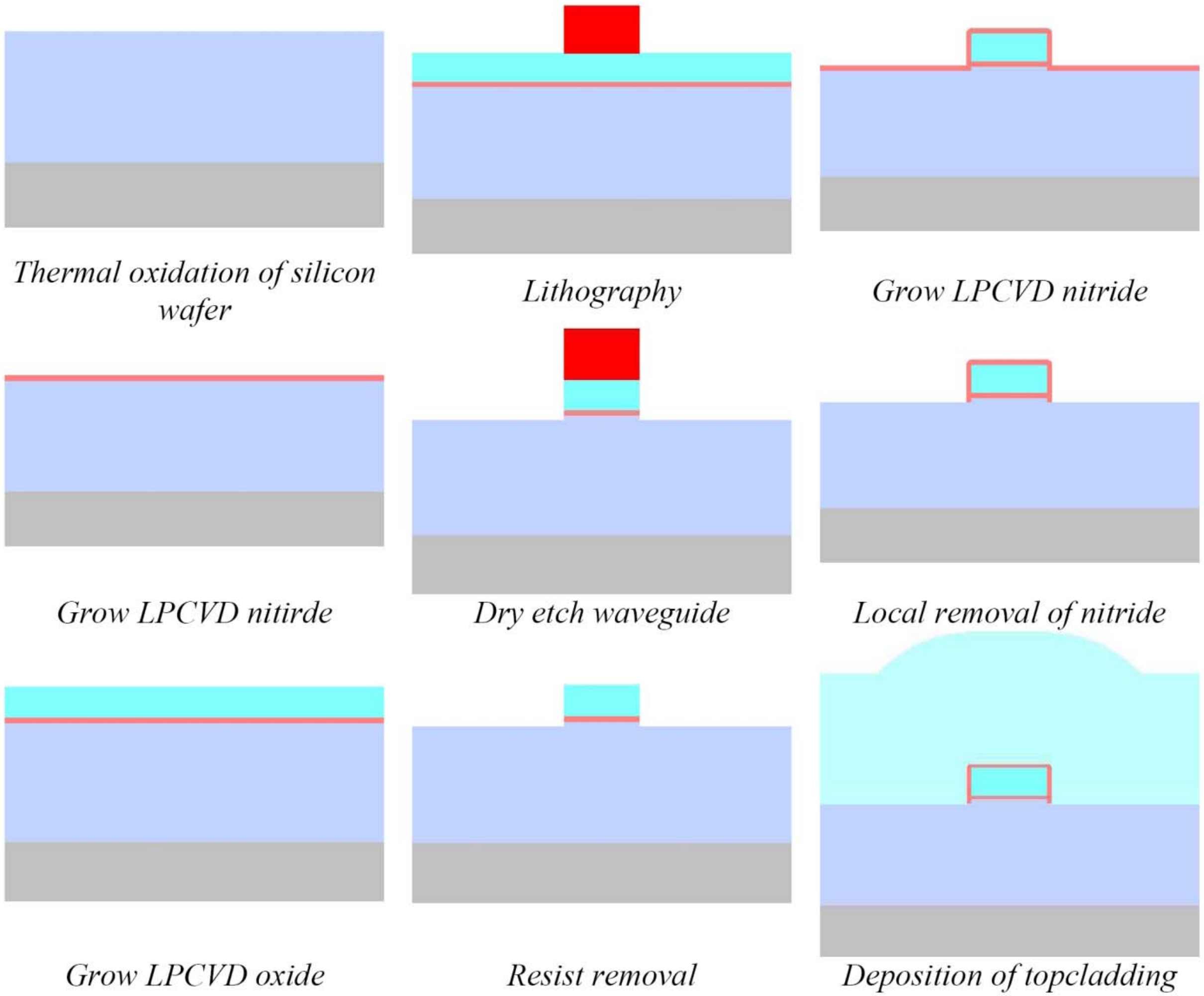


1 output

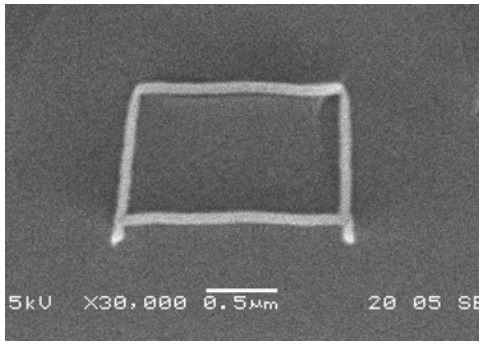
12 rings
7 combiners
→ 31 tuning elements

3. Optical beamformer: chip fabrication

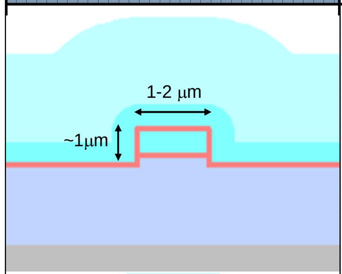
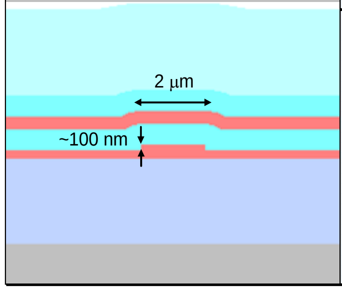
Fabrication process of TriPleX Technology



LioniX



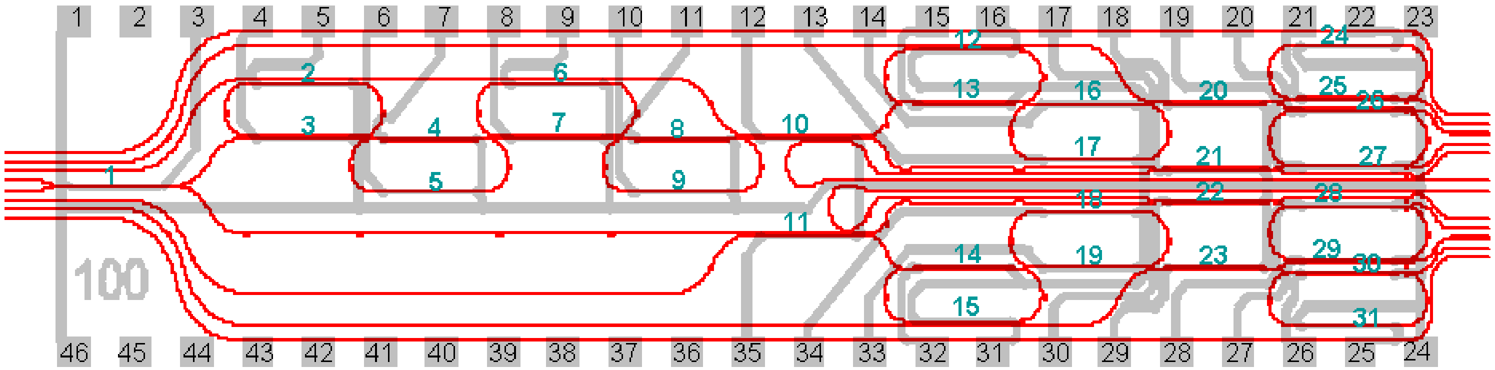
TriPleX™ results

	Group birefringence (B_g)	Channel attenuation (dB/cm)	Polarization dependent loss (PDL, in dB)	Insertion loss (IL) without spot size converter (dB)
	$\leq 1\times10^{-4}$	≤ 0.10	0.12 [1]	1.4 [2]
	1.1×10^{-1}	0.12	0.20 [1]	8.0 [2,3]

[1]: chip length 3 cm
[2]: here, small core fibers were used (MFD of 3.5 µm)
[3]: minimal bend radius ~400 µm

