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OBFN activities within Thales Photonic Lab

D. Dolfi, L. Morvan,… Thales Research & Technology – Fr
J. Chazelas, C. Fourdin, S. Formont,… Thales Systèmes Aéroportés
T. Merlet,… Thales Air Systems
M. Maignan, M. Sotom,… Thales Alenia Space

Research & Technology

- **Introduction**
- **Early experiment**
- **Recent achievements**
  - Ultra-Wideband free-space beamforming
  - Beamforming for ground radar
  - Beamforming for communications
- **Advanced studies :**
  - OBFN concepts : adapted LO as an example
  - OBFN components :
    - Tunable delays : PBG, SOA
    - Switches : new EO materials
    - Dual-frequency / SSB modulation schemes : DFL

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Thales Photonics BGs-Corporate Lab.

Thales Alenia Space
satellite applications

Thales Comm.
Mil Com applications

Thales Laser
solid state lasers

Thales Netherlands
naval applications

Thales Sensors UK
naval ESM appli.

Alcatel-Thales 3-5 Lab.
optoelectronic components

Thales Aerospace Div.
- RF modules and optical links developments
- Photonic architectures in airborne systems

Thales Air Systems Div
- RF & Digital optical link developments
- Photonic architectures for ground based radars

Thales Research & Techno.
- photonic architectures optoelectronic processing

TTCS
- photonic architectures for PAA

Thales@NTU
- photonic components

Research Institutes
- Wideband RF Summation
- Switching matrices
- Photo HBT & mixers
- Dual frequency sources….

SMEs
- RF optical modules
- Integrated WDM modules
- Optical waveguides
- …

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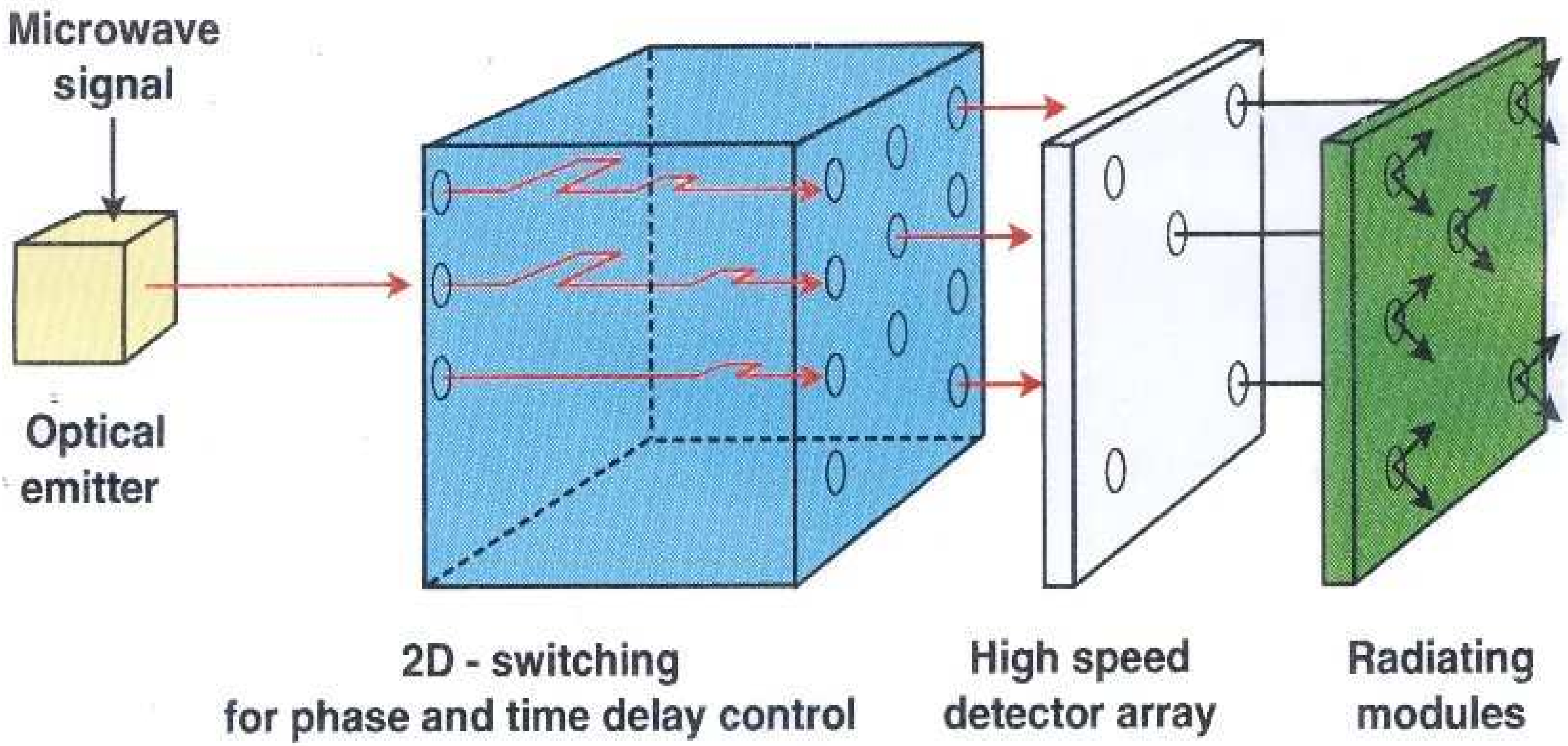
Transmit mode



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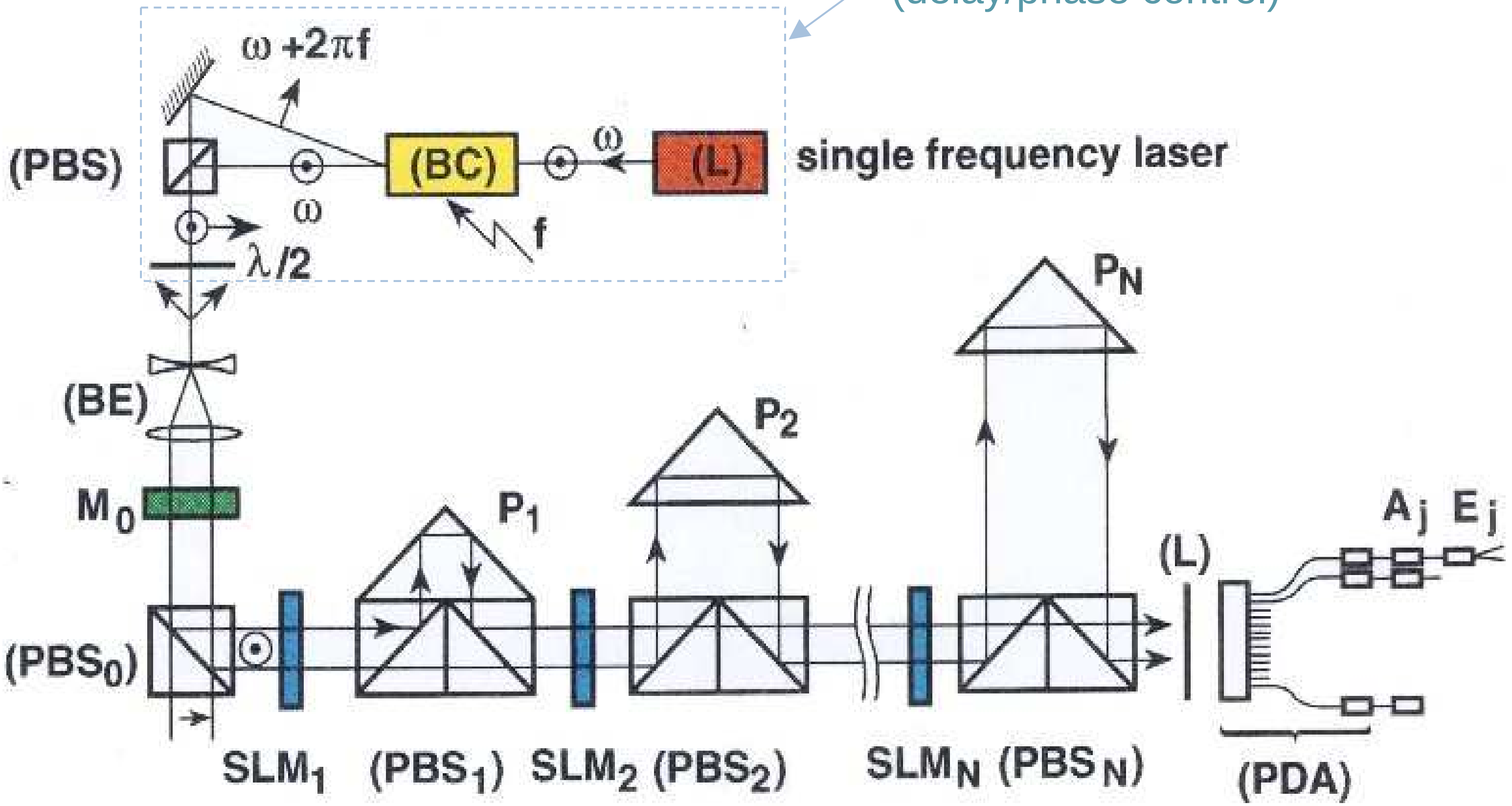
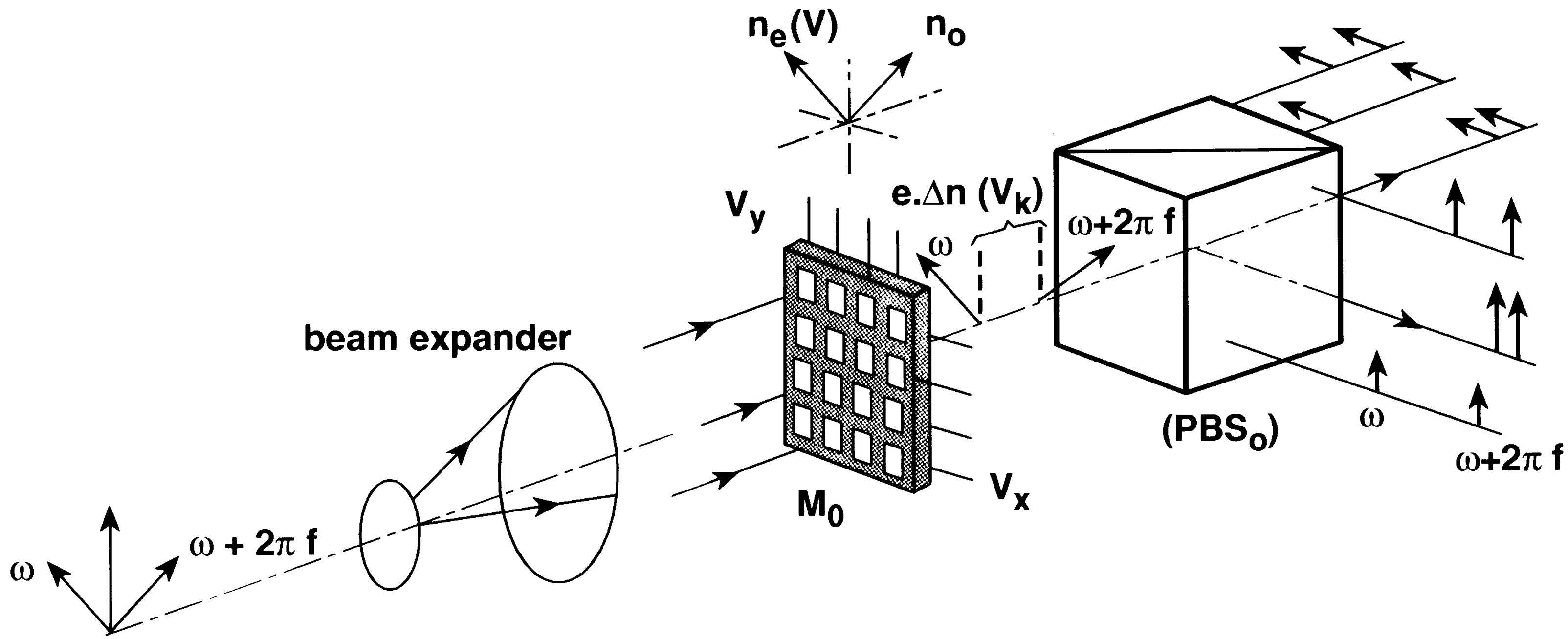
RF signal heterodyne generation (delay/phase control)



SLM_i : polarization rotation



- Electrically controlled birefringent mode
- p x p pixels
- on channel k: $i(k)=i_0 \cos(2\pi f t + 2\pi e \Delta n(V_k)/\lambda)$ with $\Delta n(V_k)=n(V_k)-n_0$

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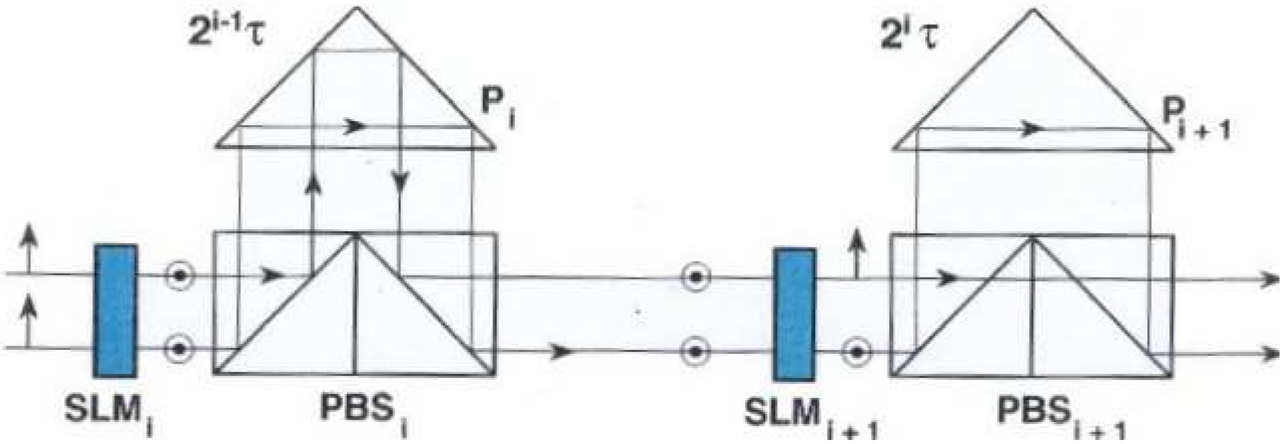