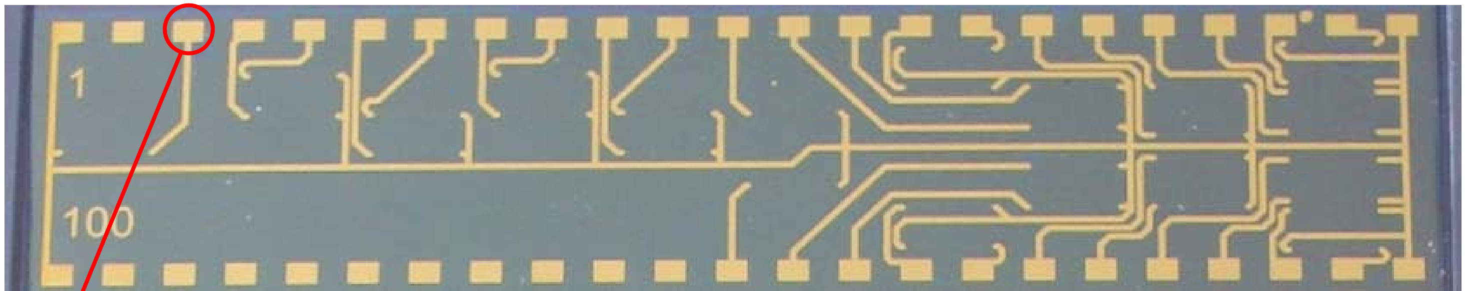
3. Optical beamformer: 8x1 OBFN chip

Single-chip 8x1 OBFN realized in CMOS-compatible optical waveguide technology



LioniX **TriPleX Technology**

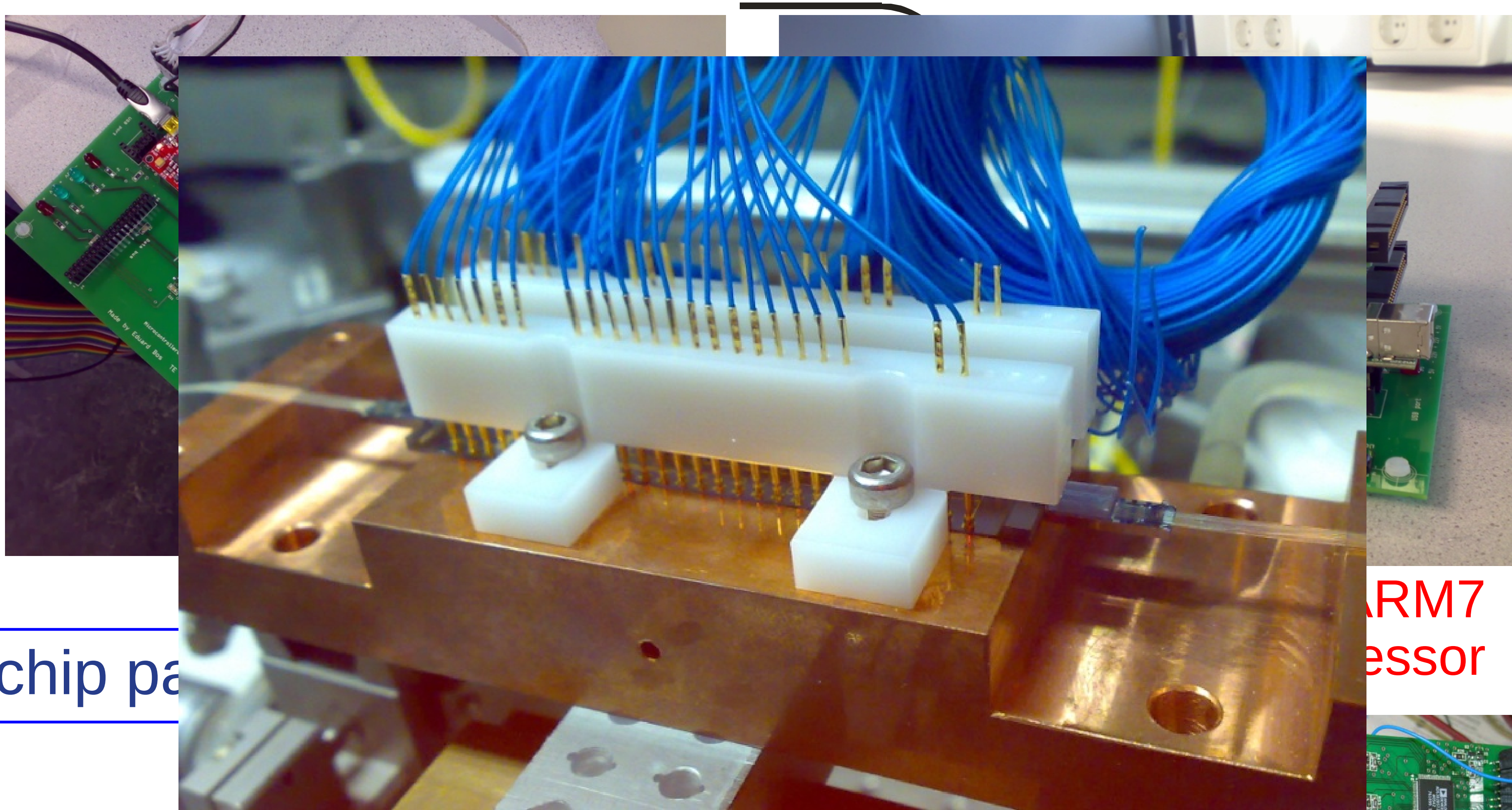
1 cm



Heater bondpad

4.85 cm x 0.95 cm

3. Optical beamformer: OBFN control block

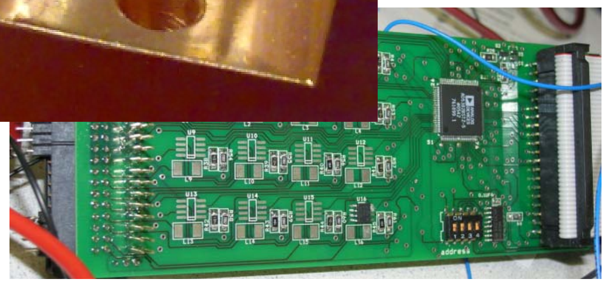


RM7
essor

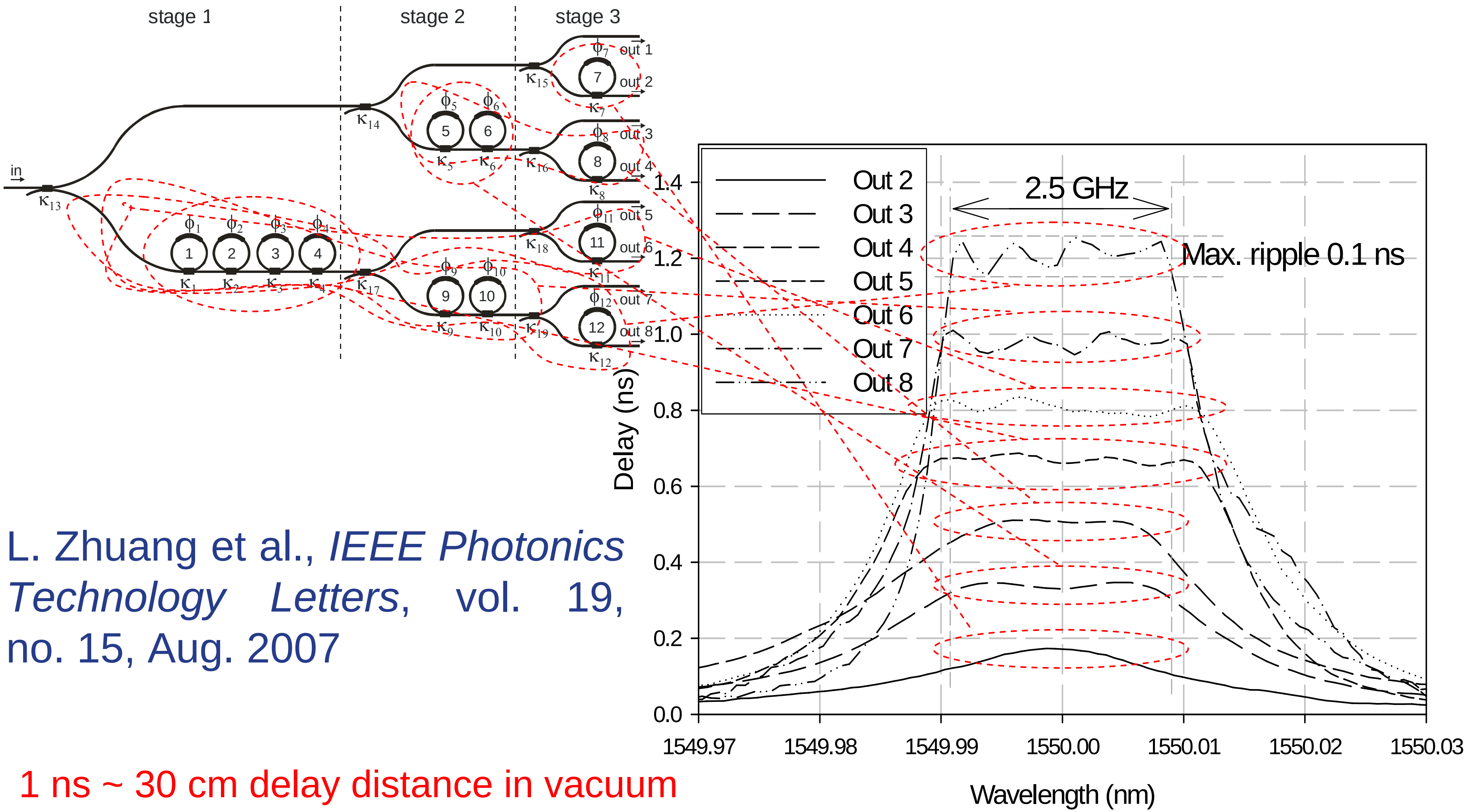
chip pa

& amplification

heater voltages



OBFN Measurement results

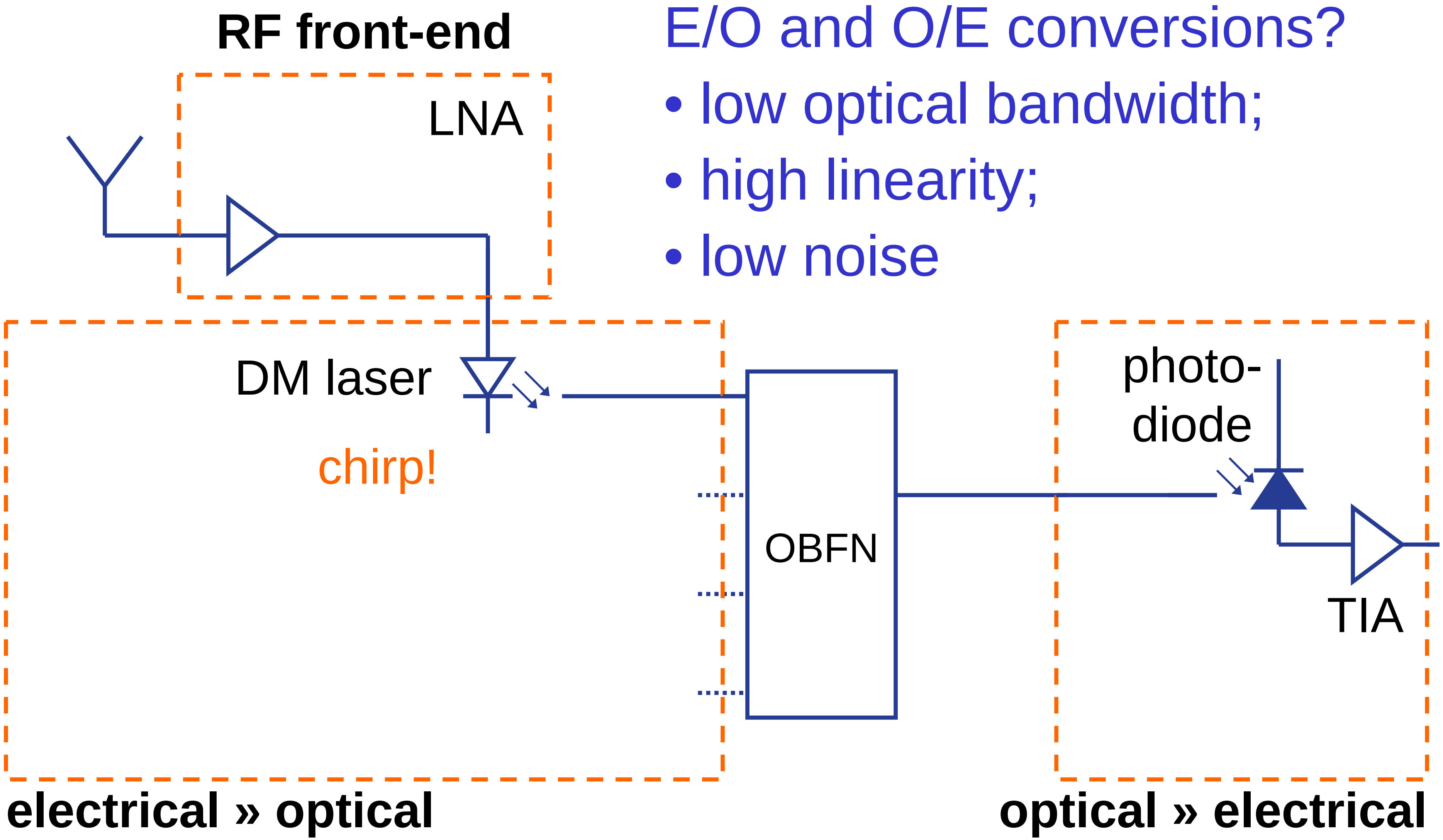


L. Zhuang et al., *IEEE Photonics Technology Letters*, vol. 19, no. 15, Aug. 2007

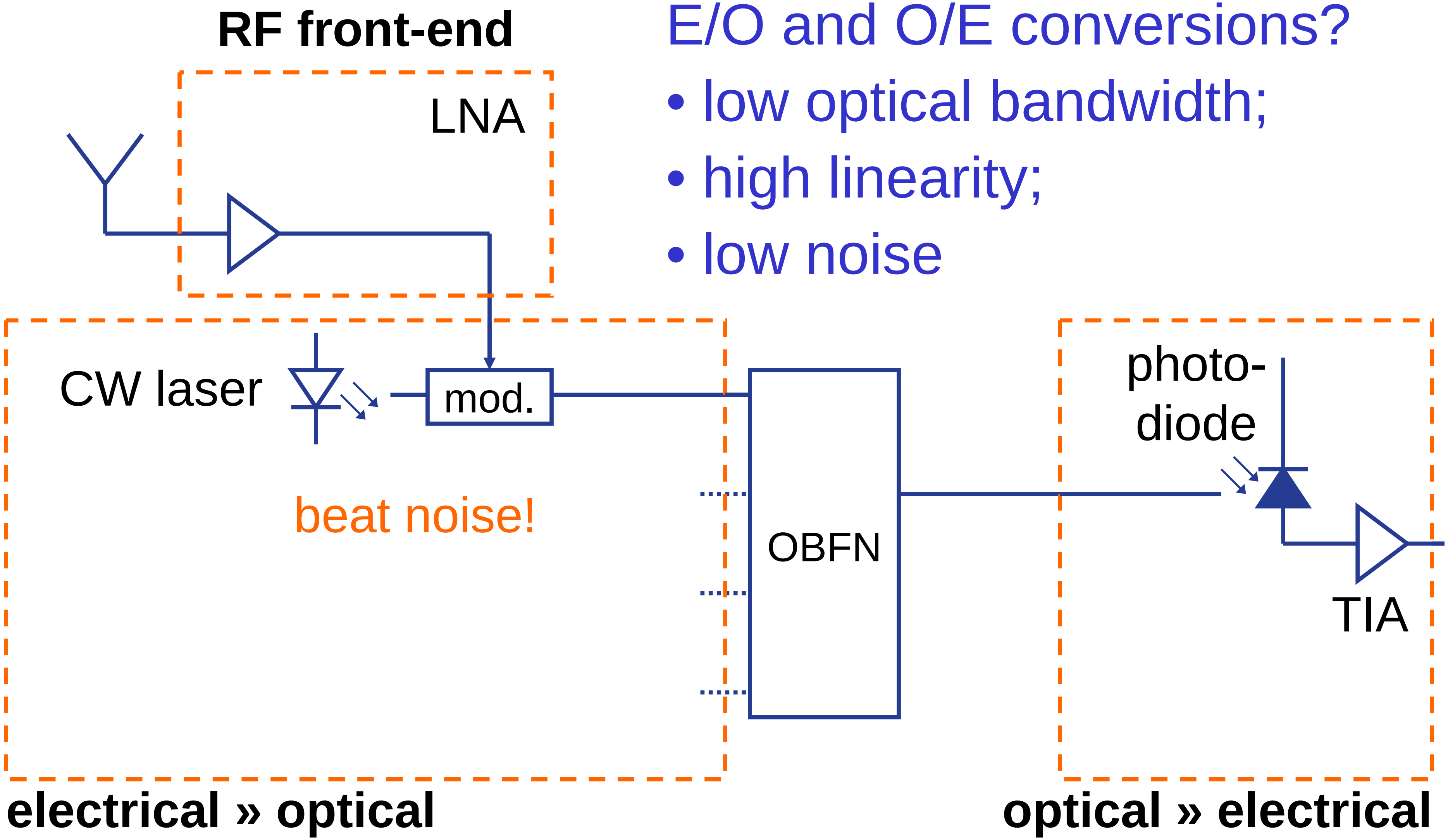
1 ns ~ 30 cm delay distance in vacuum

3. Optical beamformer: E/O and O/E conversion

E/O and O/E conversions?
- low optical bandwidth;
- high linearity;
- low noise



3. Optical beamformer: E/O and O/E conversion



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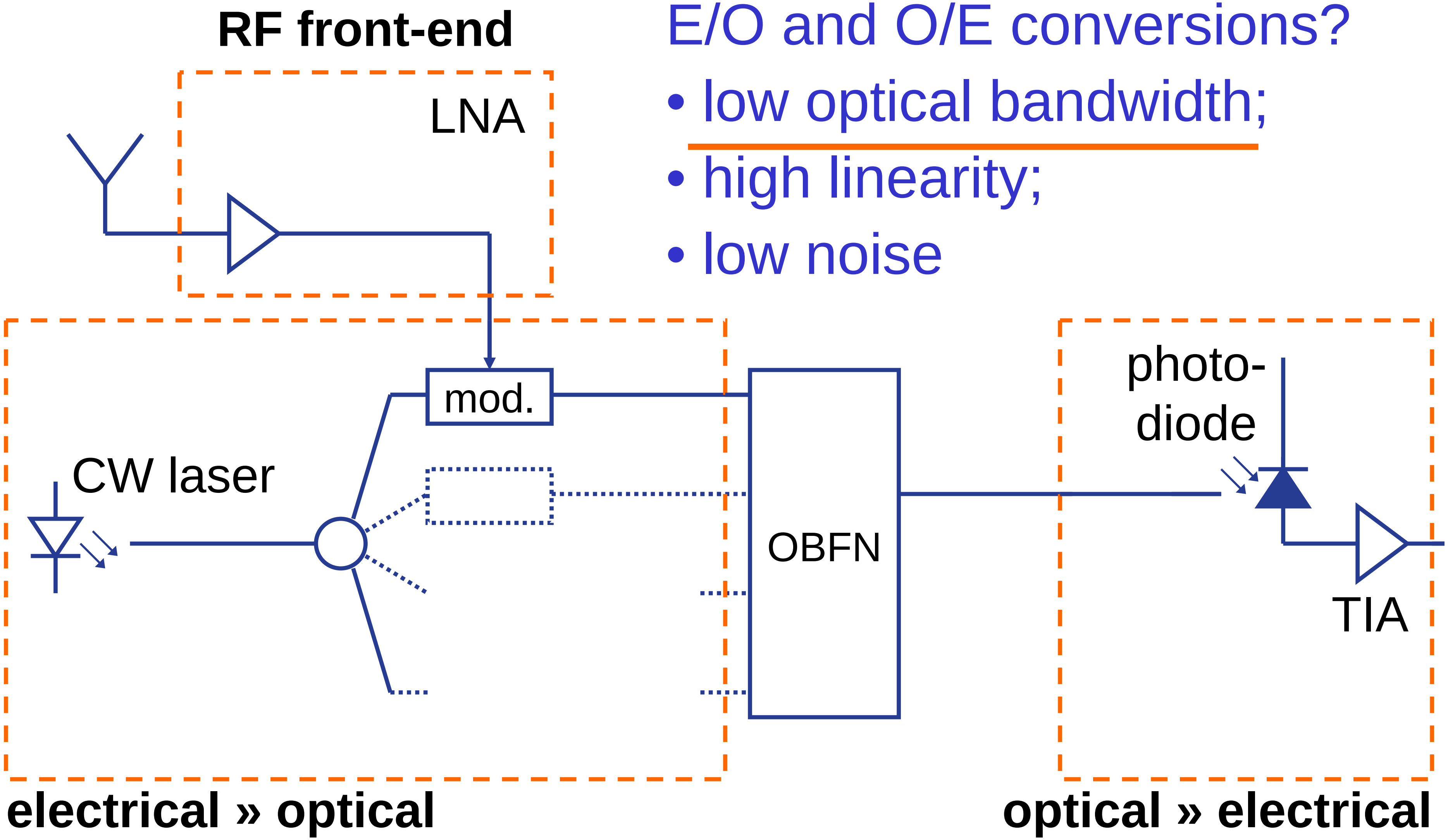
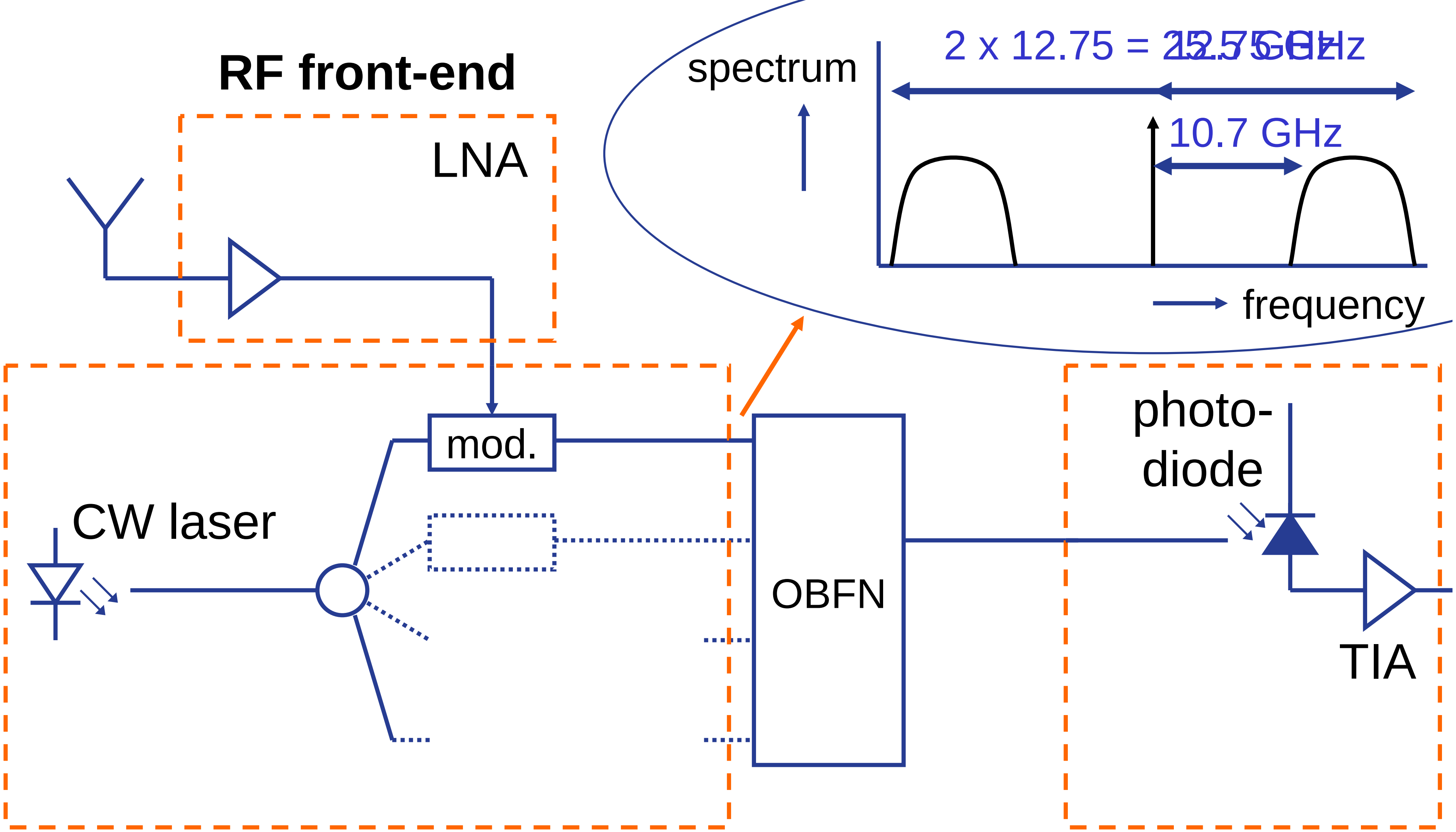
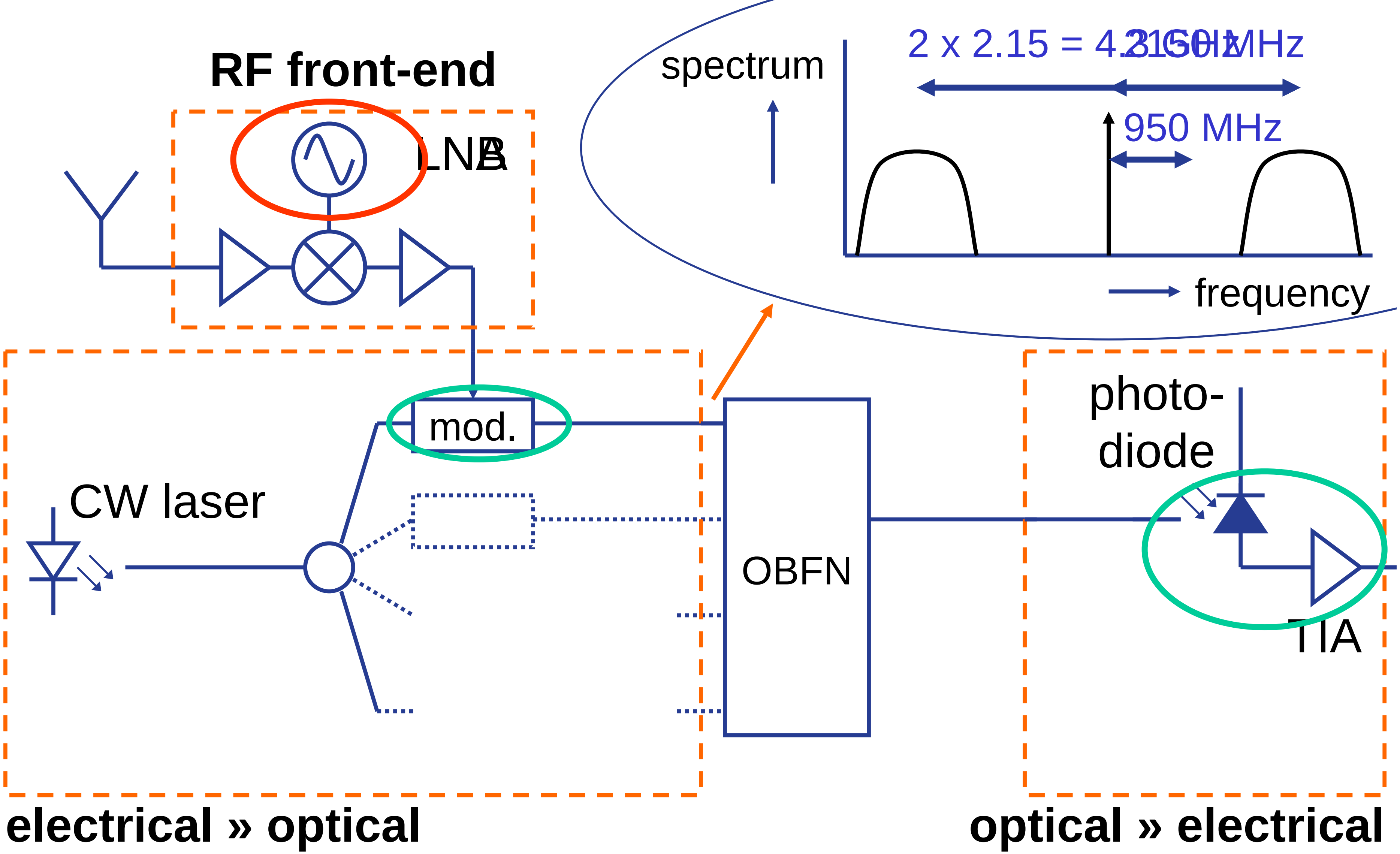


3. Optical beamformer: E/O and O/E conversion



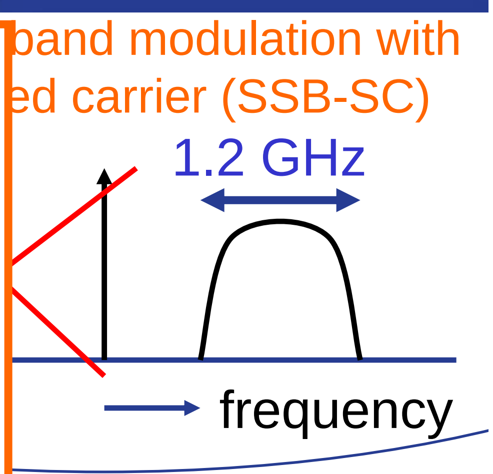
electrical » optical **optical » electrical**


RF front-end
LNA
LNB
spectrum
2 x 2.15 = 4.3 GHz
2150 MHz
950 MHz
frequency
mod.
CW laser
OBFN
photo-
diode
TIA
electrical » optical
optical » electrical

3. Optical beamformer: E/O and O/E conversion

Implementation of optical SSB modulation?

1. Optical heterodyning;
2. Phase shift method;
3. Filter-based method.



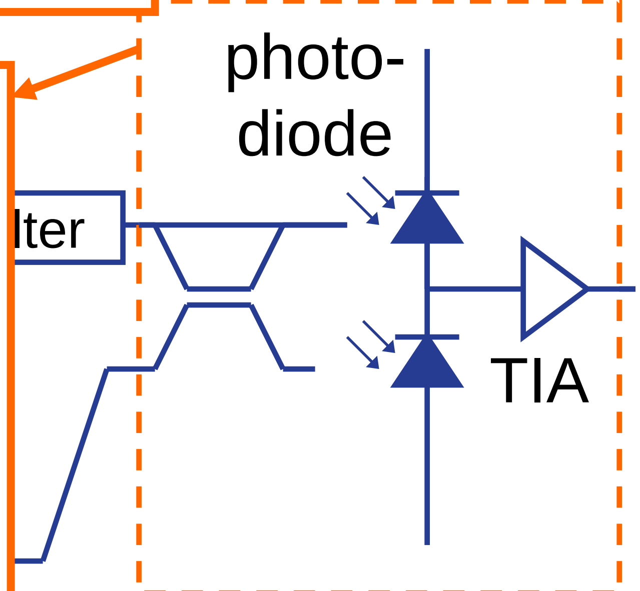
Balanced optical detection:

→ cancels individual ......sity terms;

→ mixing term remains;

→ reduces laser intensity noise;

→ enhances dynamic range.



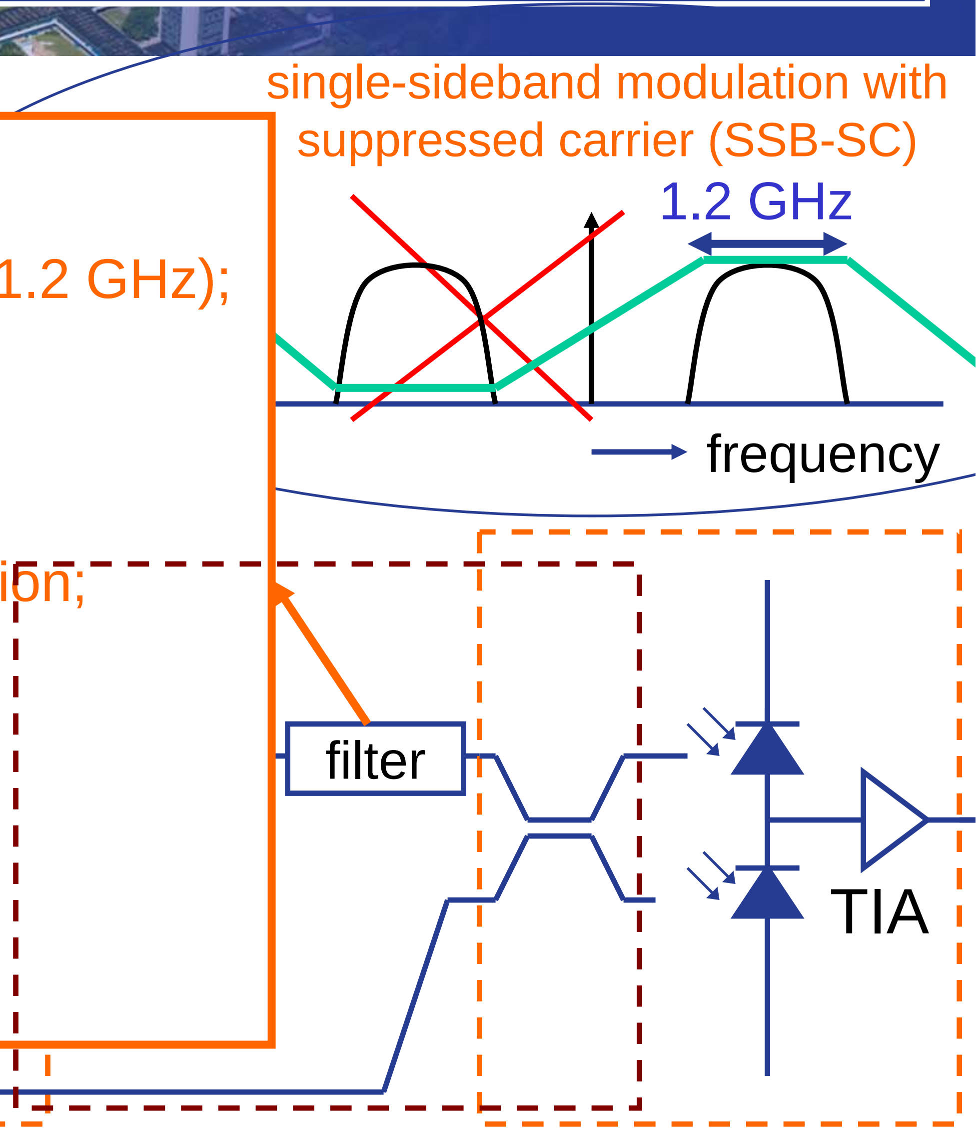
elec

optical » electrical

3. Optical beamformer: E/O and O/E conversion

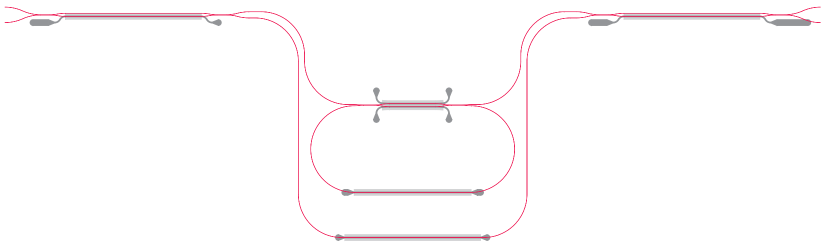
Filter requirements:

- Broad pass band and stop band (1.2 GHz);
- 1.9 GHz guard band;
- High stop band suppression;
- Low pass band ripple and dispersion;
- Low loss;
- Compact;
- Same technology as OBFN.