- N SLMs ⇨ 2^N delays
  - each SLM_i : pxp pixels
  - channel k: $i_k(t)=i_0 \cos(2\pi f t + 2\pi f \Sigma \varepsilon_{kj} 2^{j-1} \tau)$
    - If reflexion on PBSj $\varepsilon_{kj} = 1$
    - Else $\varepsilon_{kj} = 0$

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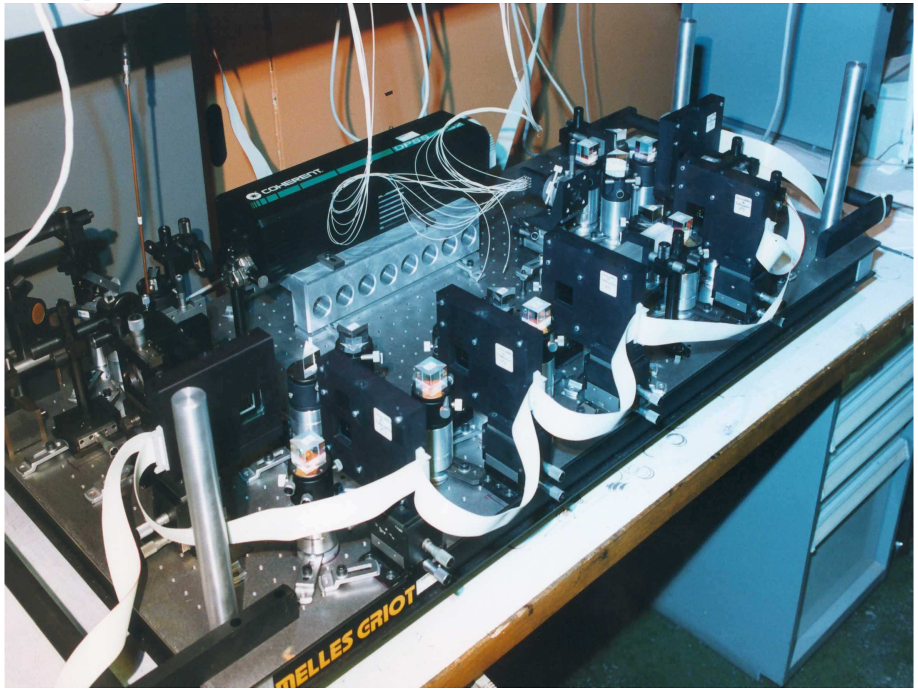
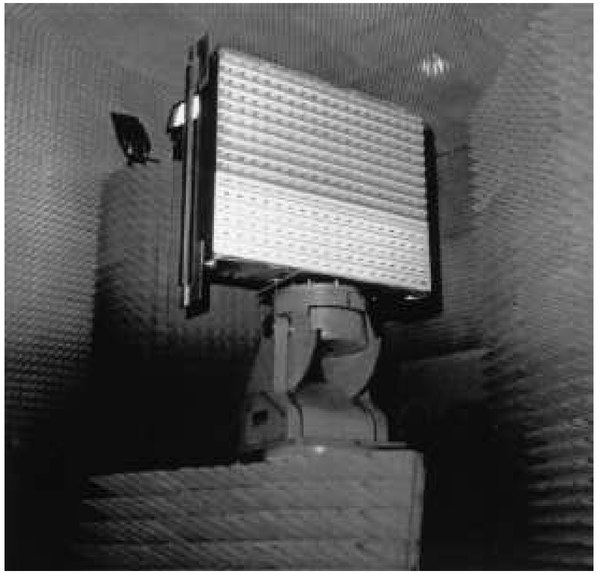
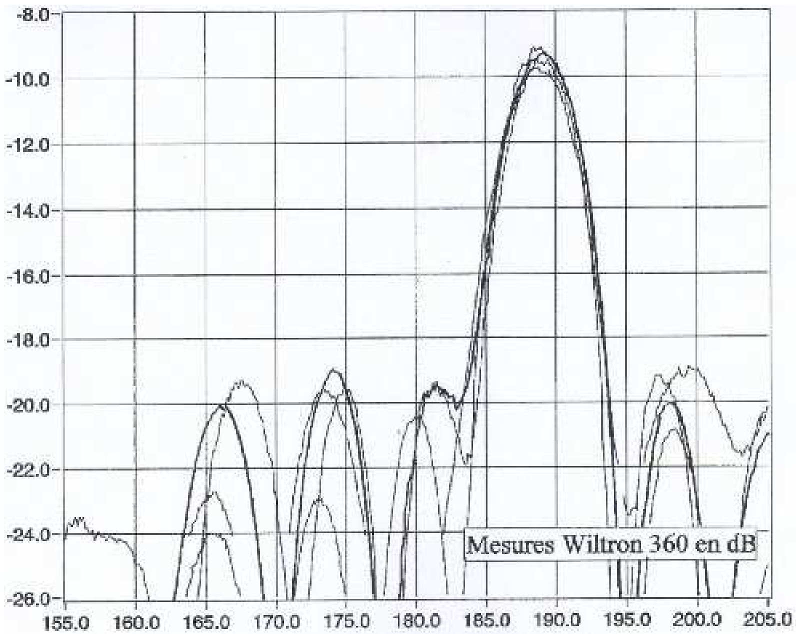
Free-space optical TTD for S band antenna scanning







- delays: 5 bits
- phase control: 6 bits
- 16 channels, 16 radiating elements
- antenna beam pattern:
  - scan angle : ± 20°
  - BW : 2700 - 3100 MHz
  - no beam squint

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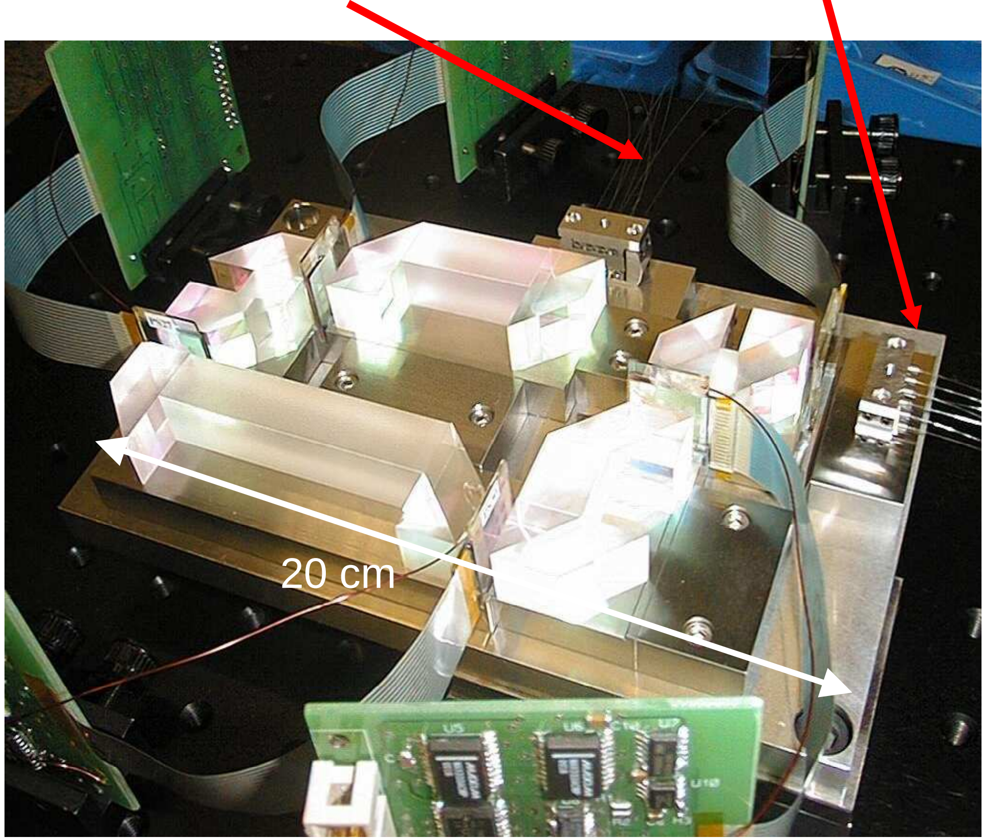
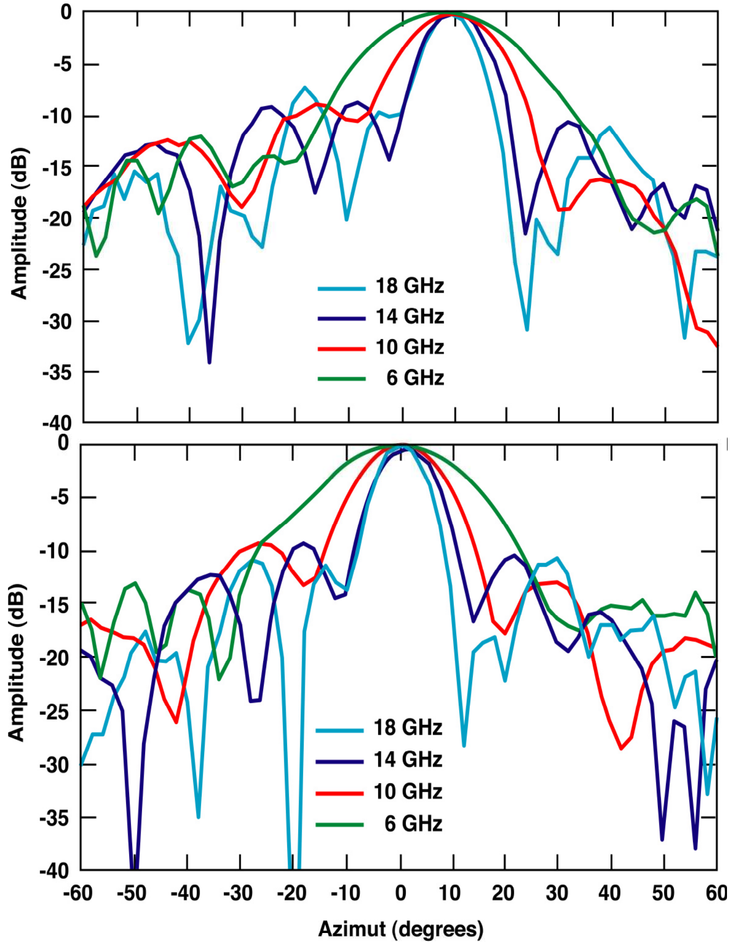
    - Dual-frequency / SSB modulation schemes : DFL, SSB, FS

Compact True Time Delay module
for transmit and receive modes





- BW = 2-20GHz
- 8 channels, 8 radiating elts
- unit delay τ=6.5ps
- 5 SLMs ➔ 32 delays/ch.
- t_{on}=20ms, t_{off}=100ms

measured far field pattern for:

- scan angle : ± 20°
- frequency : 6 – 18 GHz
- no beam squint

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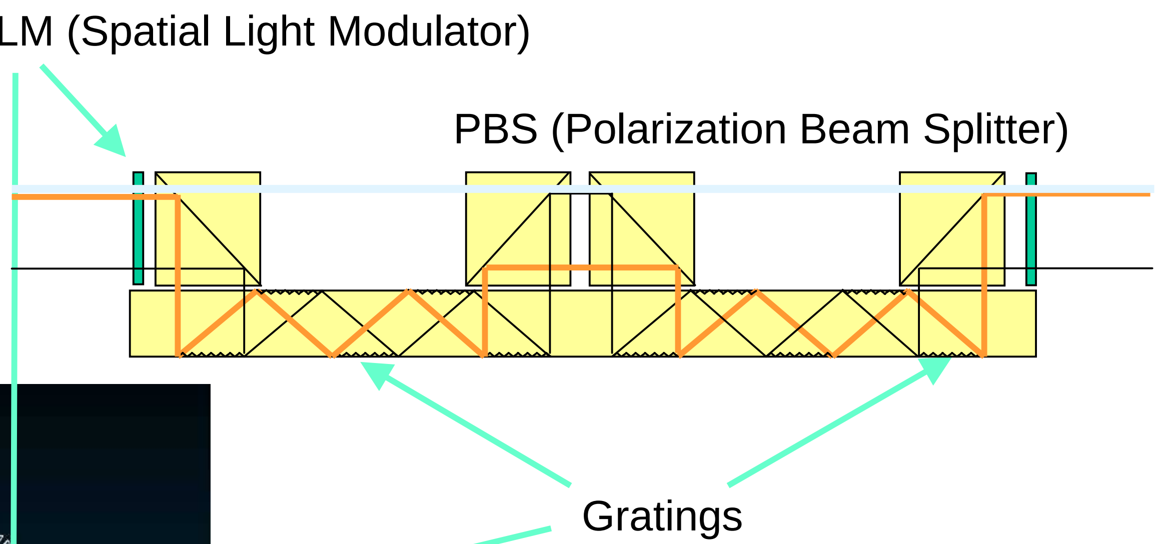
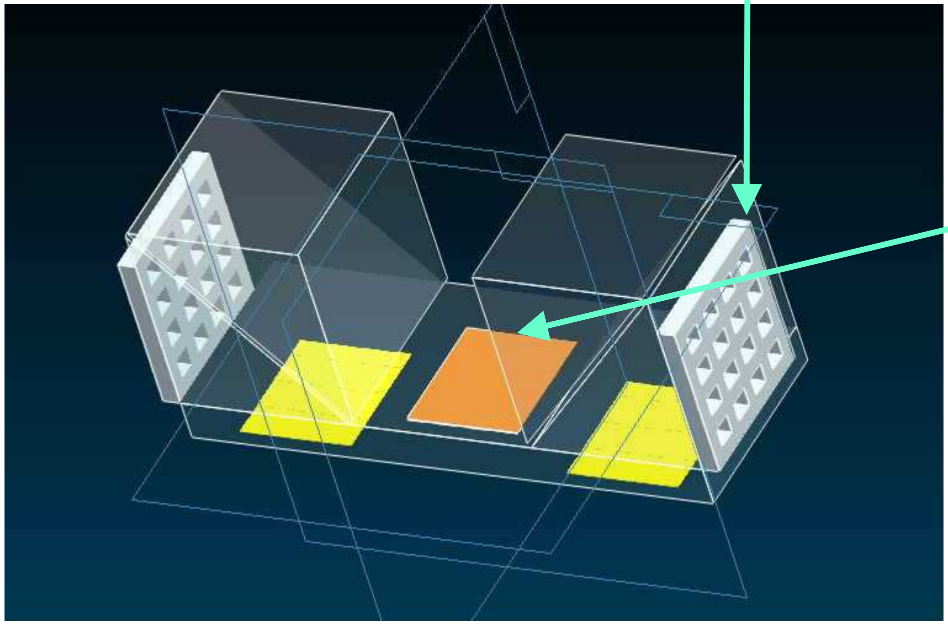
Advanced concept for ultra-compact architecture





- ➔ *Holographic backplane concept*
- ➔ Integrated 2D True time delay implementation
- ➔ for airborne applications

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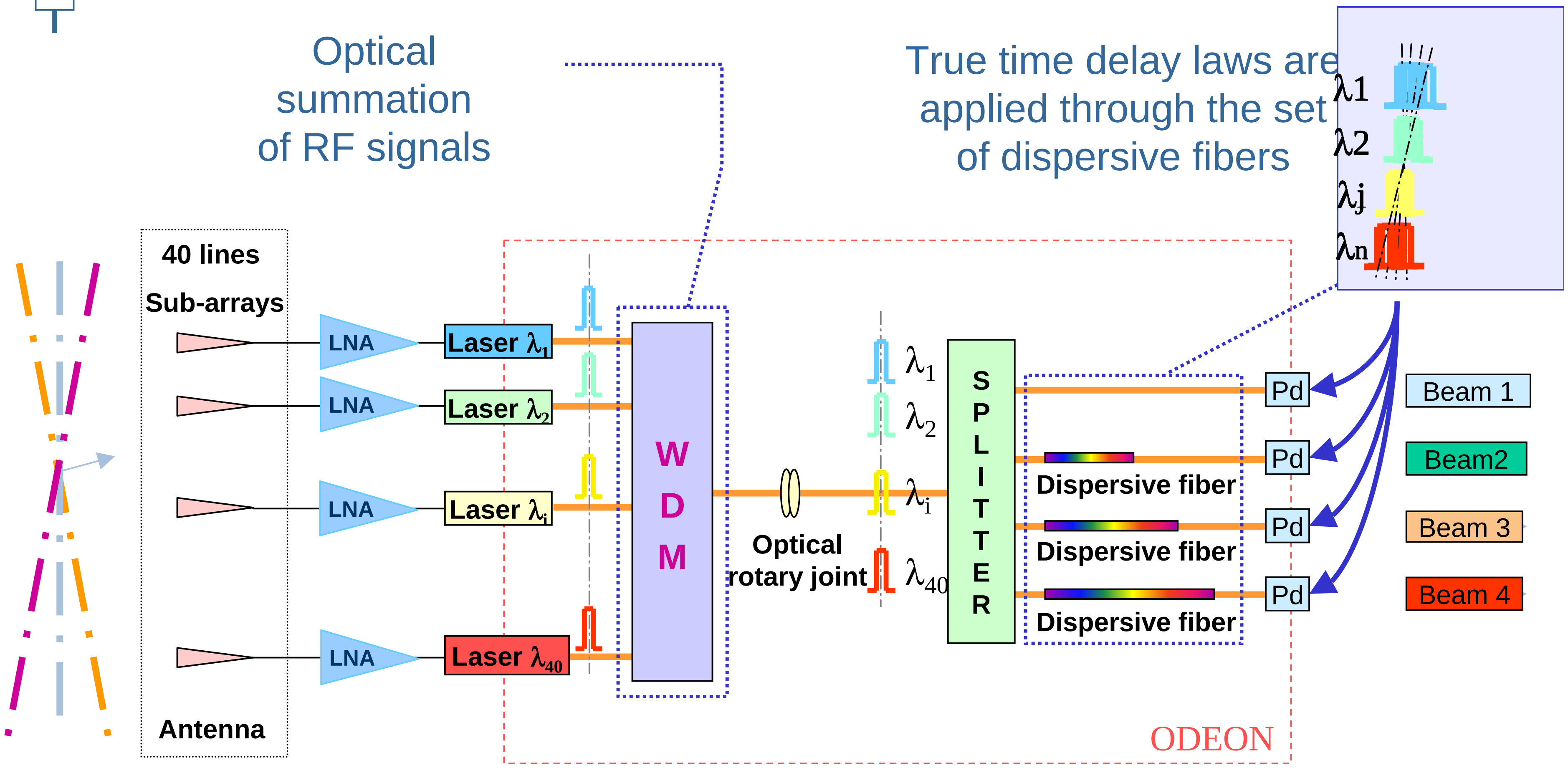
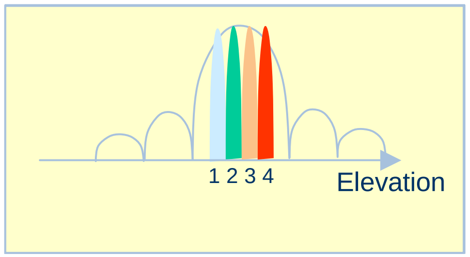
Rx Dispersive OBFN principle



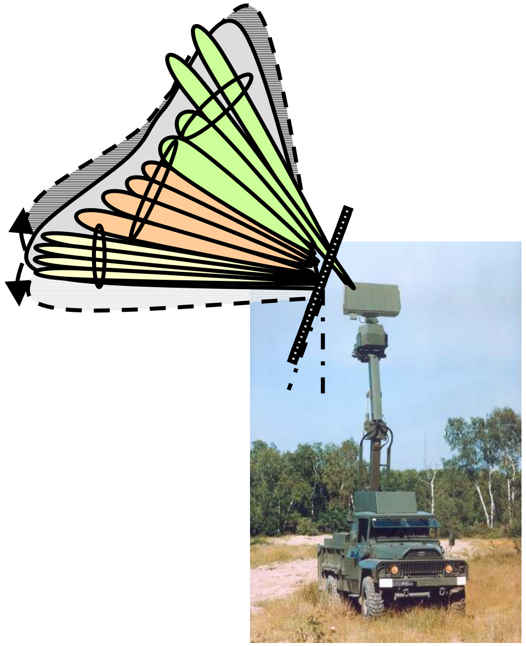


LNA : Low Noise Amplifier
WDM : Wavelength Division Multiplexing
Splitter : standard balanced optical power splitter

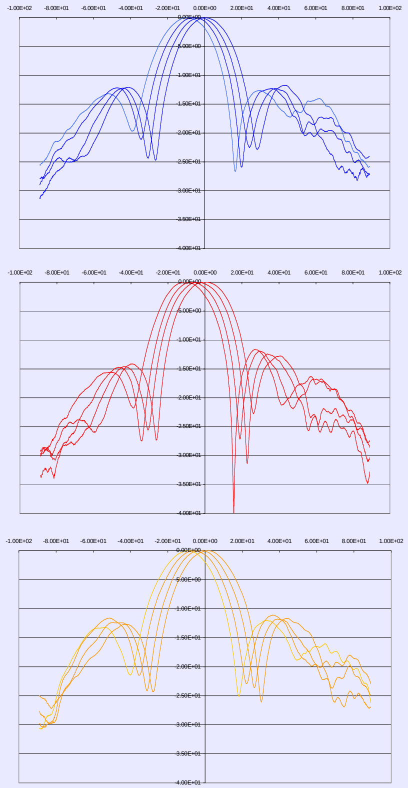
Dispersive OBFN

principle has been validated with a 4 channel mock-up

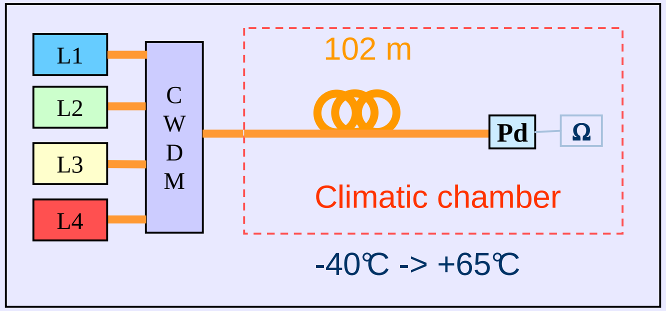
- Radiating patterns without beam squint
- No temperature sensitivity

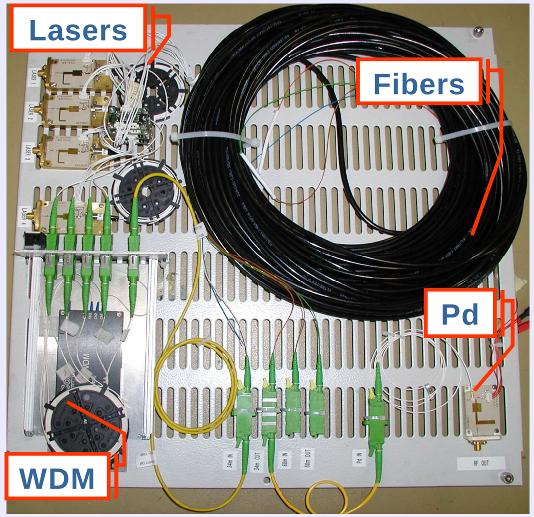


Dispersive OBFN MOCK-UP



3 GHz
3.3 GHz
2.7 GHz





Several OBFN architectures have reached TRL 4 mainly depending on operating bandwidth

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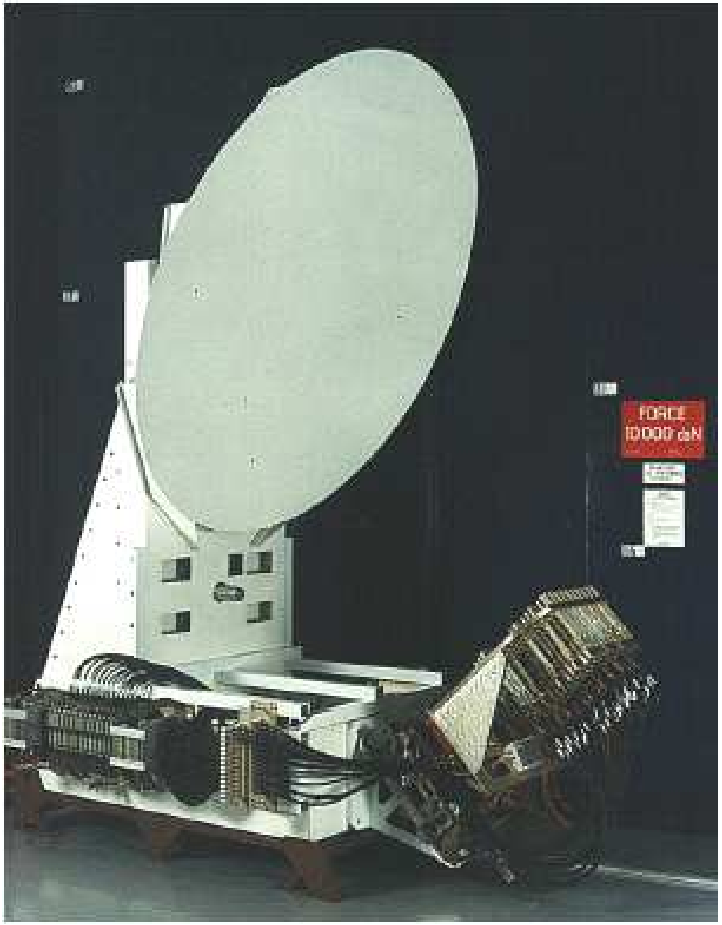
Within SATn'LIGHT :

- Optically Controlled Antenna demonstrator
- Building blocks overview
  - Dual-Frequency laser
  - Single-polarization Modulator
  - Phase & Amplitude Spatial Light Modulators
  - Optical summation module

Selected antenna concept

Within SAT 'N LIGHT we have selected a FAFR (Focal Array Fed Reflector) Rx antenna as a "study case".