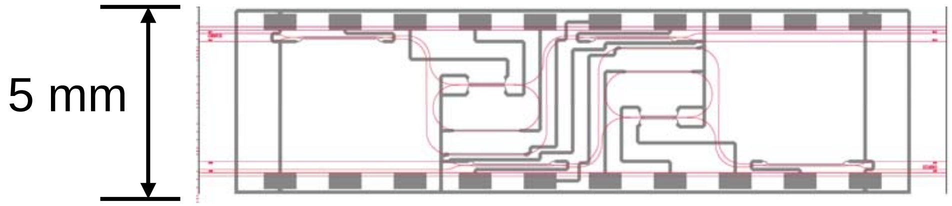


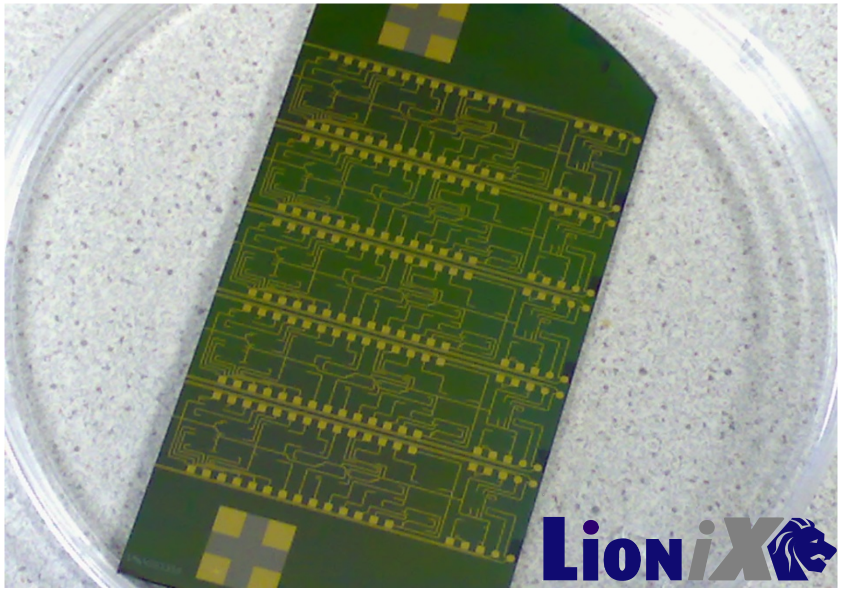
electrical » optical **1 chip !** **optical » electrical**

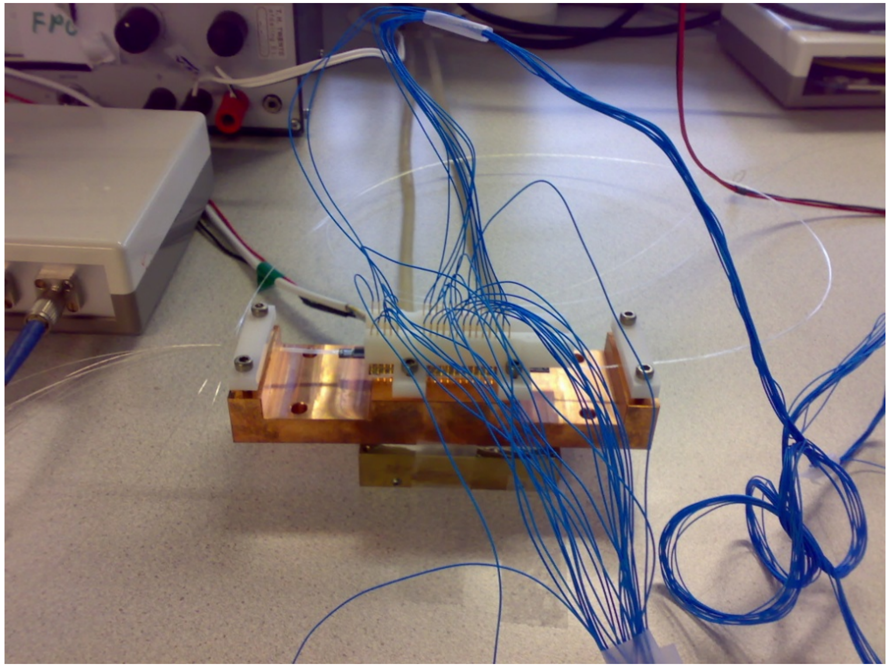
Optical sideband filter chip
in the same technology as the OBFN