- **well-suited for narrow angular coverage for GEO satellite**
- **based on cheap radiating aperture of a reflector**
- **many clusters of horns form numerous beams**



Ka band, 1 GHz bandwidth, diameter = 1.2 m, focal length = 1 m

170 feeds for 34 beams in Northern Hemisphere

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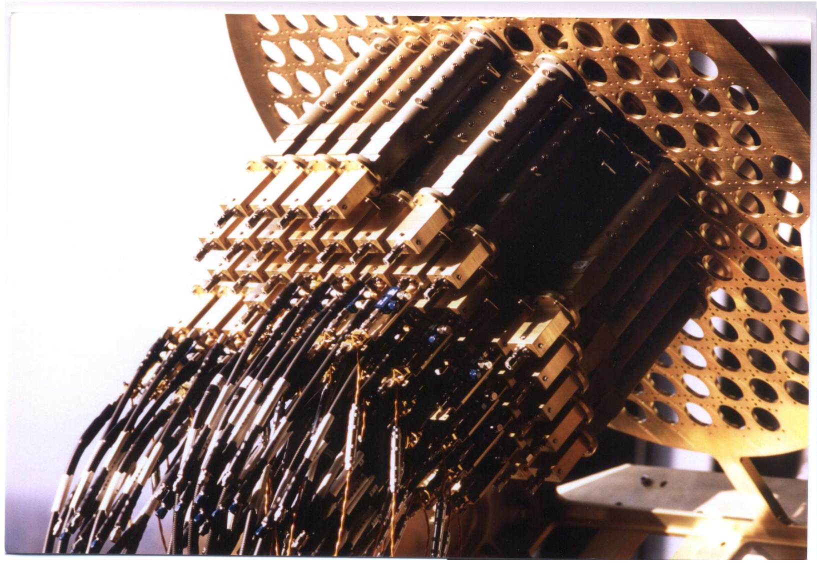
Why to optically steer an active antenna ?

Beam forming is a complex architecture from 170 RF inputs towards 34 outputs with

≈ 400 RF amplitude controls

≈ 400 RF phase controls

≈ 200 splitters / combiners



Optical architectures lead to drastic weight and volume savings.

Among the 2 classes of optical architectures :

- **True Time Delay Beam Steering**
- **“Coherent” Phase Steering**

Coherent Optical Controlled Antenna (OCA) estimation :*

•Mass < 50 kg

•Consumption < 220 W

•Volume < 6 liters

** From SAT N LIGHT phase 1*

We have selected the latter approach since it corresponds to the ultimate integration capacity for satellite application

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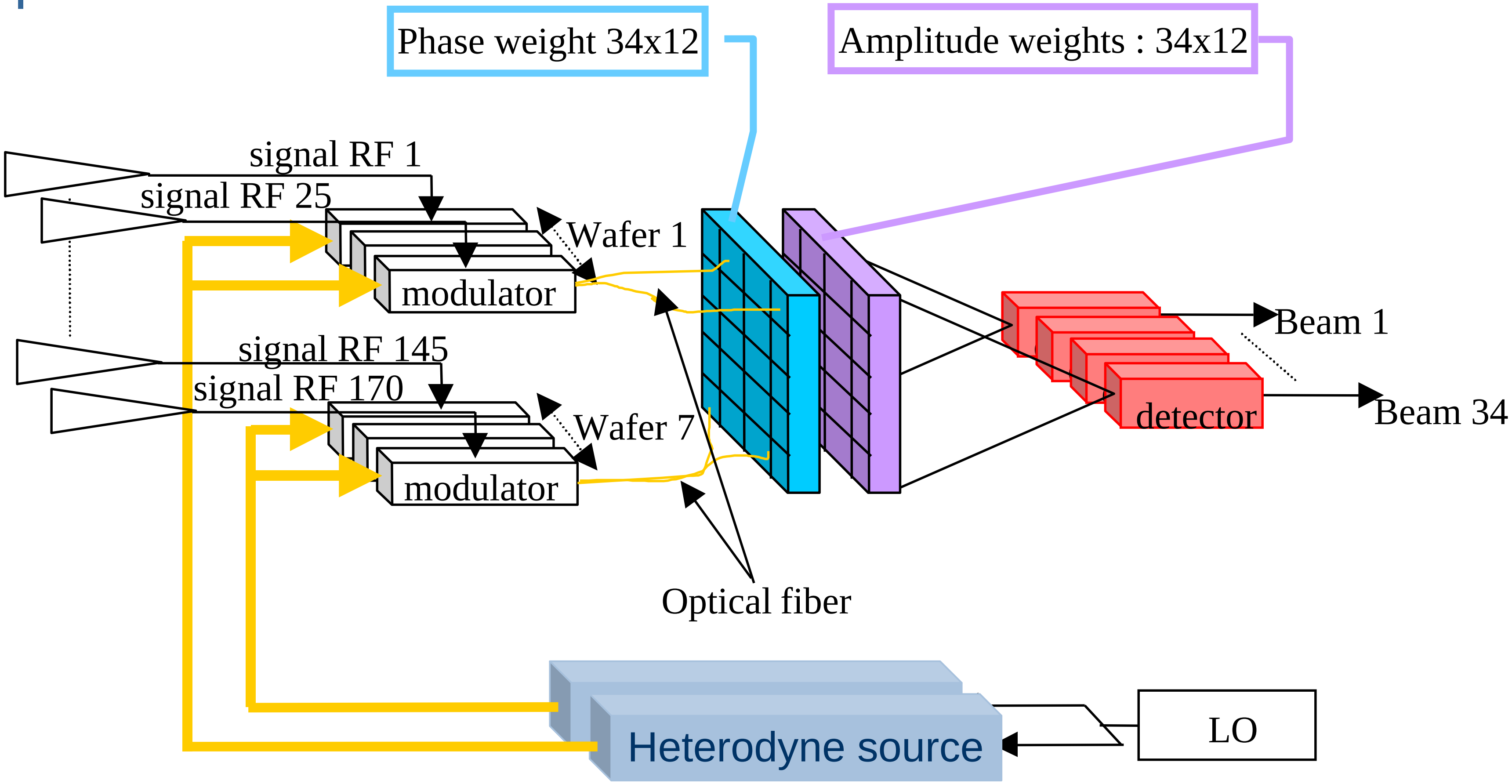
FAFR implementation of OCA architecture



Patent Fr 99 13358 (registration number) T. MERLET, O. MAAS « Dispositif de commande pour la formation de plusieurs faisceaux simultanés de réception radar à antenne à balayage électronique »
Patent Fr 2 779 579 T. MERLET, O. MAAS, D. DOLFI « Dispositif de commande optique pour l'émission et la réception d'un radar large bande »

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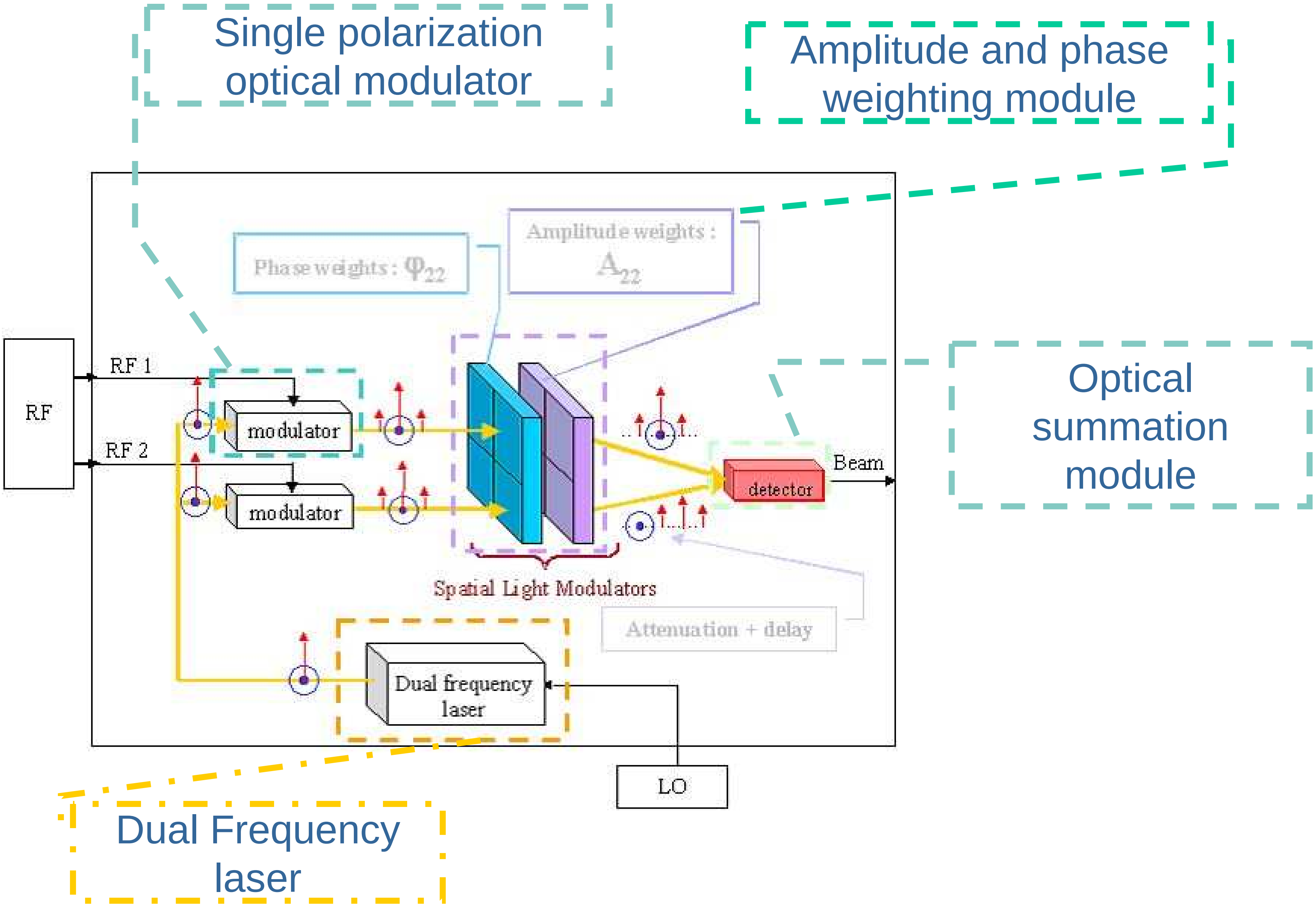
Optically-controlled antenna demo

- Optically Controlled Active antenna (OCA) is a proof of concept demonstrator based on a coherent optical architecture
  - Heterodyne LO generation owing to cross-polarised modes in a solid-state cavity. *New concept*
  - RF Phase modulation on a single-polarisation *New concept*
  - Parallel 2D matrix for phase and amplitude weightings
  - Optical summation and optical Mixing on a single device *New concept*

- OCA demonstrator is composed of 4 building blocks
  - Dual-Frequency Laser
  - Single-polarization optical modulator
  - Amplitude and phase weighting module
  - Optical Summation module

Optically-controlled antenna demo



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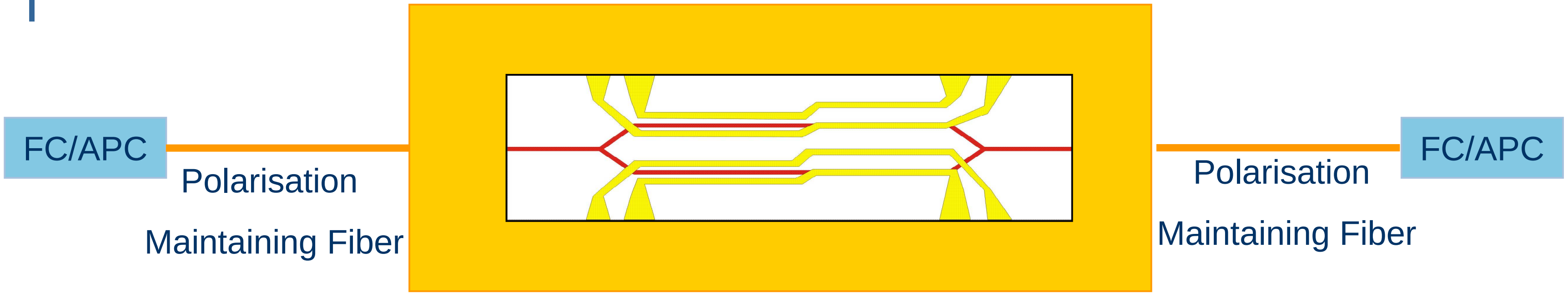
Single Polarization Modulator



Coherent architectures are based upon delay coding in the range of 1 optical wavelength (1 µm).

- For RF phase stability, optical beams shall witness the same variations.
- Beams need to be carried on superposed on the same media

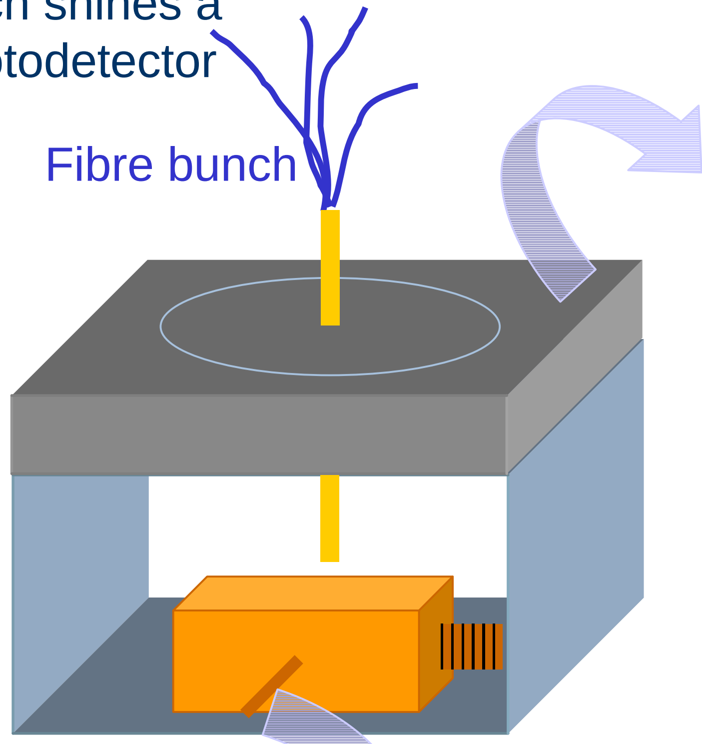
"Single polarization modulator" means :

- A modulator that transmit both polarizations, contrary to usual modulators.
- A modulator that only modulates one of the polarization.

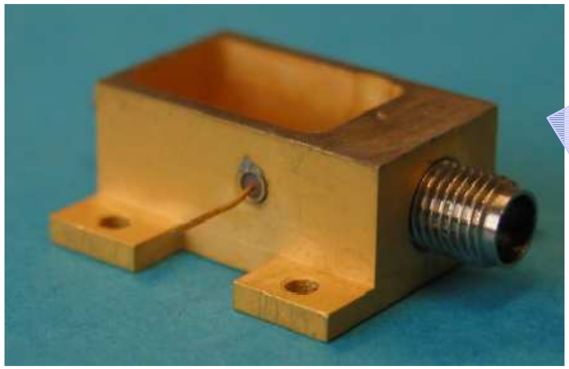
Refer to Photline presentation for detailed explanations

Summation module : manufacturing

8 fibers gather in a bunch shines a single large surface photodetector

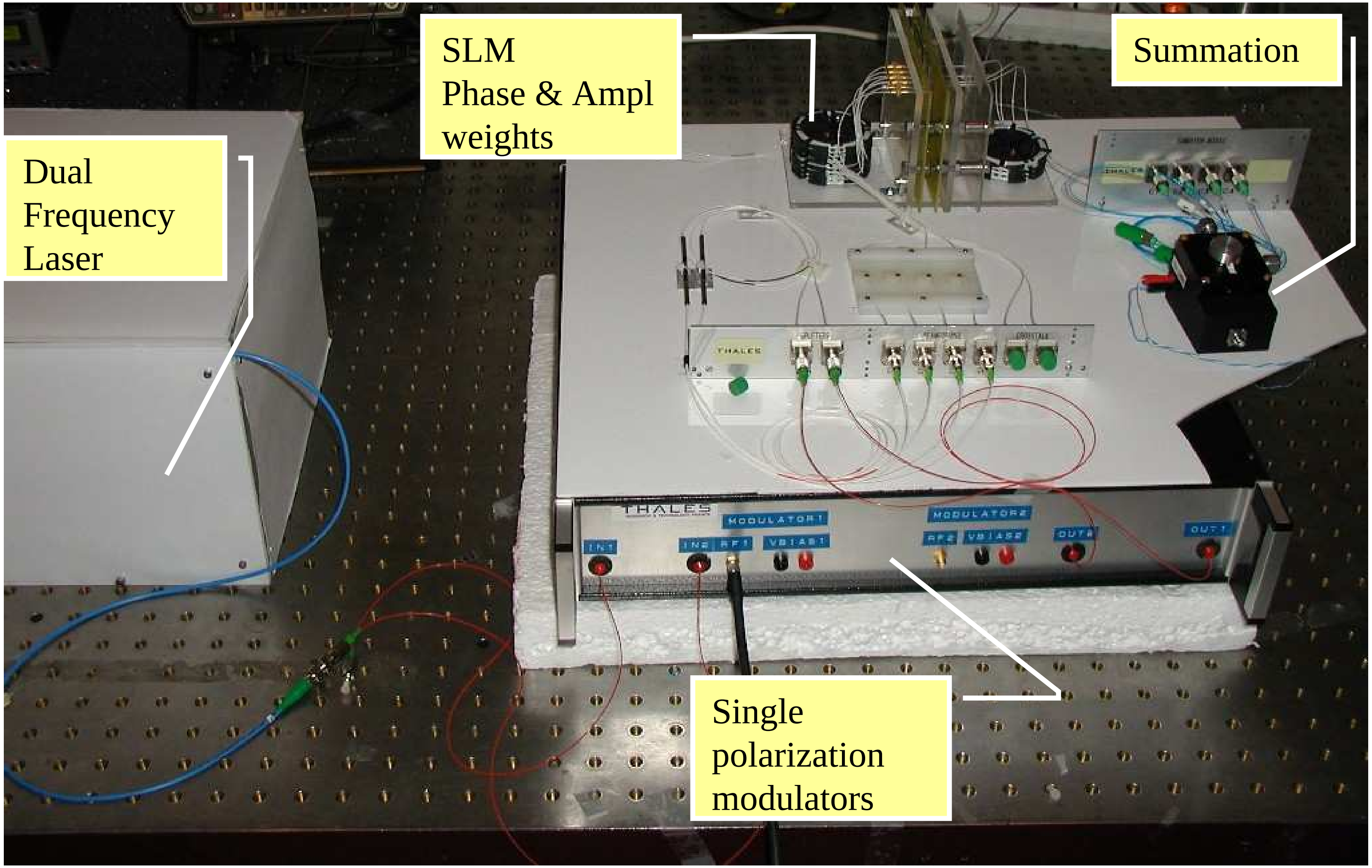


XYZ positioner to adjust optical fibre position before hermetic sealing



Box with:
- integrated PIN detector
- MW output (and DC bias)

OCA Integrated Demonstrator



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Analog processing of the receive mode

- **microwave signals spread over a large dynamic range (up to 100 dB)**
- **frequency bandwidth from <10% (radar, comm) up to 2-18 GHz (E.W)**
- **in-phase addition over a large frequency BW of the received signals with a precision of few degrees**

➔ need of pxp analog microwave / optical links with large dynamic range and low noise figure

➔ limited dynamic range of opto-links (typ. 90-95 dB in 1 MHz BW)

➢ *architecture with matched local oscillator* ***(time-delayed and optically carried)***

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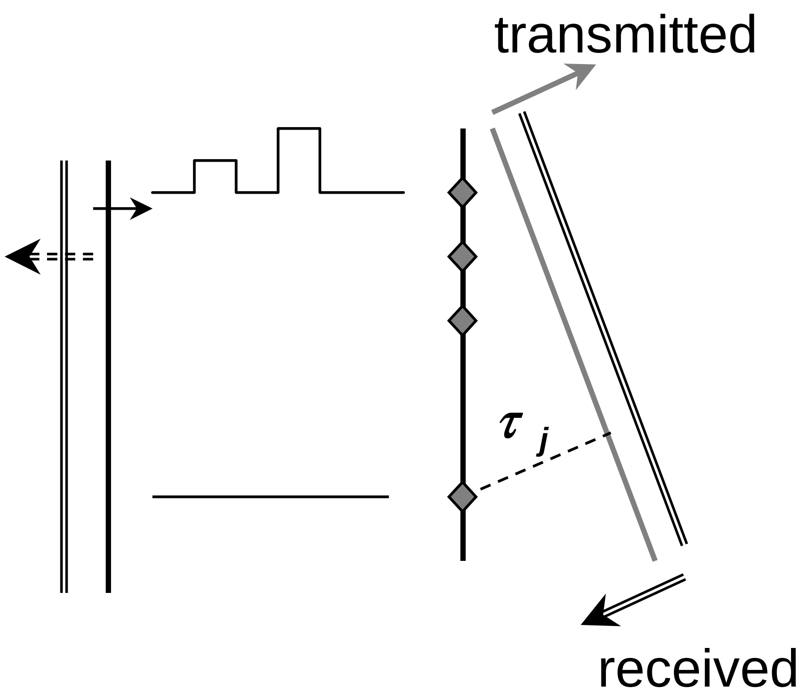
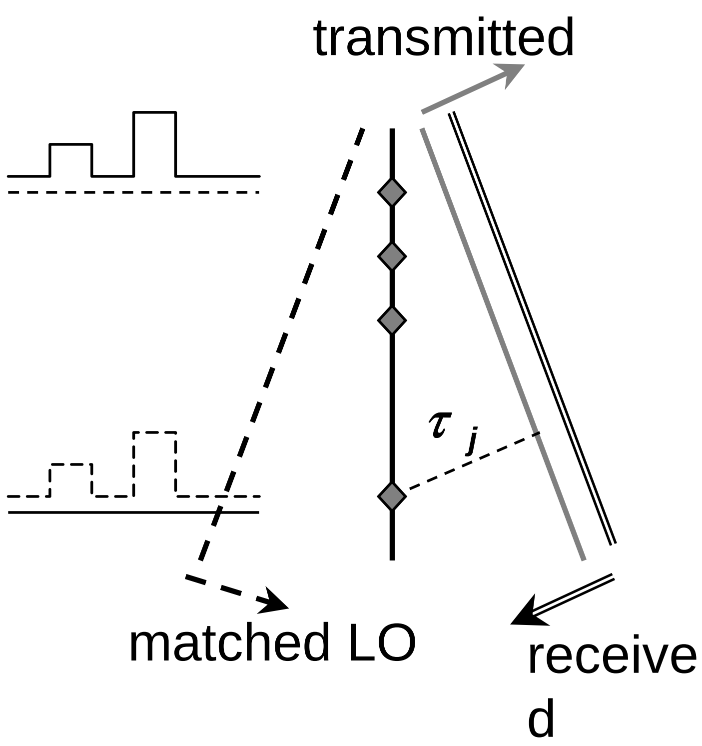
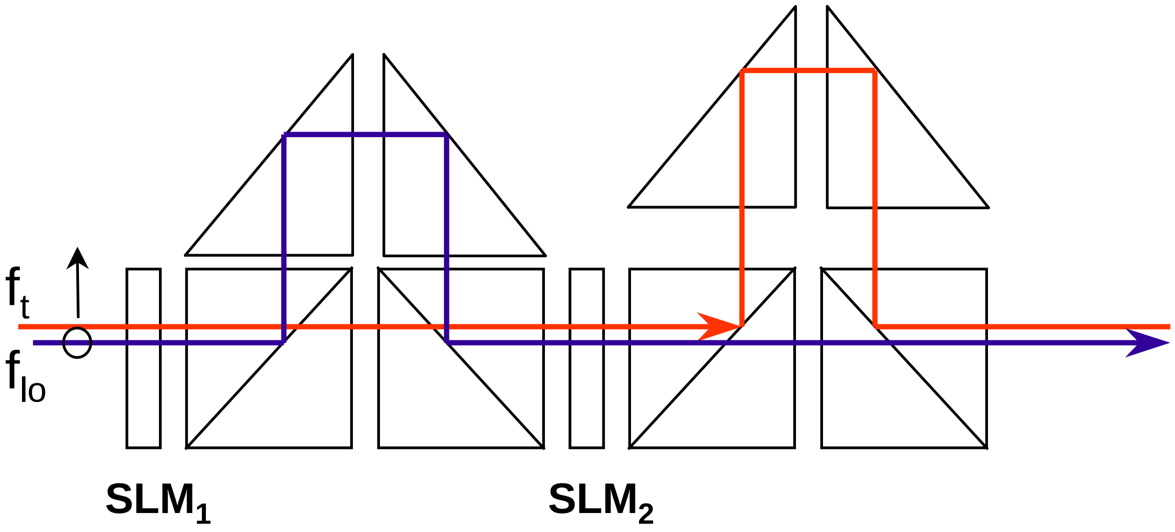
Time reversal vs matched L.O