MZI + Ring

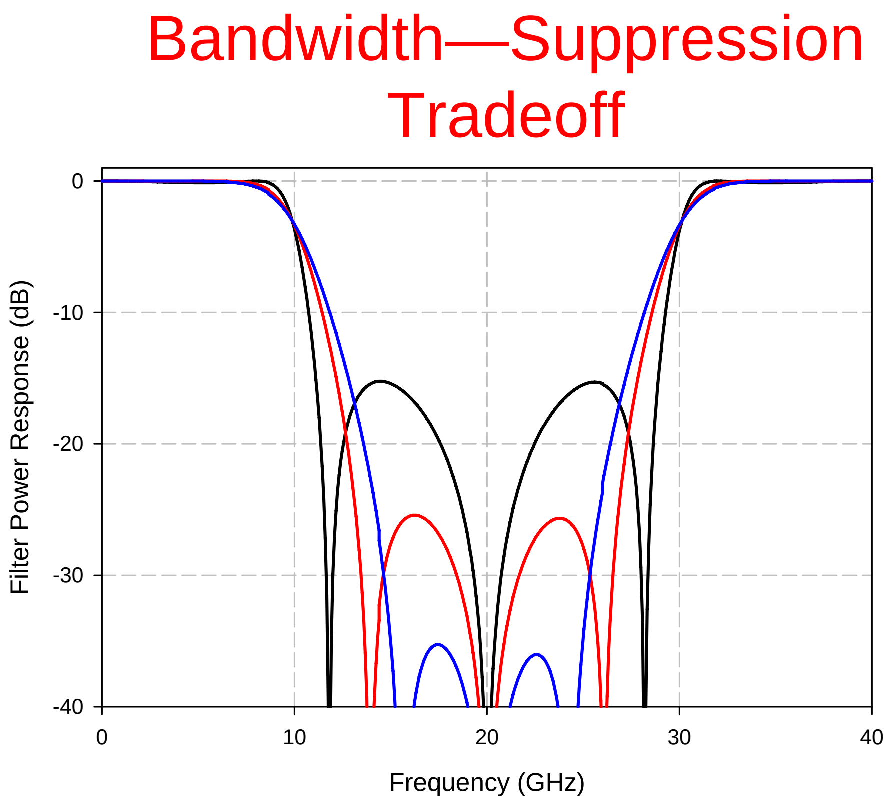


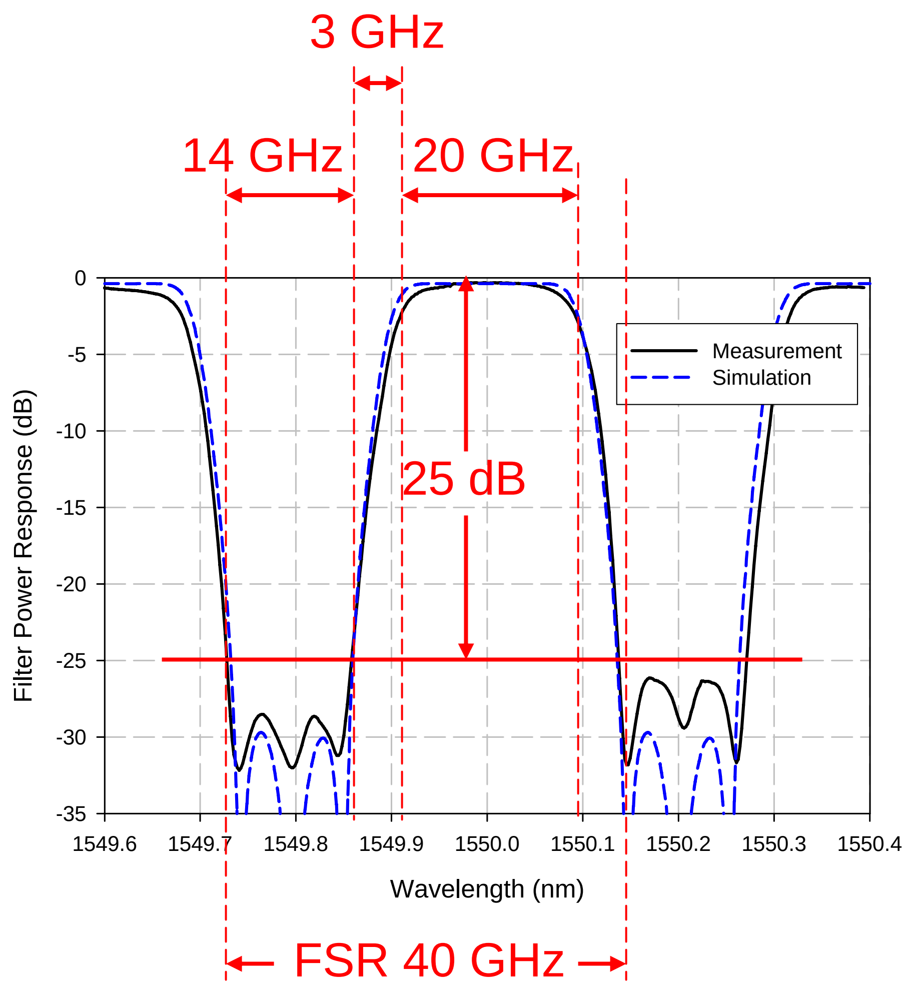




3. Optical beamformer: E/O and O/E conversion

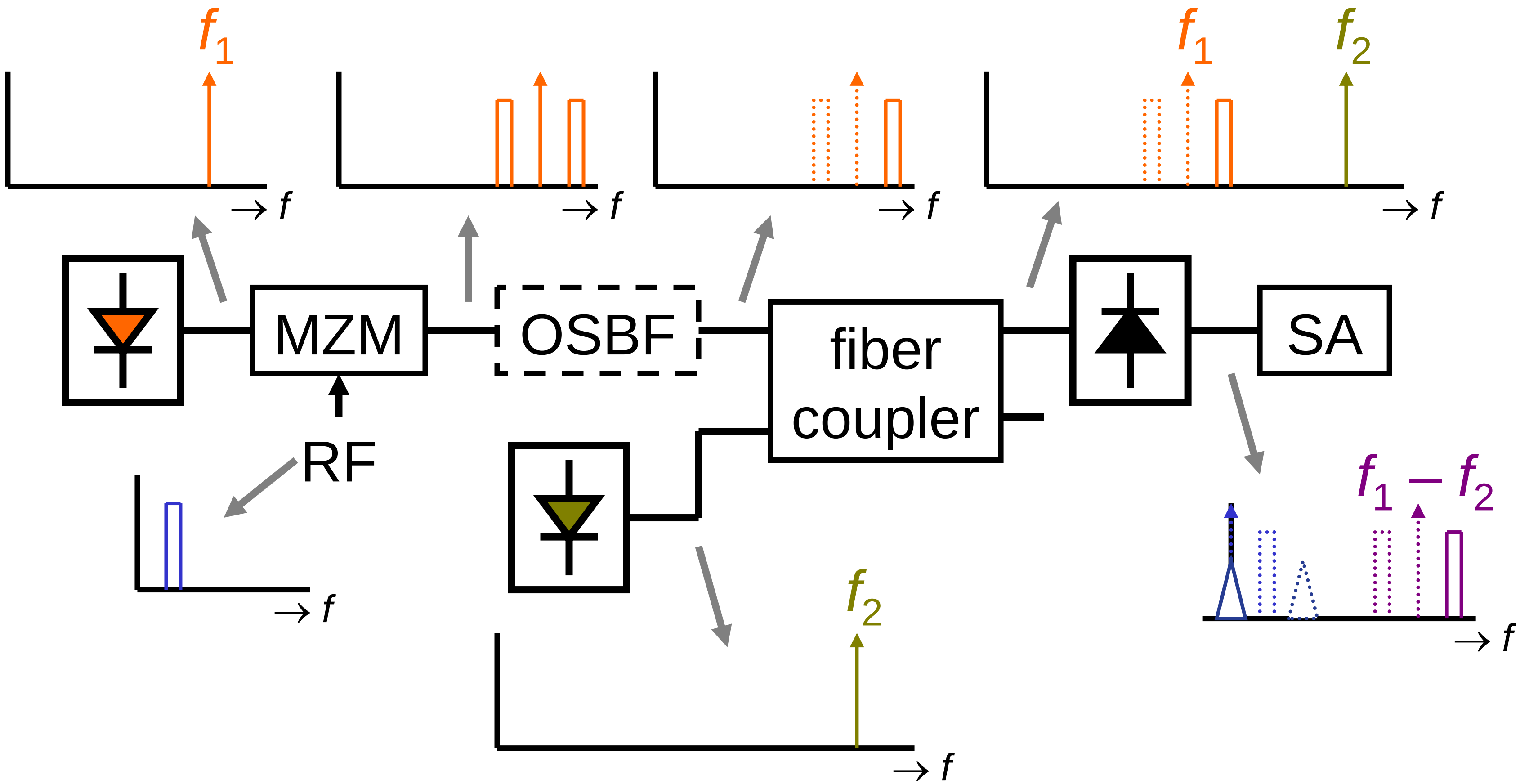
Measured filter response



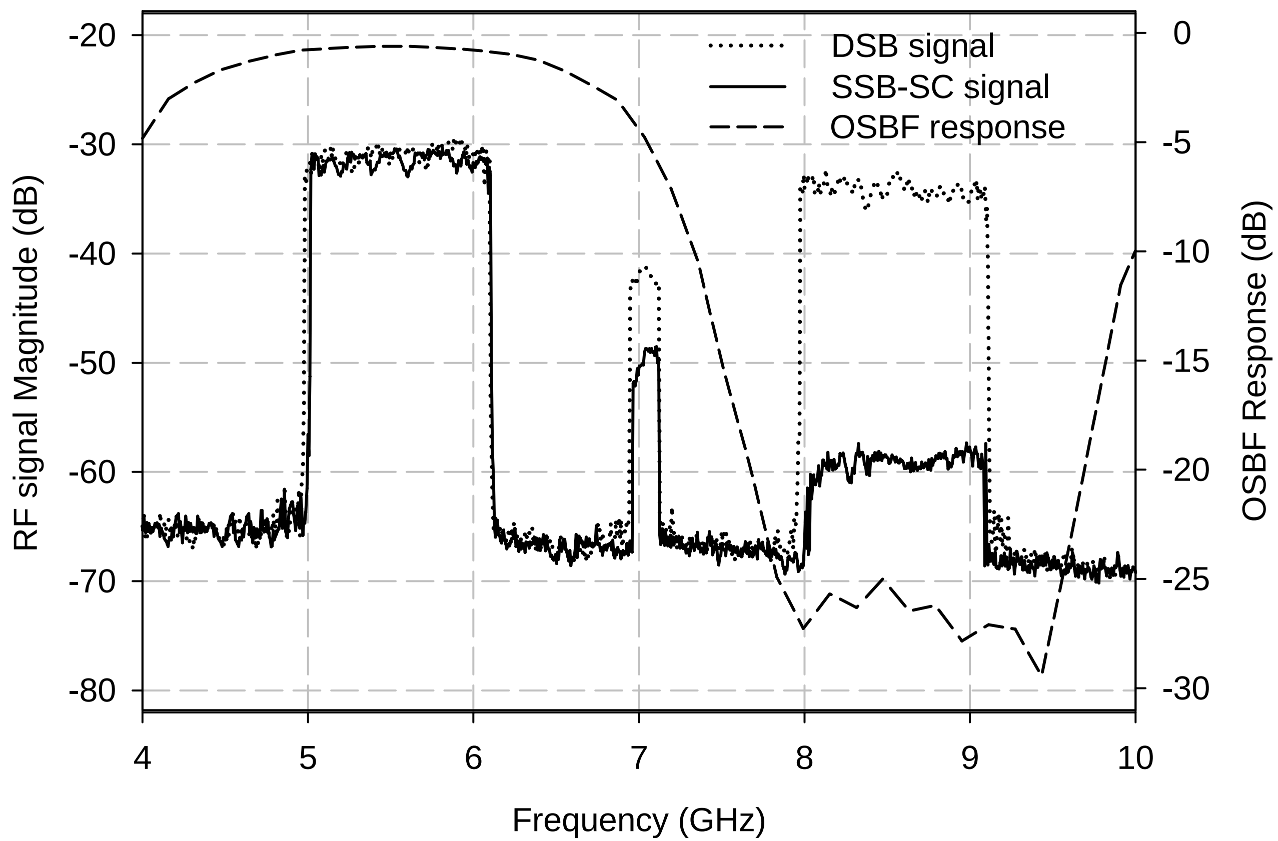


Spectrum measurement of modulated optical signal

Optical heterodyning technique:

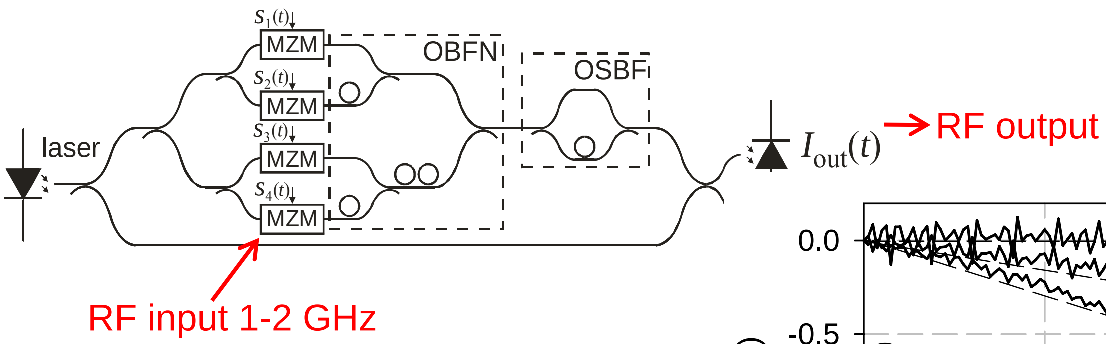


Spectrum measurement of modulated optical signal

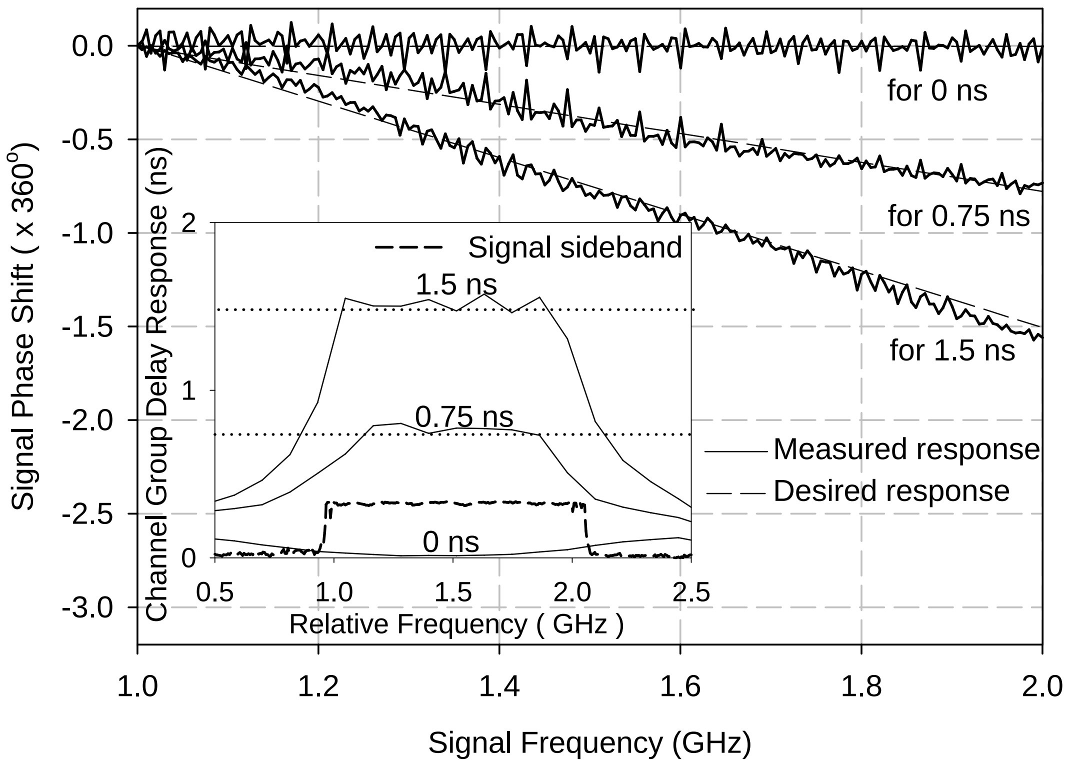


Measured filter response, and measured spectrum of modulated optical signal, with and without sideband-filtering

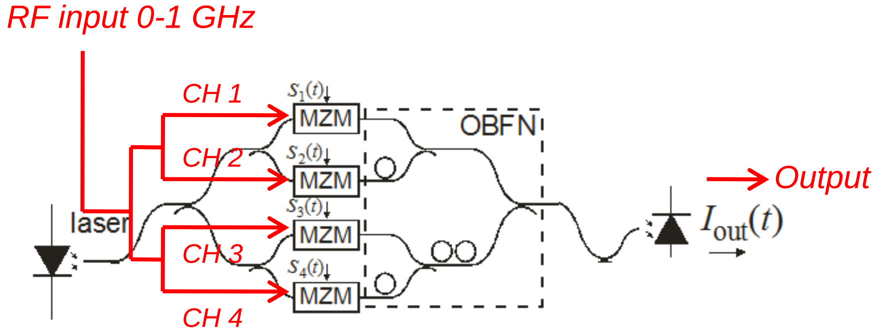
RF phase response measurements

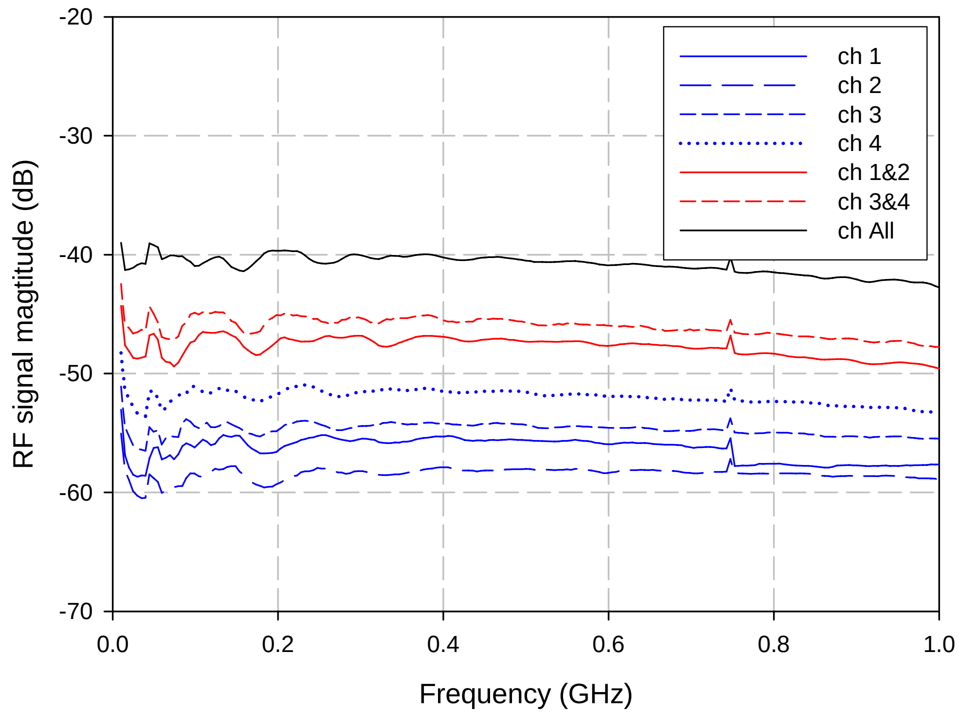


Measured RF phase response of one beamformer channel, for different delay values.



Signal combination measurements





Measured output RF power of beamformer with intensity modulation and direct detection, for

- 1 channel,
- 2 combined channels,
- 4 combined channels

Conclusions

- A novel squint-free, continuously tunable beamformer mechanism for a phased array antenna system has been described and partly demonstrated. It is based on filter-based optical SSB-SC modulation, and ORR-based OBFN, and balanced coherent detection.
- This scheme minimizes the bandwidth requirements on OBFN and enhances the dynamic range.
- Different measurements on optical beamformer chip successfully verify the feasibility of the proposed system.

Questions

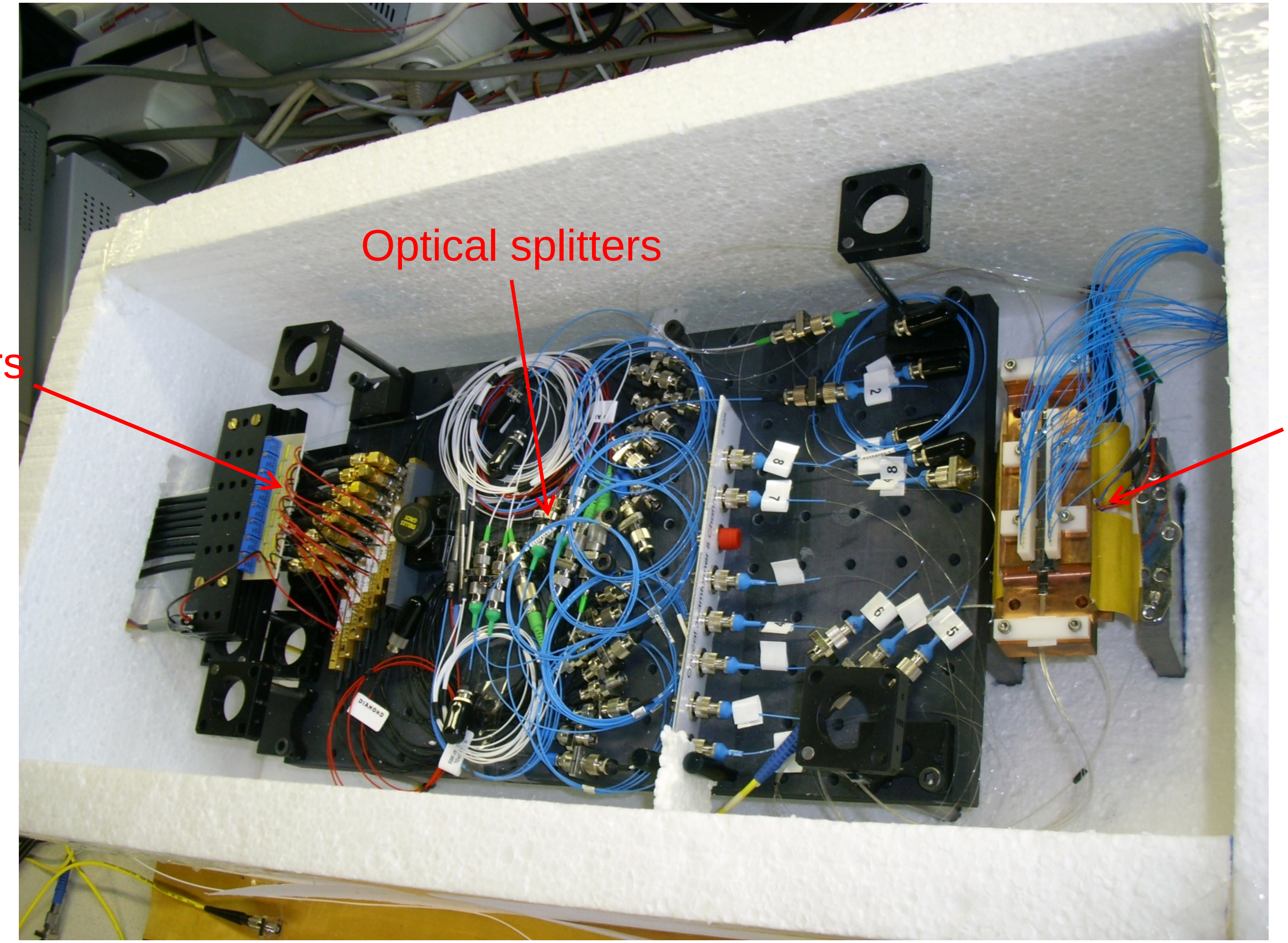
Thank you!

Questions

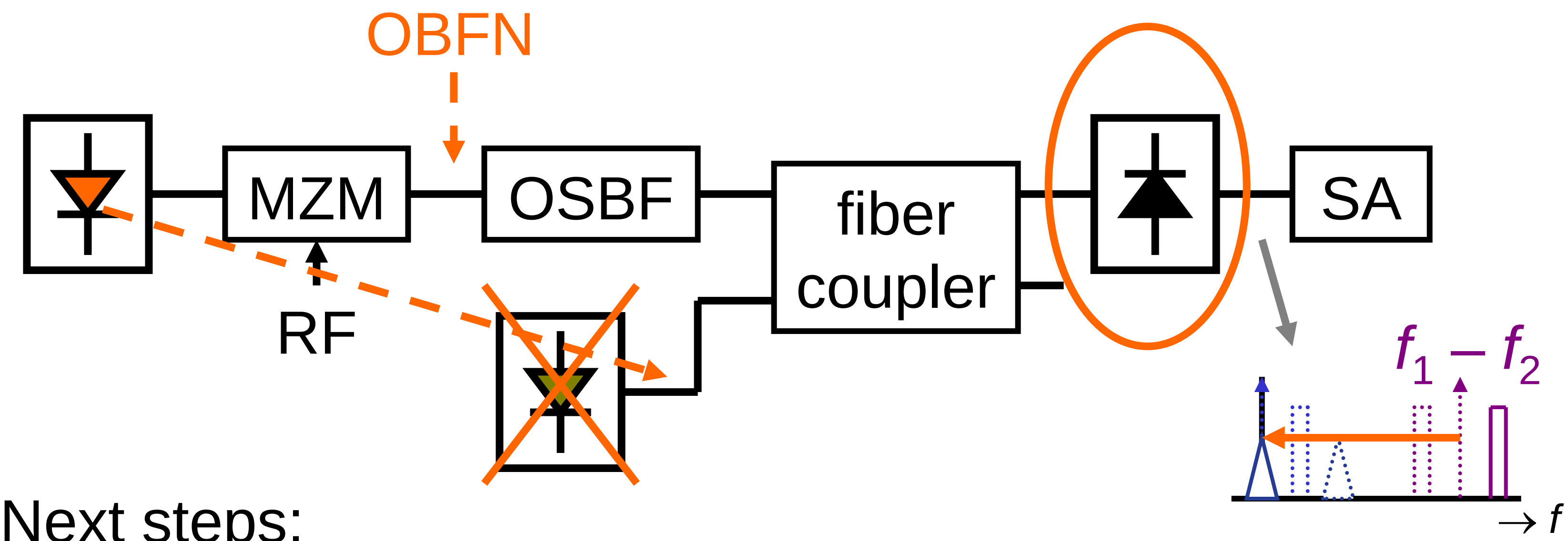
Thank you!

Questions?

3. Optical beamformer: System setup



Further demonstration of chip functionality

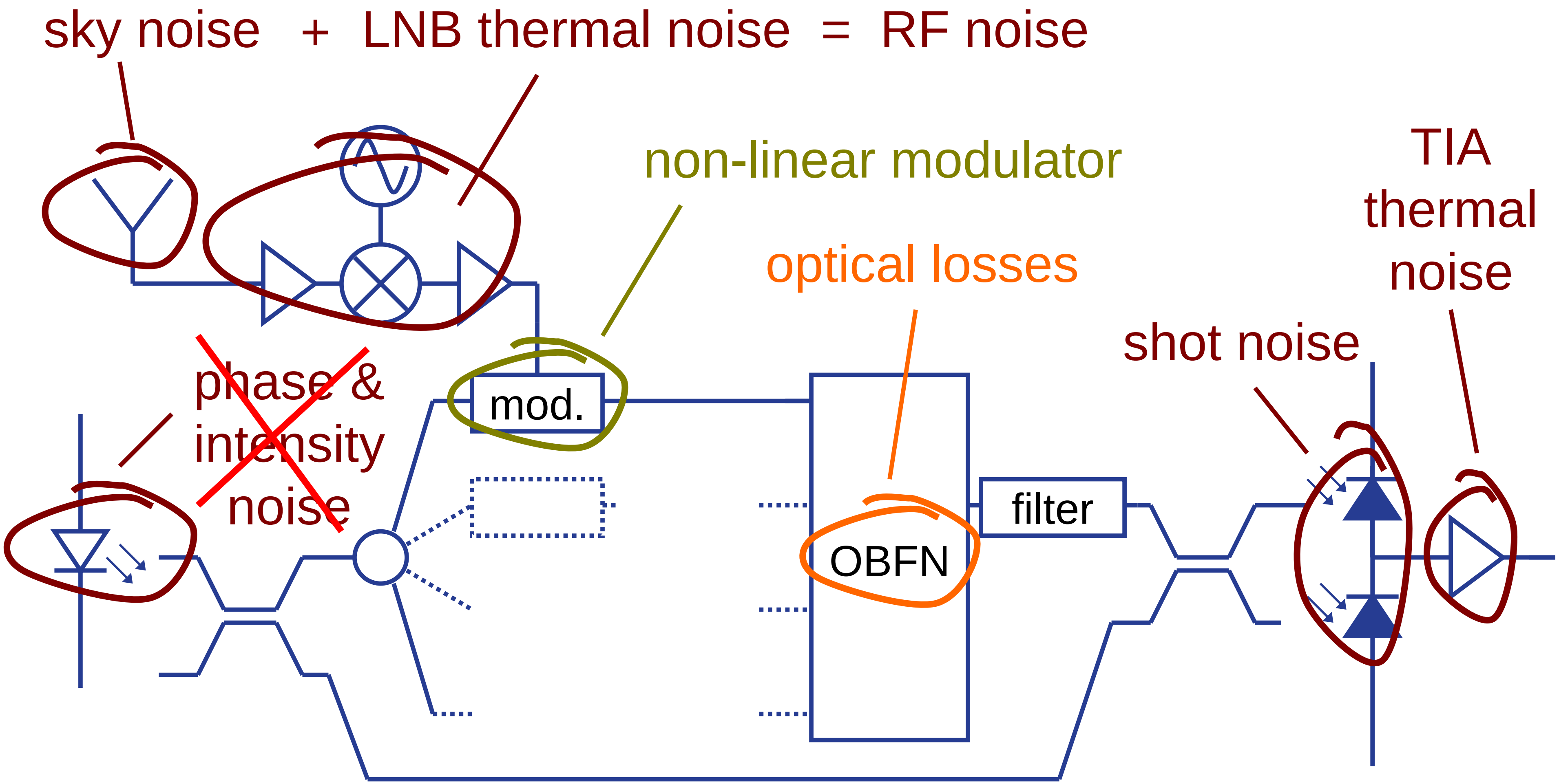


Next steps:

- Demonstrate optical homodyning by balanced detection;
- Demonstrate delay of broadband RF signal in OBFN;
- Combine multiple signals in OBFN by optical phase-locking .

3. Optical beamformer: noise performance

Losses, noise, and distortion



gives an expression for the modulated signal

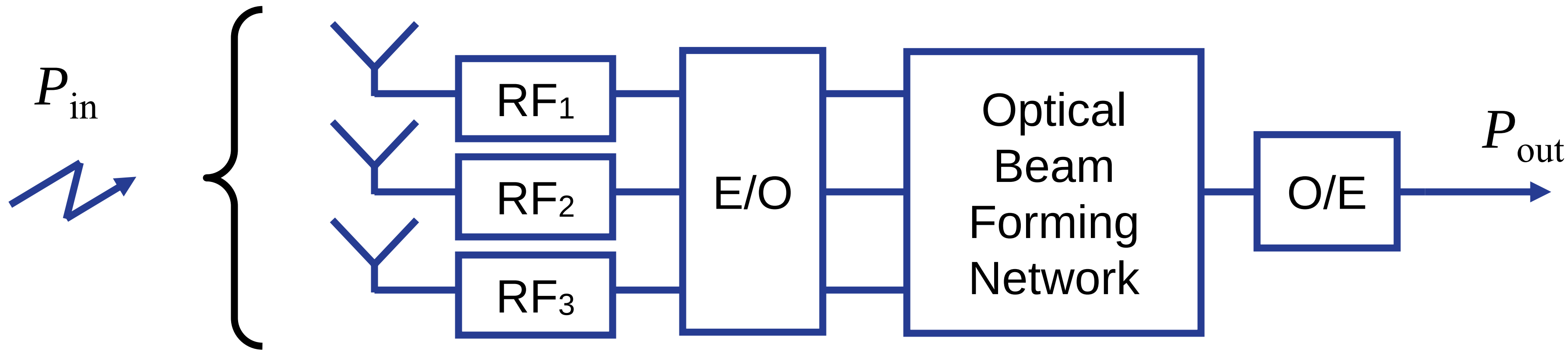
$$
\begin{aligned}
E_{\mathrm{MZM},m}(t) = \frac{E_{\mathrm{in},m}(t)}{2\sqrt{L_{\mathrm{x}}}} & \left[\exp\left\{\mathrm{j}\,\frac{\pi\,\Delta V}{2V_{\pi,\mathrm{DC}}}\right\} \prod_n \sum_{k_n} \mathrm{J}_{k_n}(A_n) \exp\left\{\mathrm{j}\;k_n\left[\phi_n + \frac{\pi}{2}\right]\right\}\right. \\
& \left. + \exp\left\{-\mathrm{j}\,\frac{\pi\,\Delta V}{2V_{\pi,\mathrm{DC}}}\right\} \prod_n \sum_{k_n} \mathrm{J}_{k_n}(A_n) \exp\left\{\mathrm{j}\;k_n\left[\phi_n + \frac{3\pi}{2}\right]\right\}\right] \\
= \frac{E_{\mathrm{in},m}(t)}{2\sqrt{L_{\mathrm{x}}}} & \sum_{k_1}\cdots\sum_{k_N}\left[\prod_n \mathrm{J}_{k_n}(A_n)\right] \\
& \cdot\left[\exp\left\{\mathrm{j}\,\frac{\pi\,\Delta V}{2V_{\pi,\mathrm{DC}}} + \mathrm{j}\sum_n k_n\left[\phi_n + \frac{\pi}{2}\right]\right\}\right. \\
& \left. + \exp\left\{-\mathrm{j}\,\frac{\pi\,\Delta V}{2V_{\pi,\mathrm{DC}}} + \mathrm{j}\sum_n k_n\left[\phi_n + \frac{3\pi}{2}\right]\right\}\right]. \qquad (4.58)
\end{aligned}
$$

Next, we use

$$
\exp\{\mathrm{j}\alpha\} + \exp\{\mathrm{j}\beta\} = 2\ \cos\left(\frac{\alpha-\beta}{2}\right)\ \exp\left\{\mathrm{j}\ \frac{\alpha+\beta}{2}\right\} \qquad (4.59)
$$

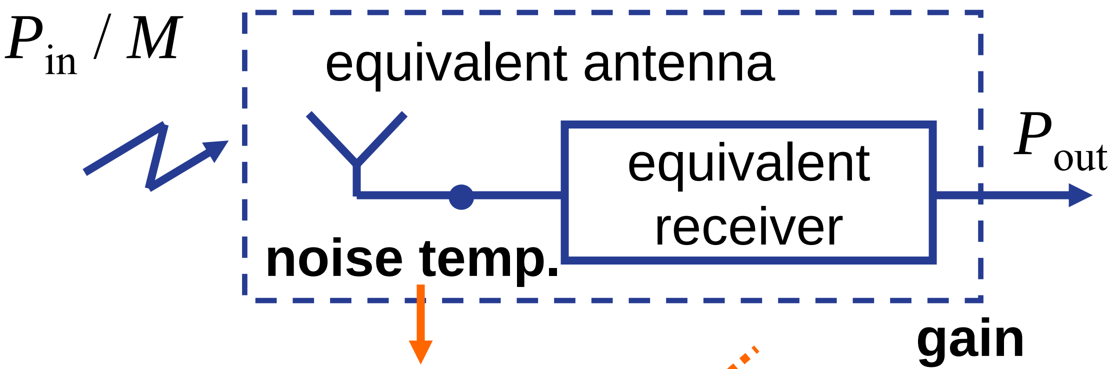
to rewrite this as

3. Optical beamformer: noise performance



analog optical link, multiport

RF component, two-port



$T_{sys} = T_{sky} + T_{LNB}$ ~~$+ T_{OBF}$~~

Equivalent antenna gain
- antenna patterns
- number of antennas
- amplitude tapering

Noise temperature
- sky noise
- receiver noise (LNB + OBF)

4. Conclusions & future work

Conclusions:

- A novel optical beamformer concept employing a fully integrated, ring resonator-based OBFN and filter-based optical SSB-SC modulation was introduced and partly demonstrated;
- Main advantages of this concept are:
  - low loss and large instantaneous bandwidth;
  - continuous tunability (high resolution);
  - relatively compact and light-weight realization;
  - inherent immunity to EMI;
  - potential for integration with optical distribution network;
- The dynamic range of the phased array receiver system is not significantly reduced by the optical beamformer.

4. Conclusions & future work

Future work:

- Characterize demonstrator chipset;
- Finalize software for control block;
- Build up beamformer demonstrator;
- Integrate with rest of system (array + front-end);
- Scale up demonstrator to >1000 antenna elements.