direct transposition ➔ time reversal

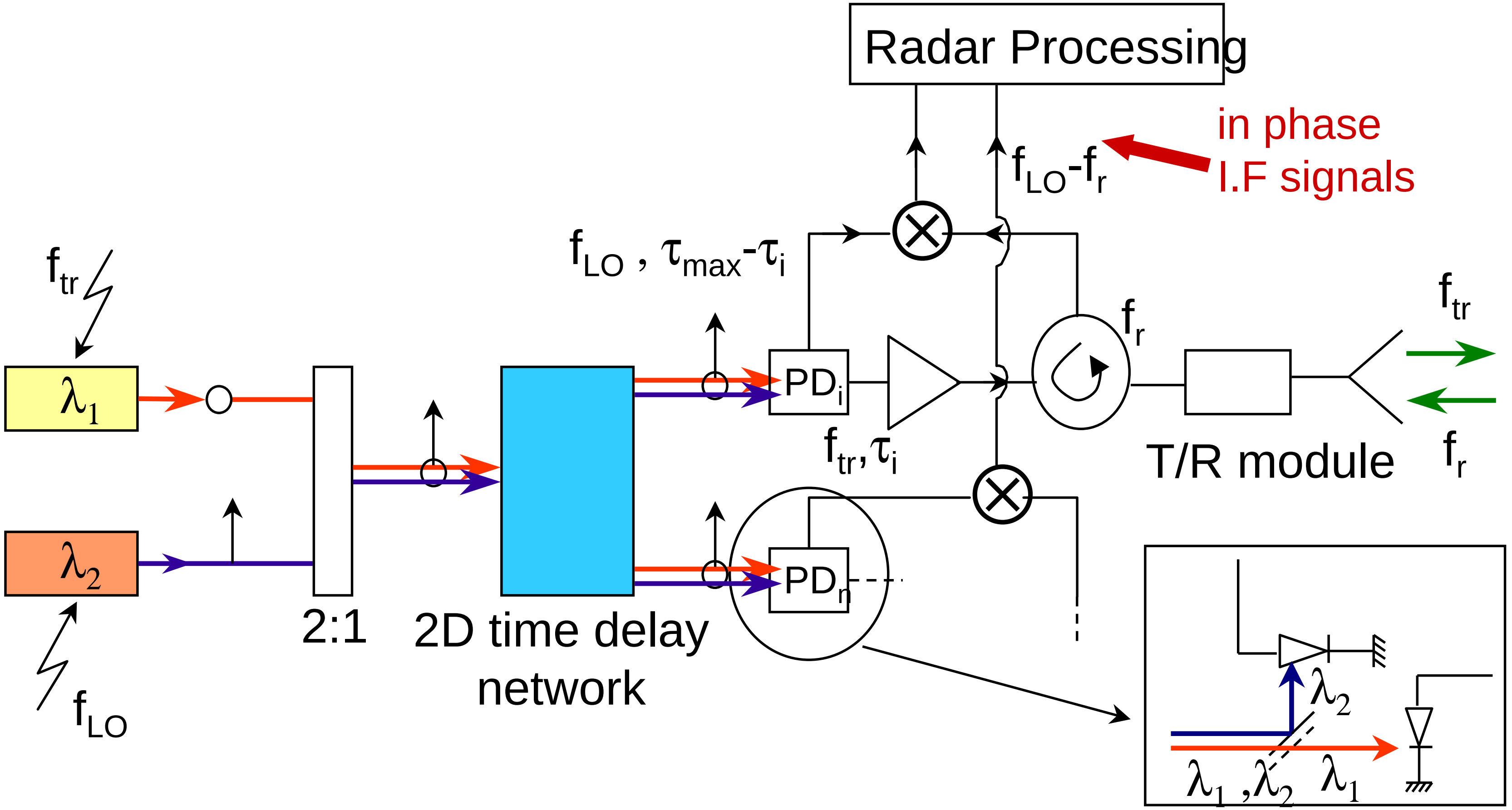


matched L.O ➔ phase conjugation



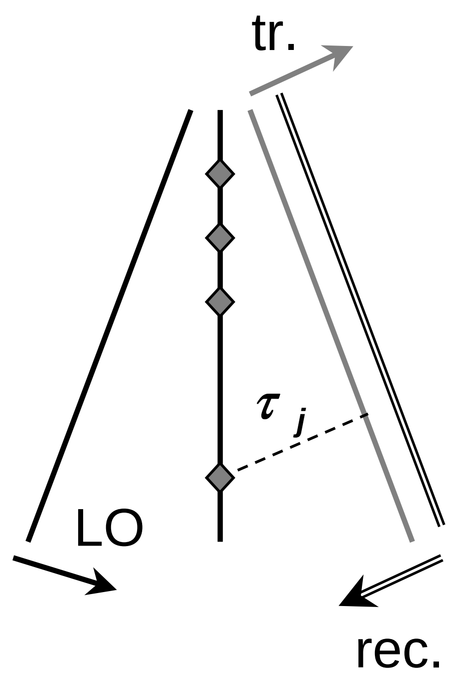
- optical carriers of the transmitted signal and of the L.O
  - with crossed polarizations
  - at different wavelengths

- complementary time delays on each channel i :
  - τ_{max}-τ_i for the matched L.O
  - τ_i for the transmitted signal


Radar Processing
in phase
I.F signals
f_{LO}-f_r
f_{LO} , τ_{max}-τ_i
f_{tr}
λ_1
λ_2
f_{LO}
2:1
2D time delay
network
PD_i
PD_n
f_{tr},τ_i
f_r
T/R module
f_{tr}
f_r
λ_2
λ_1 ,λ_2
λ_1

on channel j :

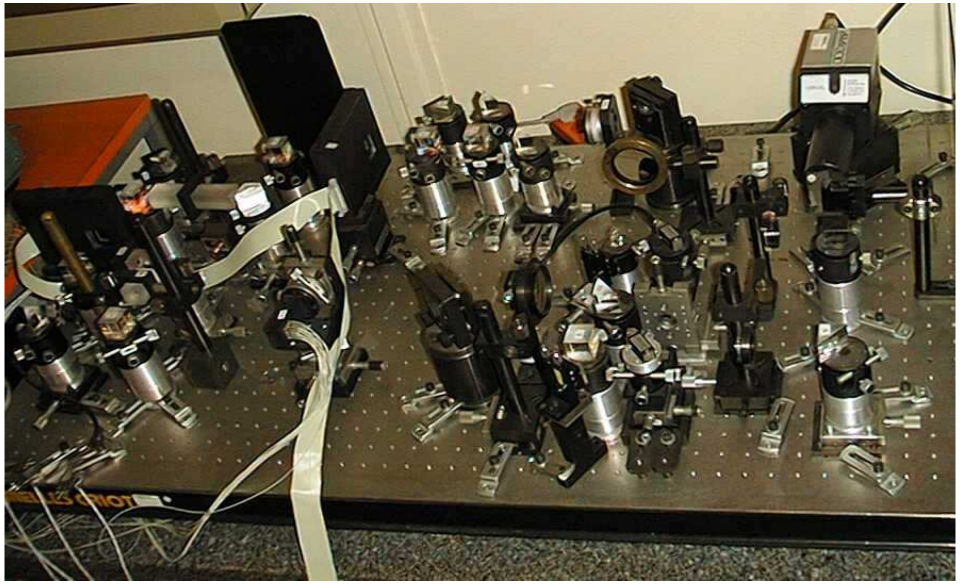
- transmitted signal : $\cos [\, 2\pi\, f_{tr} \,(t - \tau_j)\,]$
- local oscillator : $\cos [\, 2\pi\, f_{LO} \,(t - (\tau_{max} - \tau_j))\,]$
- received signal : $\cos [\, 2\pi\, f_r \,(t - T + \tau_j)\,]$
- intermediate frequency f_I signal :
  - $\cos [\, 2\pi\,(f_{LO} - f_r)\, t + \underline{2\pi\,(f_{LO} - f_r)\tau}_j - 2\pi\, f_{LO}\tau_{max} + 2\pi\, f_r\, T\,]$

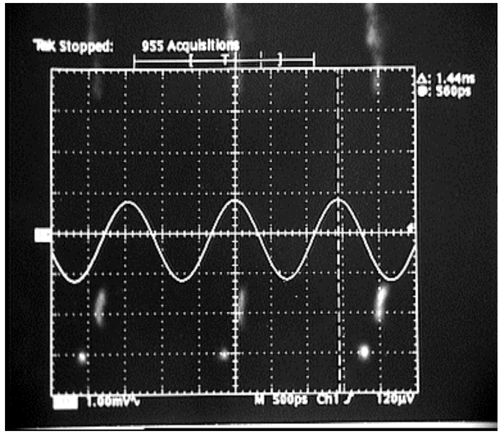


in-phase addition of the signals at f_I when $2\pi\,(f_{LO} - f_r)\,\tau_j$ << phase quantization

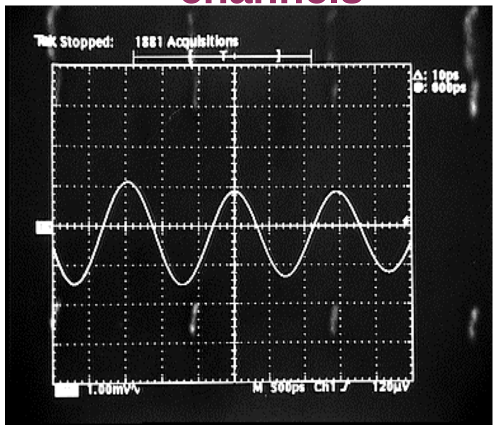
Two channel architecture with:

- f = 2.8 GHz
- I.F= 700 MHz





I.F signal for no delay between the channels



I.F signal for time delay τ = 450 ps between the channels

➔in phase I.F signals
➔residual errors $\Delta\tau < 10$ ps, $\Delta\phi \sim 5^o$

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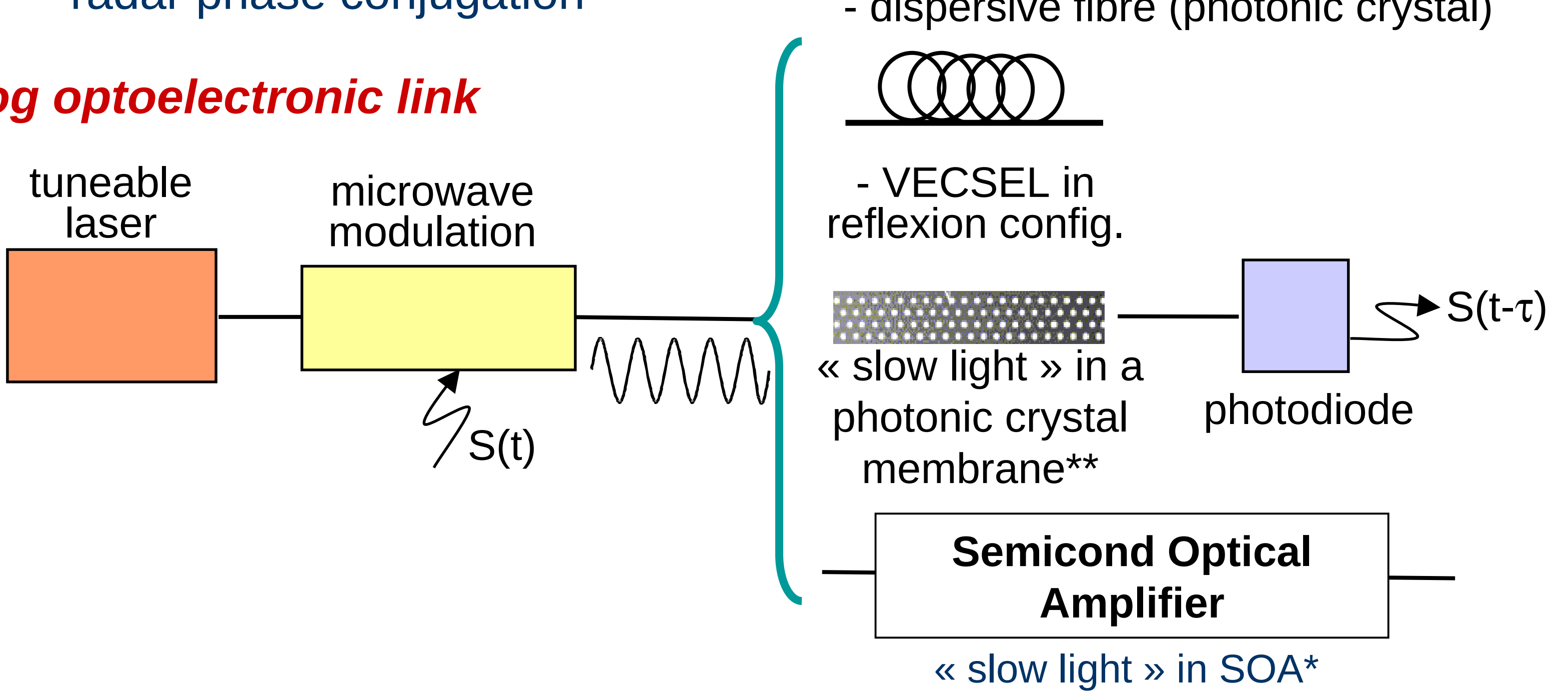
Need of variable delay lines for basic processing functions:

- beam control of phased array antennas, programmable filtering
- spectral analysis of large BW microwave signals
- radar phase conjugation

➔ ***analog optoelectronic link***



➔ *the signal of interest is the microwave modulation itself, not the envelope*

* D. Pastor *et al.,* Electron. Lett., 34, 1684, 1998** S. Combrié *et al.*, Electron. Lett., 42, 86, 2006*** J. Mørk et al., Optics Express., 13, 20, 2005

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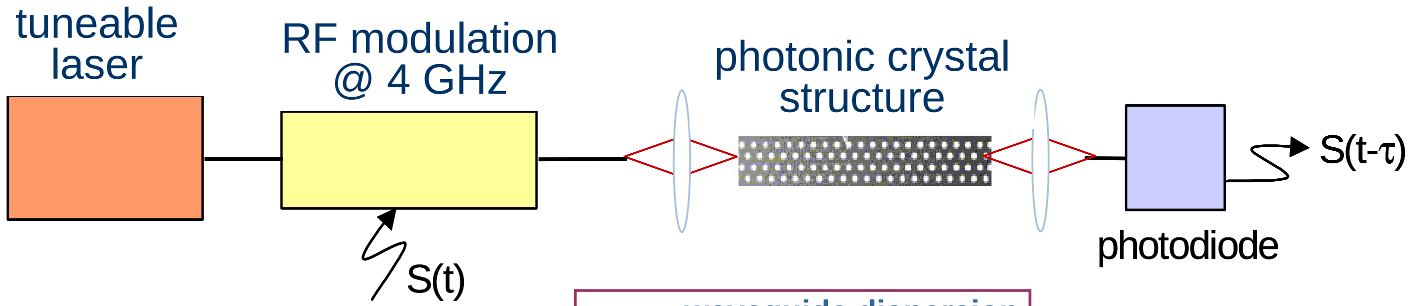
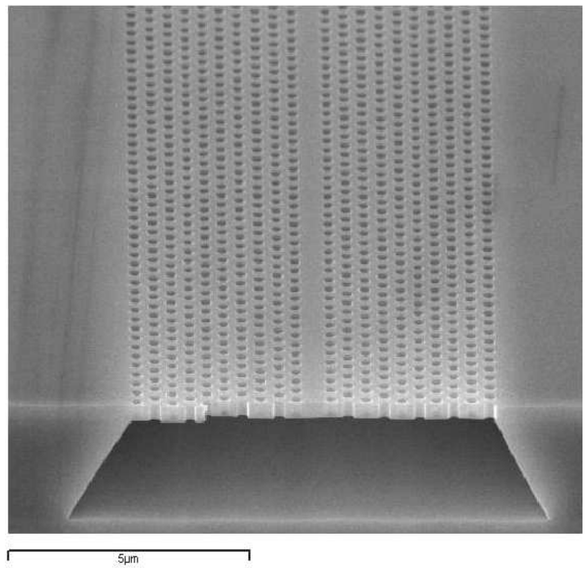
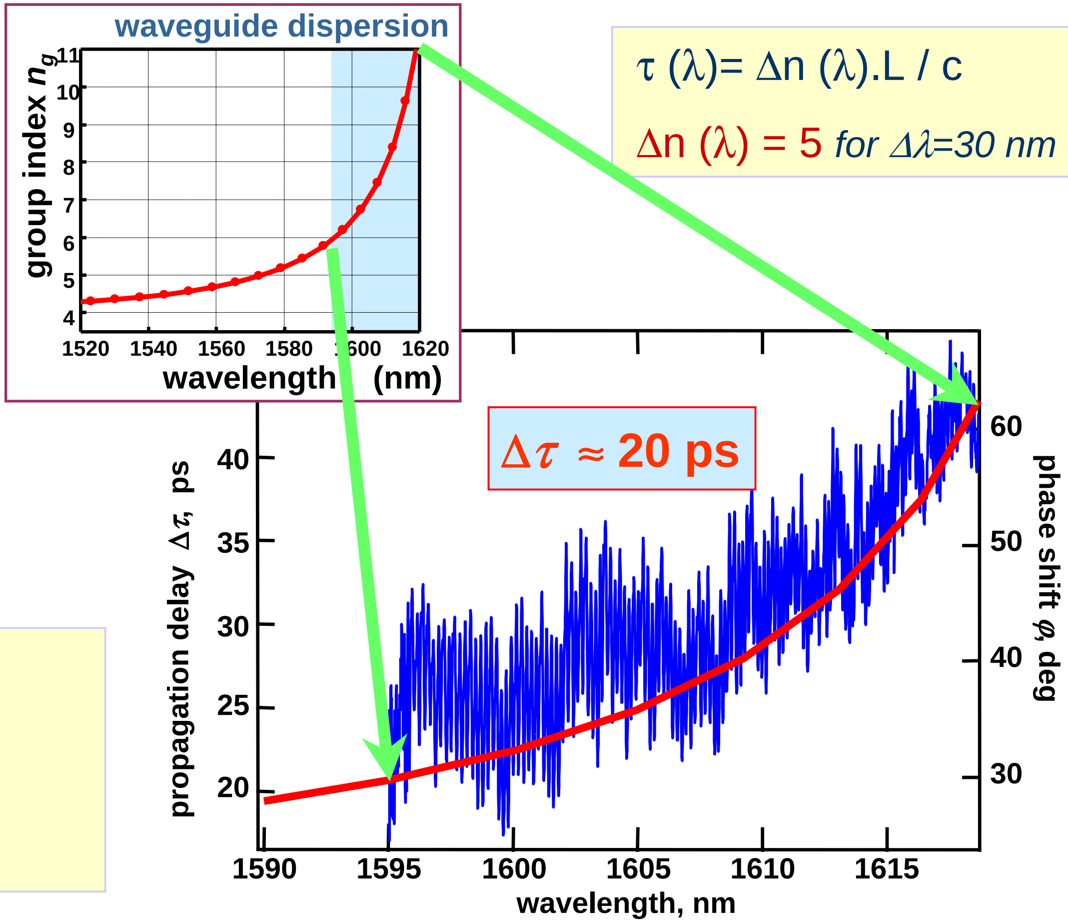
Photonic Crystal tunable delay preliminary demonstration





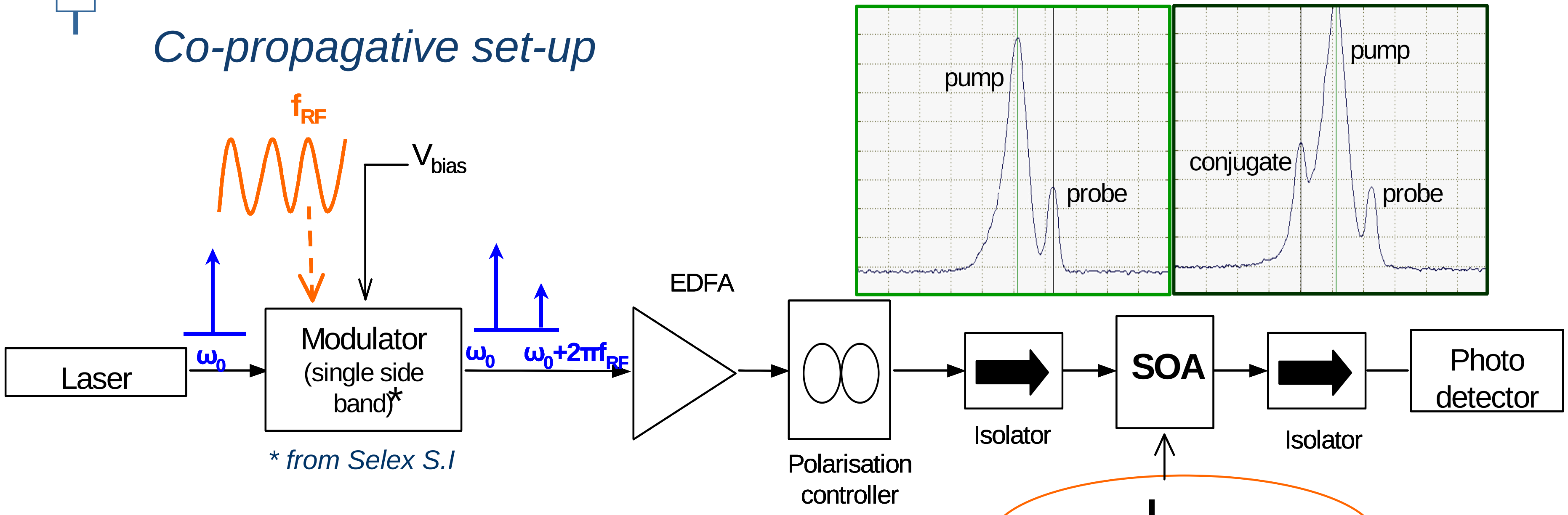


$\tau(\lambda) = \Delta n(\lambda).L / c$

$\Delta n(\lambda) = 5$ *for $\Delta\lambda$=30 nm*

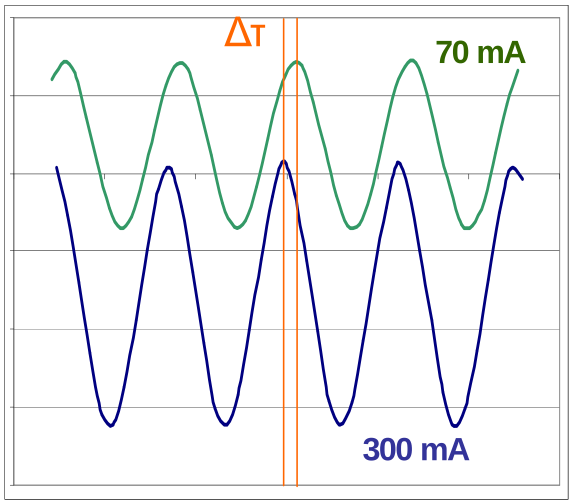
- device length: L = 1 mm
- measured phase shift: 30 deg @4GHz
- corresp. time delay: τ = 21 ps

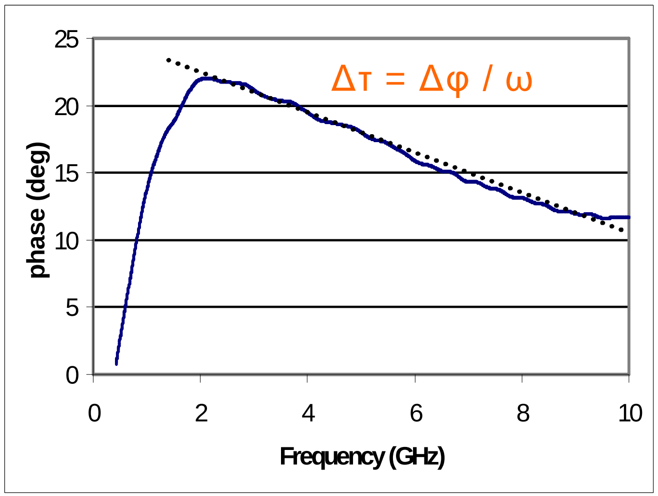
Co-propagative set-up



** from Selex S.I*

For a given f_{RF} (typ. around 5 GHz) :





$$\Delta n_g = \frac{c}{L}\Delta\tau_g$$

$$\Delta n = \frac{c}{L\,\omega_{optique}}\int \Delta\tau_g \, d\Omega$$

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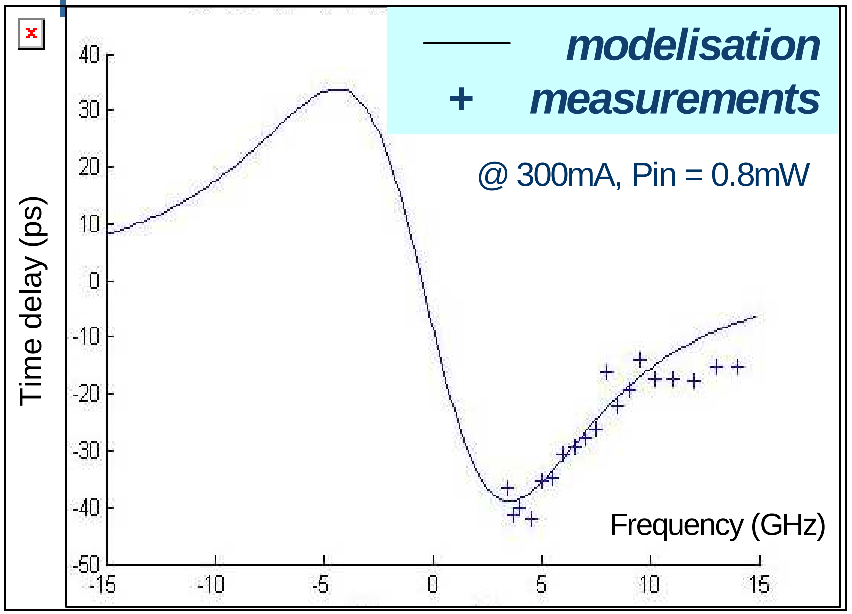
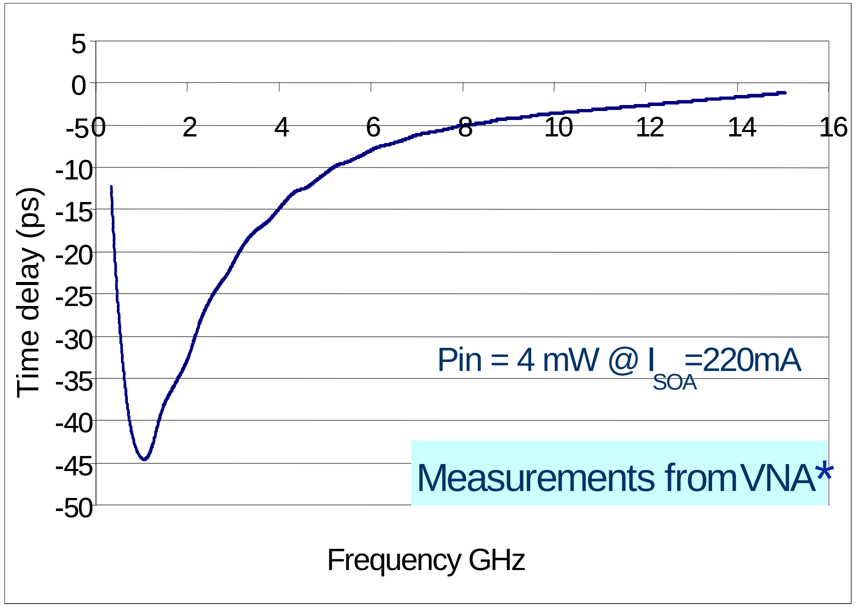
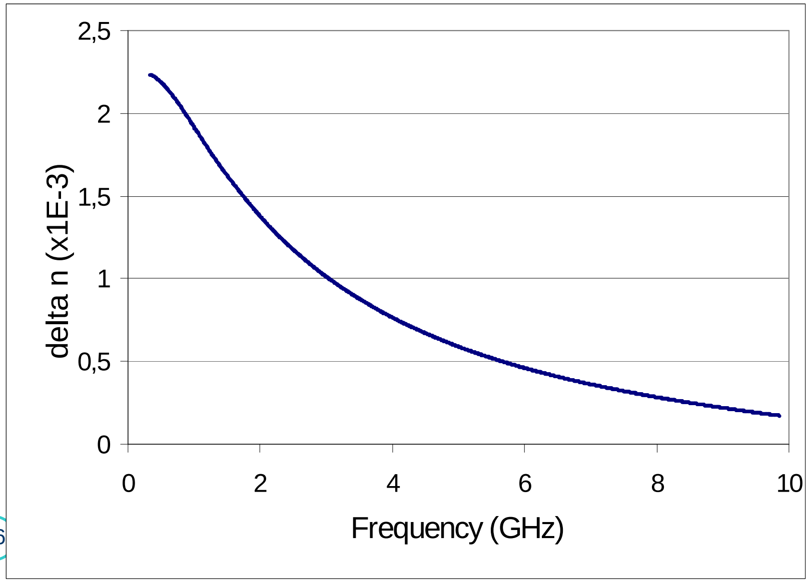
Measurement of the time delays generated with a SOA