Acknowledgement

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Rene Eveleens
Harm Schippers

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Hans van Gemeren

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Leimeng Zhuang
David Marpaung
Bas den Uyl
Mark Ruiter
Timon Vrijmoeth
Jorge Pena Hevilla
Robbin Blokpoel
Tomas Jansen
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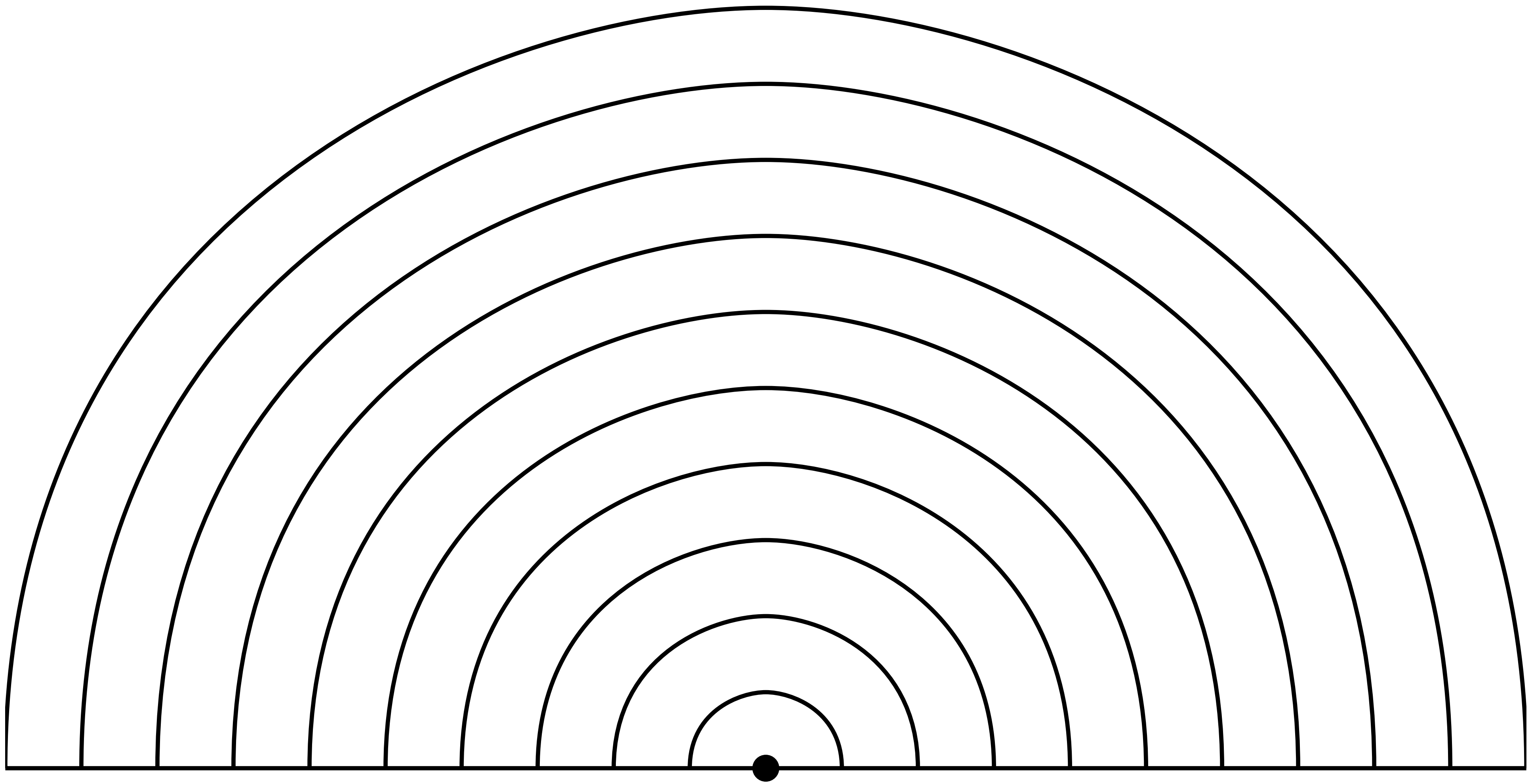
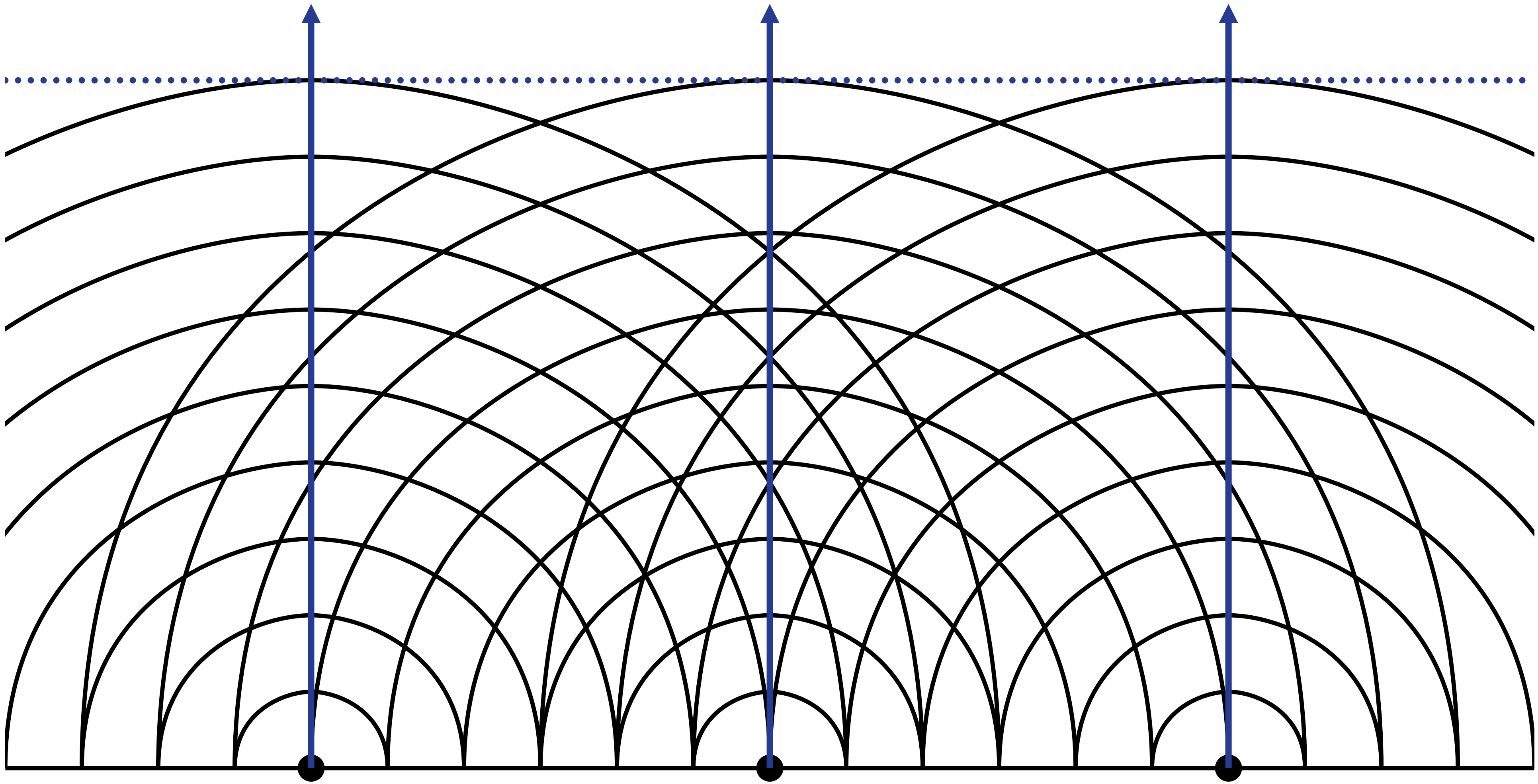
Marcel Hoekman
Douwe Geuzebroek
Robert Wijn
Rineke Groothengel
Melis Jan Gilde
René Heideman
Hans van den Vlekkert

Questions?

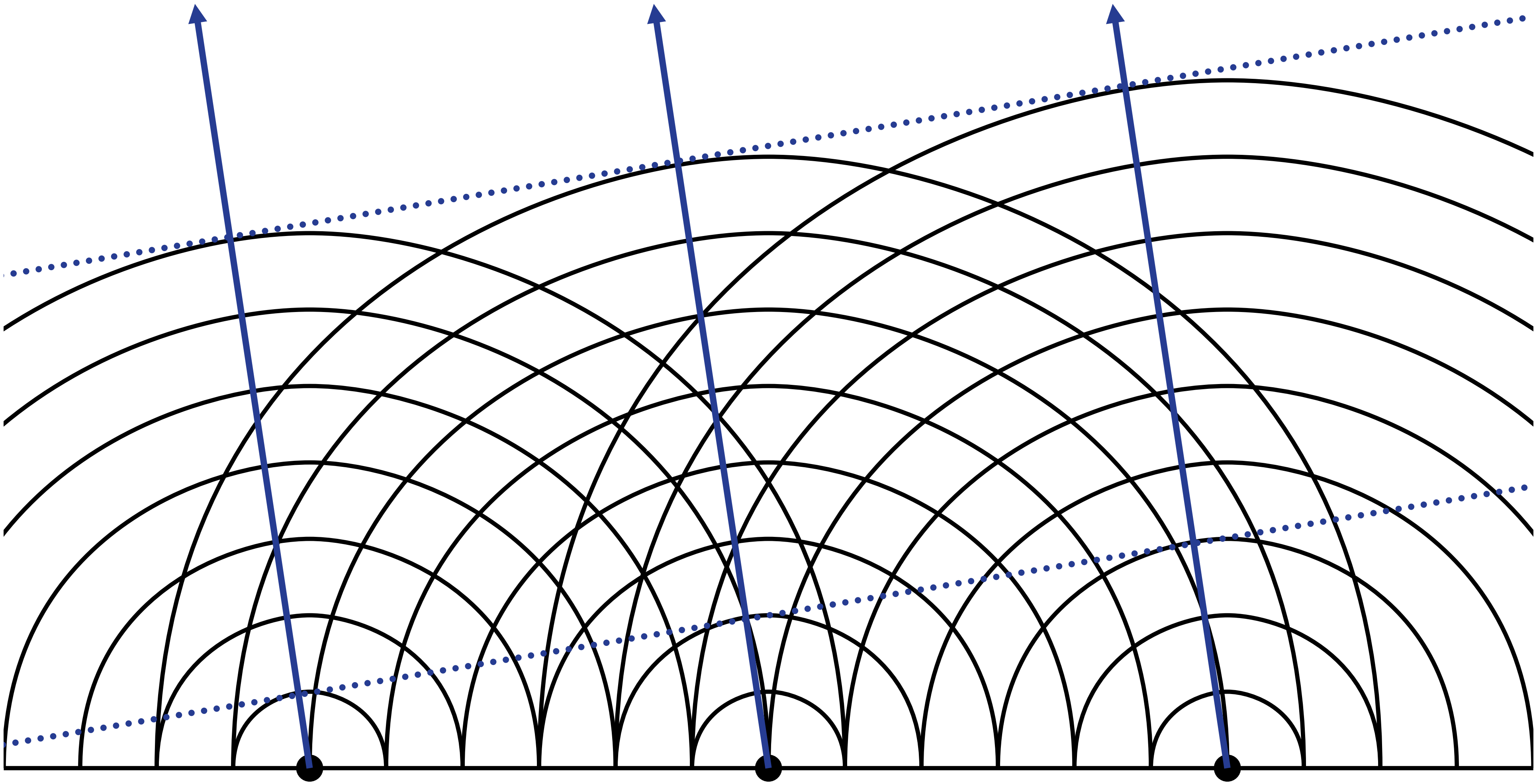
App. A: Phased Array Antenna : single antenna



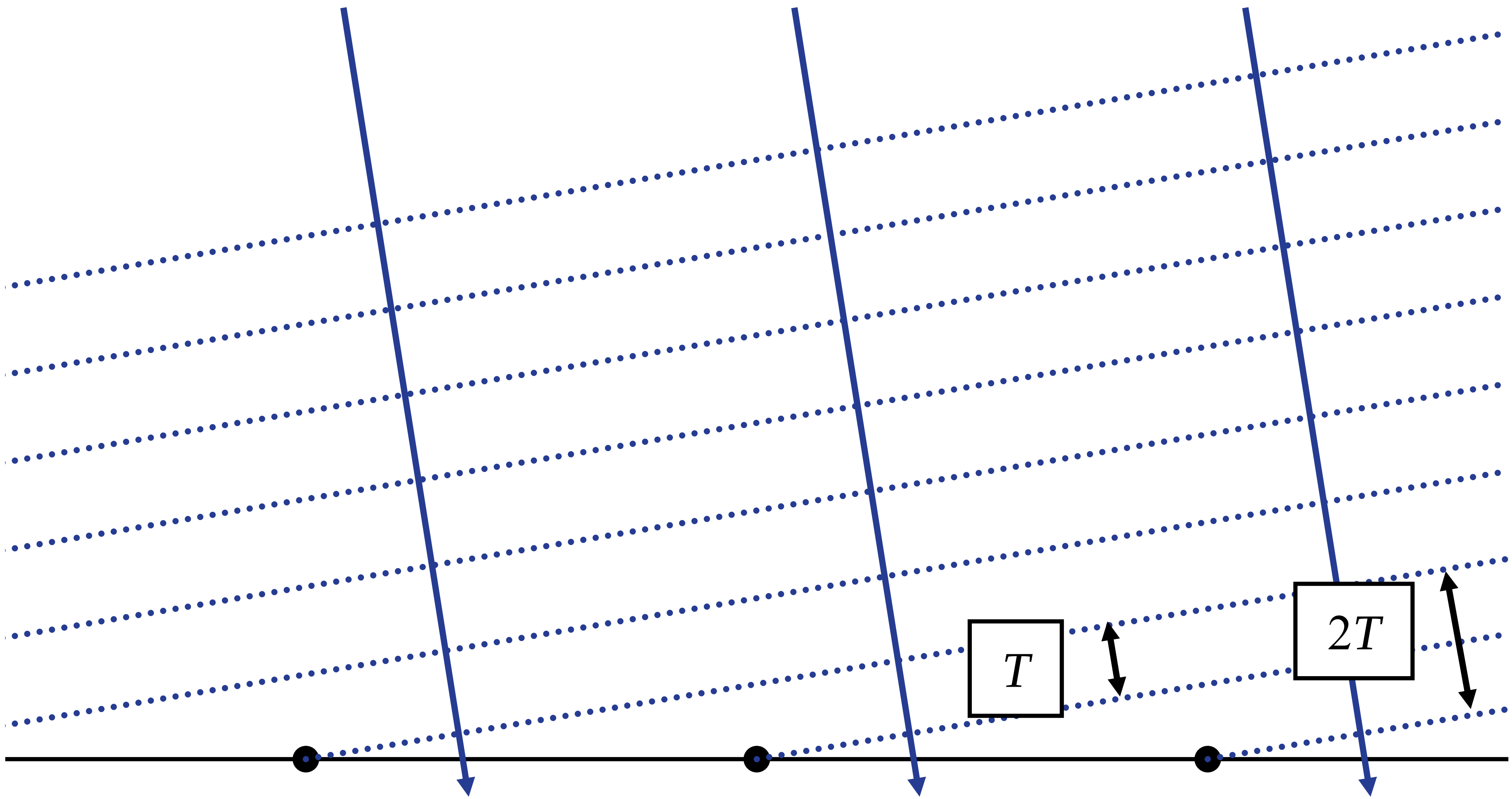
App. A: Phased Array Antenna: multiple antennas



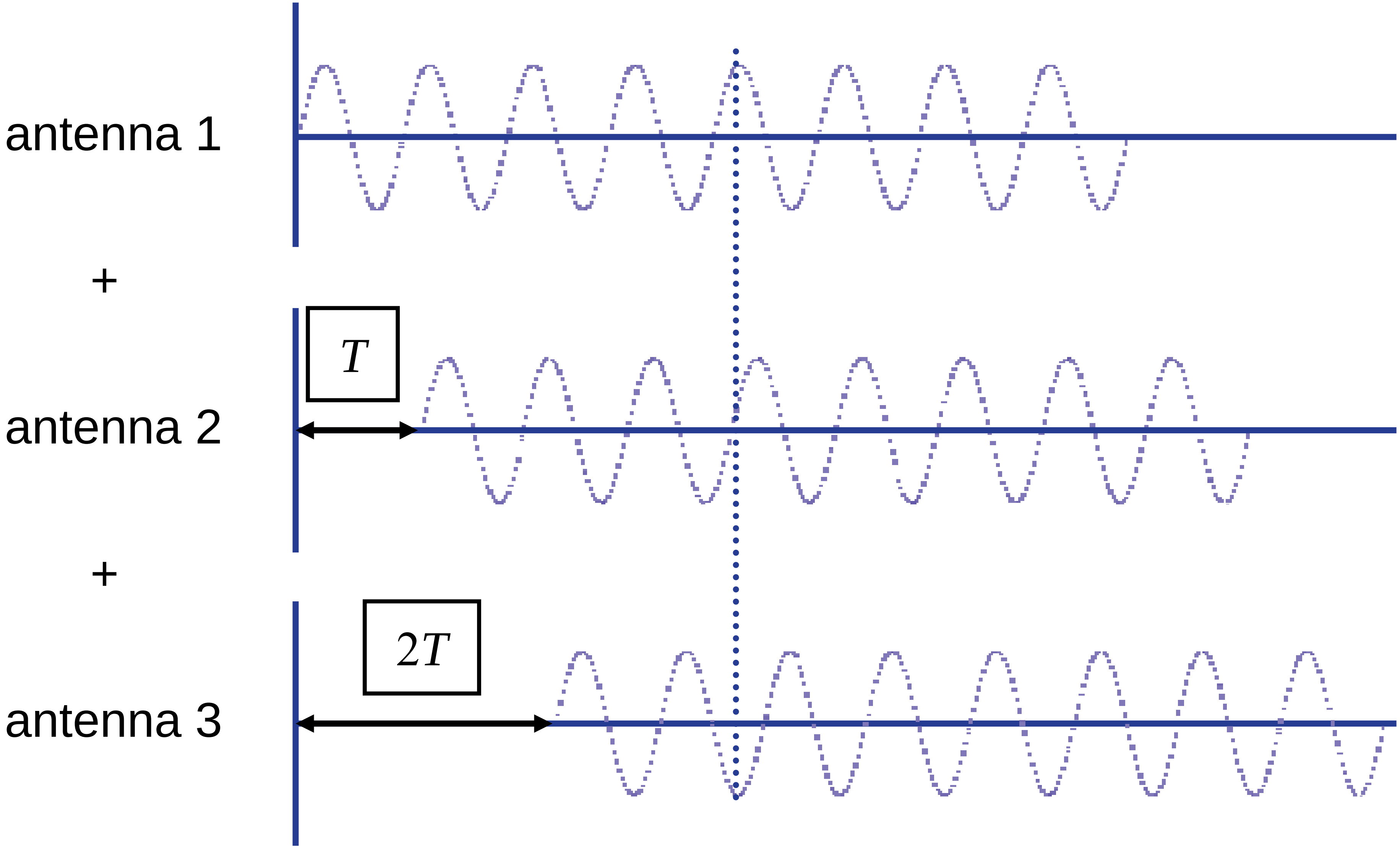
App. A: Phased Array Antenna: beam steering



App. A: Phased Array Receive Antenna: delays



App. A: Phased array antenna: beamforming network

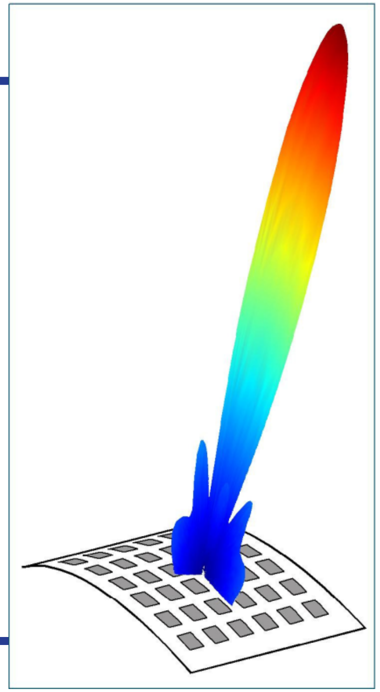


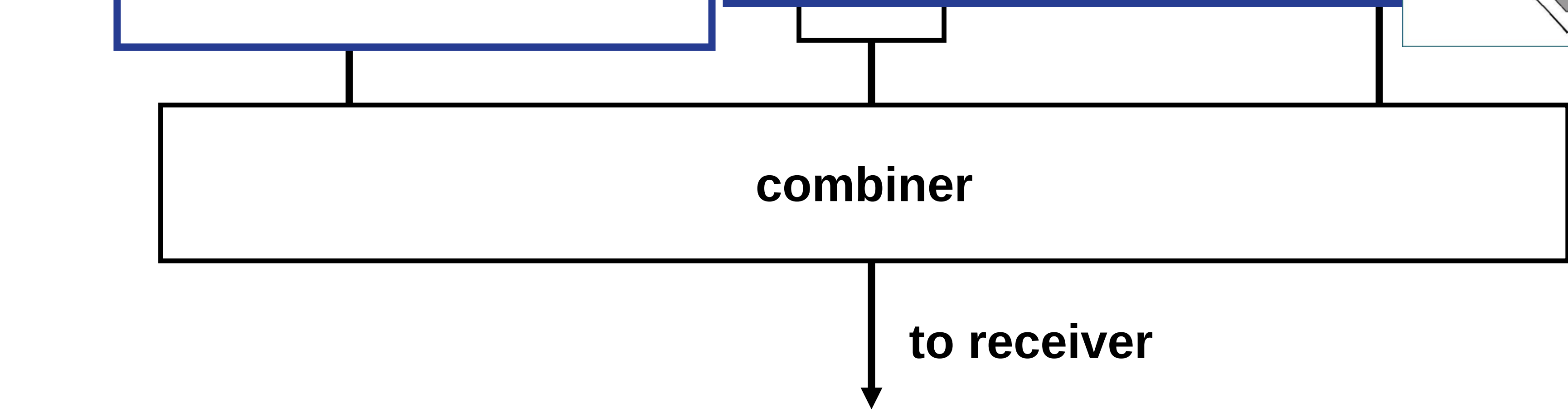
App. A: Phased array antenna: beamforming network

Challenges:

- Small beam width;
- High gain;
- Low sidelobes;
- Agile steering;
- High bandwidth;
- High resolution;
- Low costs.

→ High number of antenna elements;
→ Amplitude tapering;
→ Fast tuning;
→ True time delays;
→ Continuous tunability;
→ High integration level.





App. B: Microwave Photonics: what, and why?

What?

Microwave Photonics (MWP): [Capmany & Novak, Nature Photonics 2007]

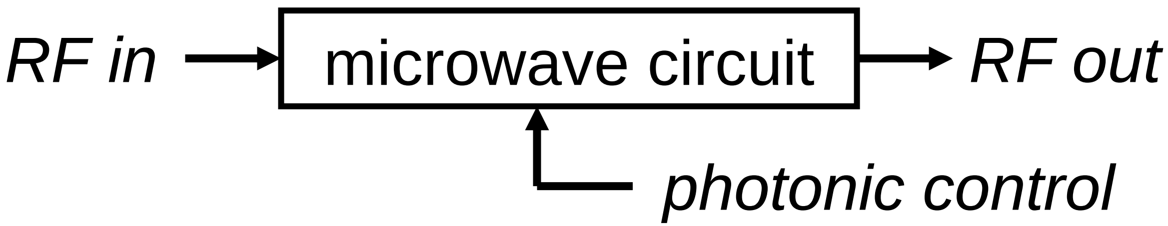
the study of photonic devices

operating at microwave frequencies

and their application to microwave and optical systems

1. Performing microwave functions in optical domain;

2. Control microwave components by means of photonics.



App. B: Microwave Photonics: what, and why?

What?

1. Signal generation, for instance
   - RF carriers;
   - ultra-short (UWB) pulses;
2. Signal transport/distribution, for instance
   - sub-carrier multiplexing (SCM) for CATV distribution;
   - antenna remoting for e.g. RADAR;
   - Radio-over-Fiber distribution in wireless access networks;
3. Signal processing, for instance
   - high-frequency filtering;
   - up/down conversion;
   - A/D conversion;
   - beamforming for phased array antennas.

App. B: Microwave Photonics: what, and why?

Why?

Inherent advantages of photonics:

- huge bandwidth (~200 THz for optical fiber);
- low-losses (<0.2 dB/km for optical fiber);
- compact & light-weight;
- immune to EMI;
- galvanic separation between blocks
  $\rightarrow$ no induction, high-voltage protection, common grounding;
- flexible: transparent to signal frequency and format;
- loss & dispersion low over large bandwidth
  $\rightarrow$ low signal distortion;

App. B: Microwave Photonics: what, and why?

Why?

Trends in enabling technologies:

- Advances in components for E/O & O/E conversion:
  high-frequency directly-modulators lasers, modulators, detectors;
- Advances in photonic integrated circuits:
  - low losses;
  - complex structures;
  - reproducibility;
  - packaging;
  - costs for mass fabrication;
- Other enabling technologies: CMOS, microwave, ...;

App. B: Microwave Photonics: what, and why?

Why?

Trends in application areas, a.o. wireless communications:

- Ever higher frequencies (*xx* GHz) and capacities (Gbps);
- Smaller cell sizes → high density of access points;
- Increasing complexity (dyn. spectrum all., channel adaptation);
- Increasing demand for flexibility;

→ some functions become difficult/impossible in microwave/CMOS;

→ desirable to centralize functionality, by means of Radio-over-Fiber;

But: MWP + electronics are not necessarily competitive

→ future trend: advancing integration of electronics and photonics

(MEMPHIS!)

App. B: Microwave Photonics: what, and why?

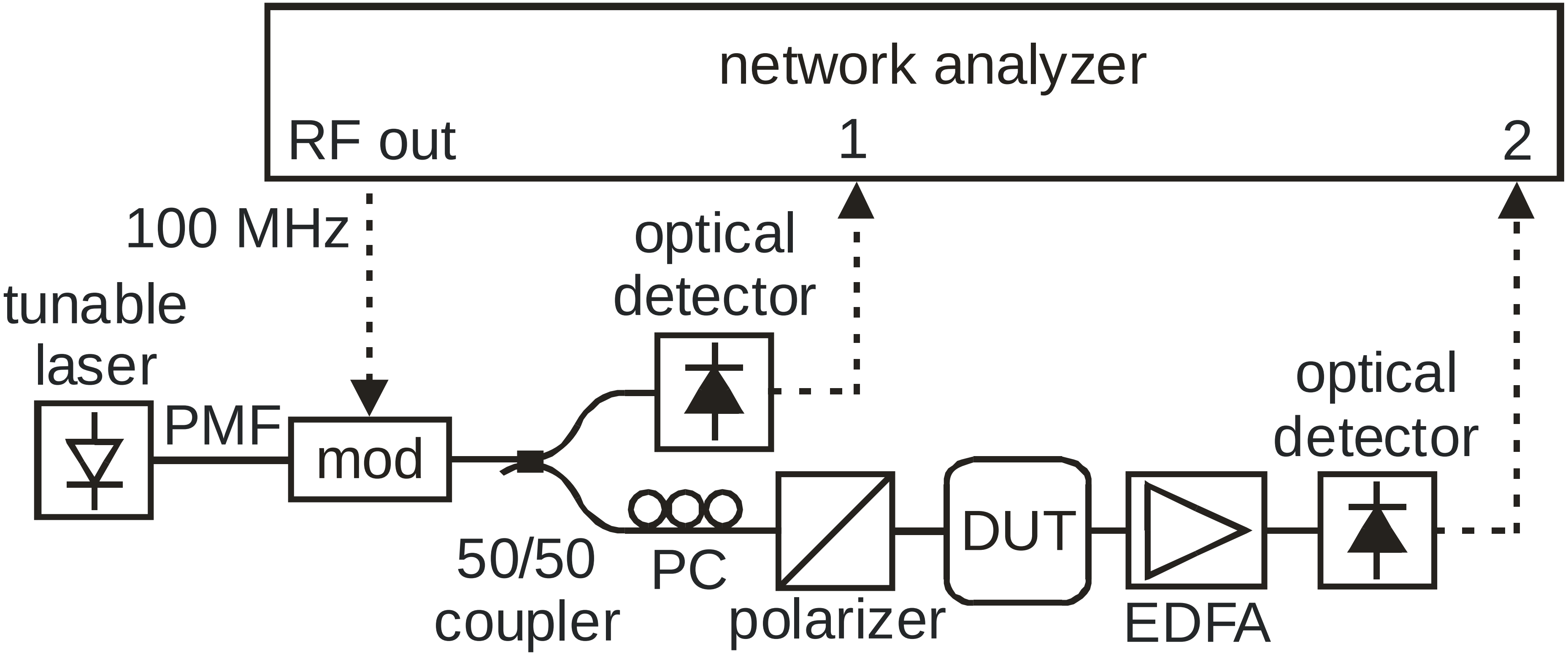
Challenges:

- Component design (modulators, detectors, photonic ICs):
  - requirements (bandwidth, loss, ...);
  - fabrication technology;
  - packaging/system integration;
- Design of efficient system architectures;
- Performance analysis and improvement (SNR, DR);
- Keep the costs low!

App. C: OBFN measurement setup

Phase-shift method:

$$\tau_g(\lambda) = \frac{\varphi_1(\lambda) - \varphi_2(\lambda)}{2\pi\ f_{RF}}$$



1. Introduction: partners & funding

Project partners:

NLR

CYNER SUBSTRATES

LioniX

Funding:

SenterNovem

Agentschap voor duurzaamheid en innovatie

EURIPIDES

Eureka Initiative for Packaging & Integration of µDevices & Smart Systems

The SMART project is part of the
Euripides project SMART
(Partners: EADS, CNAM, Radiall, CIMNE, Moyano)