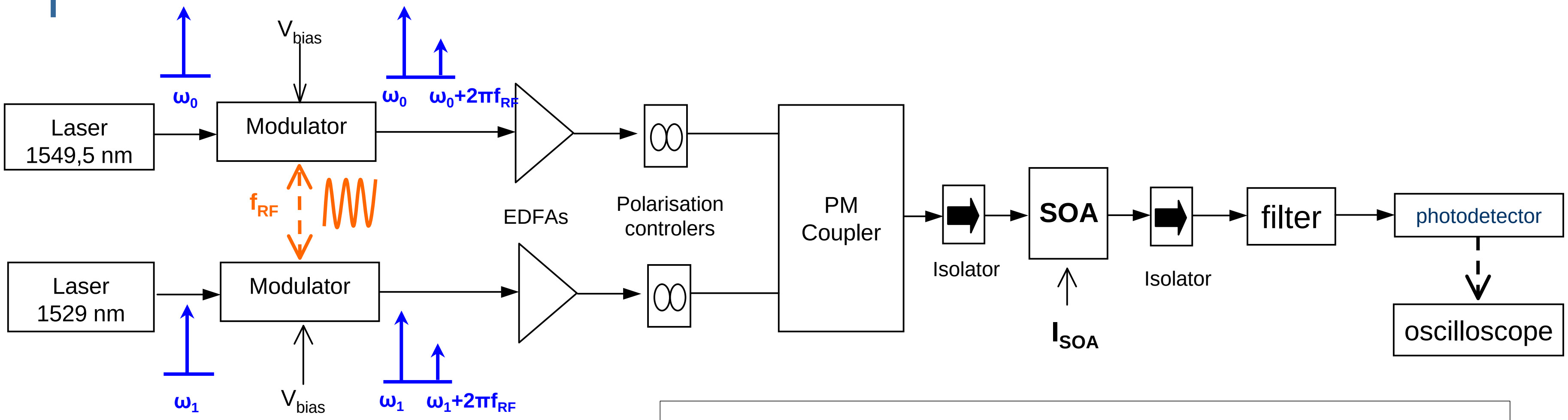
Δn (x 10^{-3})



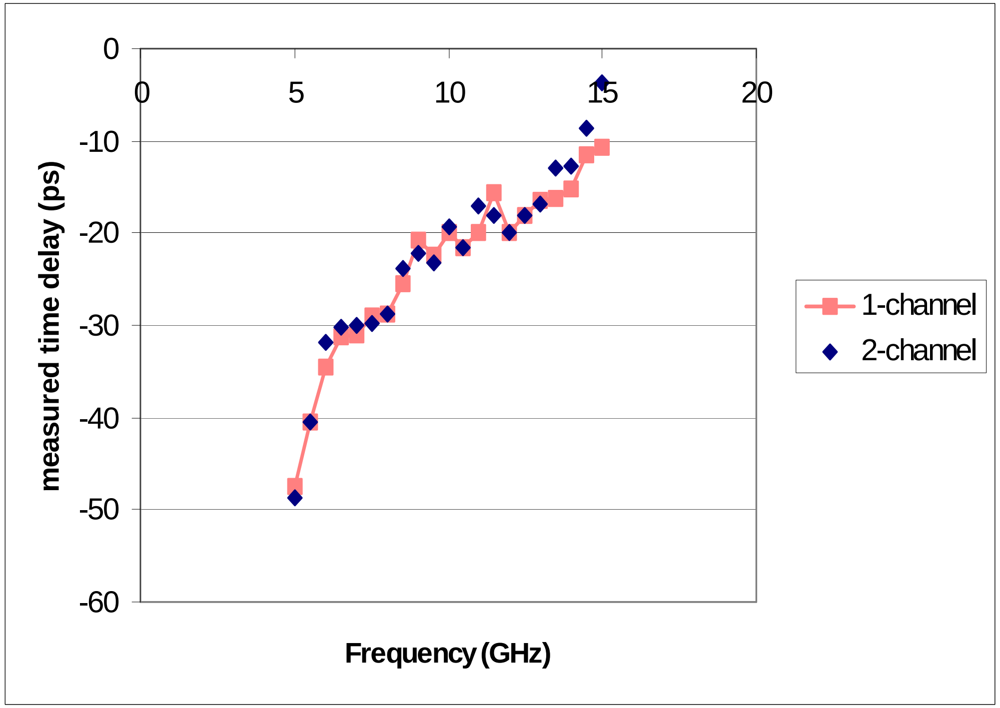
- Time delay from 4 to 45 ps
- Bandwidth : more than 10 GHz
- “Slowlight” with a factor from 2 to 20
- Index variation : few 10^{-3} (through L=750 µm)

**VNA: vectorial network analyzer*

THALES



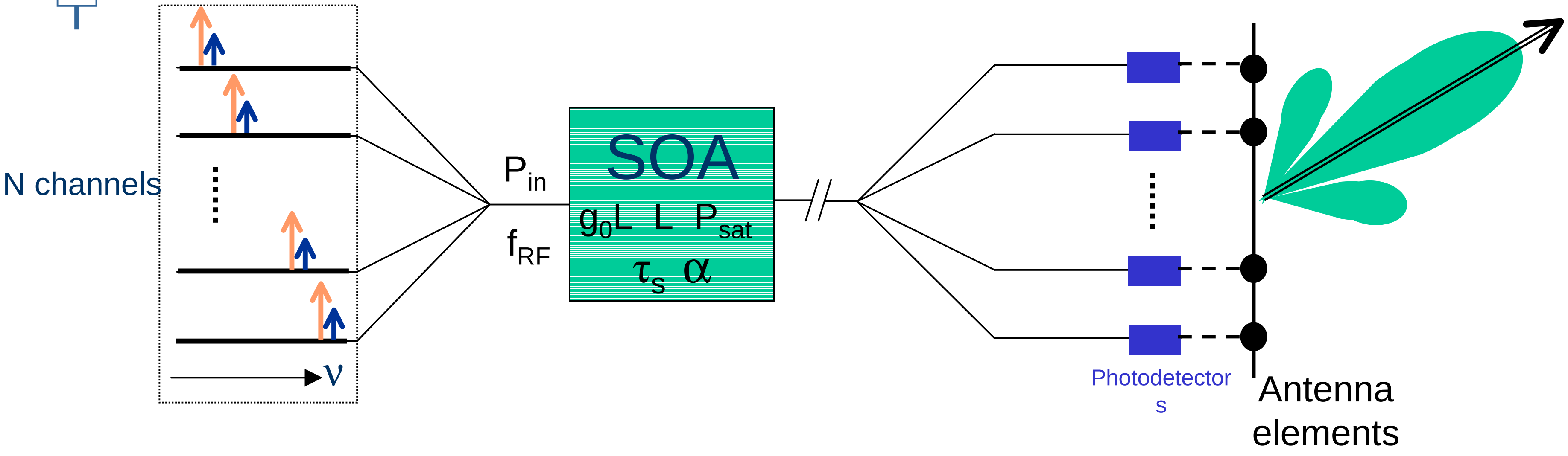
same time delay measured for the 1-channel configuration and for the 2-channel config.*



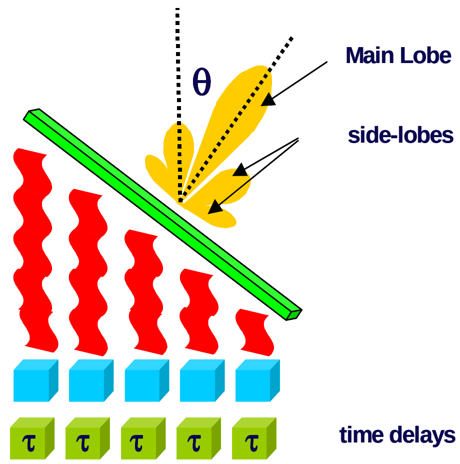
*for one channel present in the opto-link (P_{in} = 2mW) or
for two channels (P_{in} = 1mW for each)

THALES

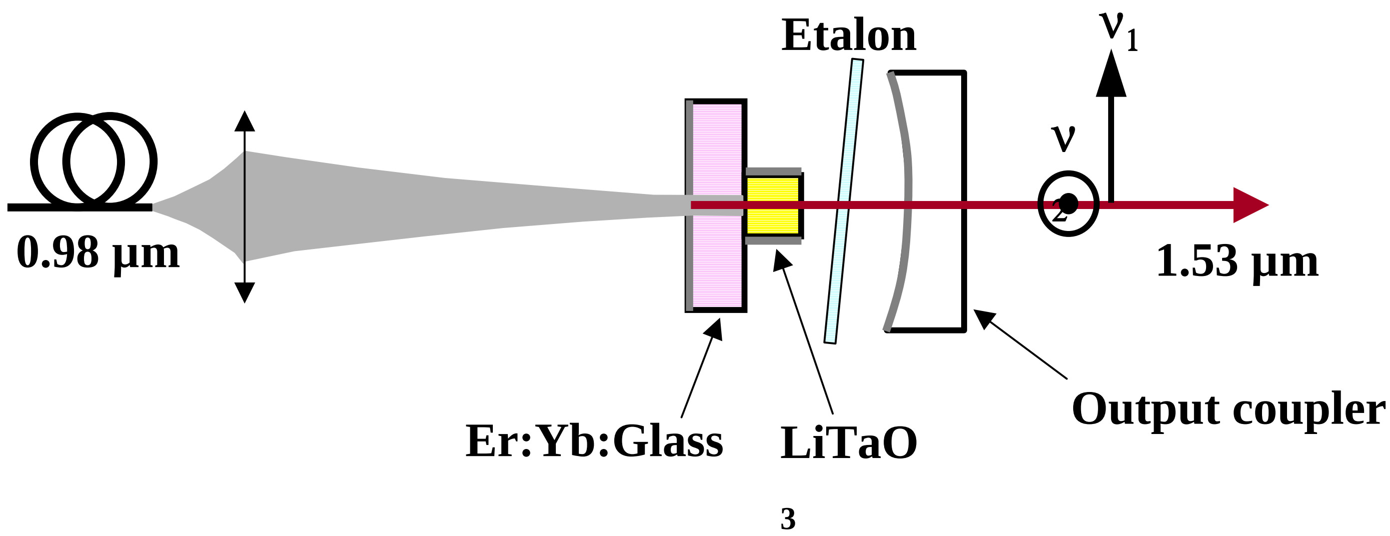
Applicability to multi-channel phased array antennas



- unchanged SOA characteristics : L τ_s α
- g_0L : homogeneous gain but depending on λ
- $P_{sat} = f(P_{in\ total})$ is unchanged ($P_{sat\ 1channel\ /N} = P_{sat}$ / N)



➔ each channel will carry the time delay that it would have carried
with the same value of P_{in}/P_{sat}



Active medium : 750 µm long Er:Yb:Glass

Birefringent element : 1 mm long $LiTaO_3$ crystal

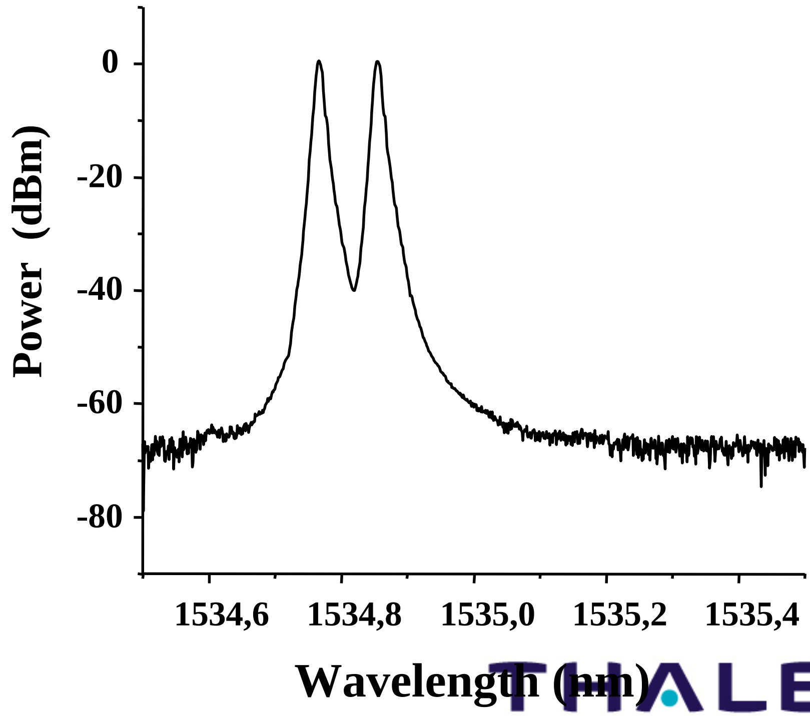
Pump : single mode diode @ 0.98 µm

Intra-cavity étalon

Frequency difference tunability :

$$\Delta\nu = \Delta\nu_0 + \underbrace{\Gamma V}_{\text{Electro-optic}} + \underbrace{\Lambda(T - T_0)}_{\text{Thermo-optic}}$$

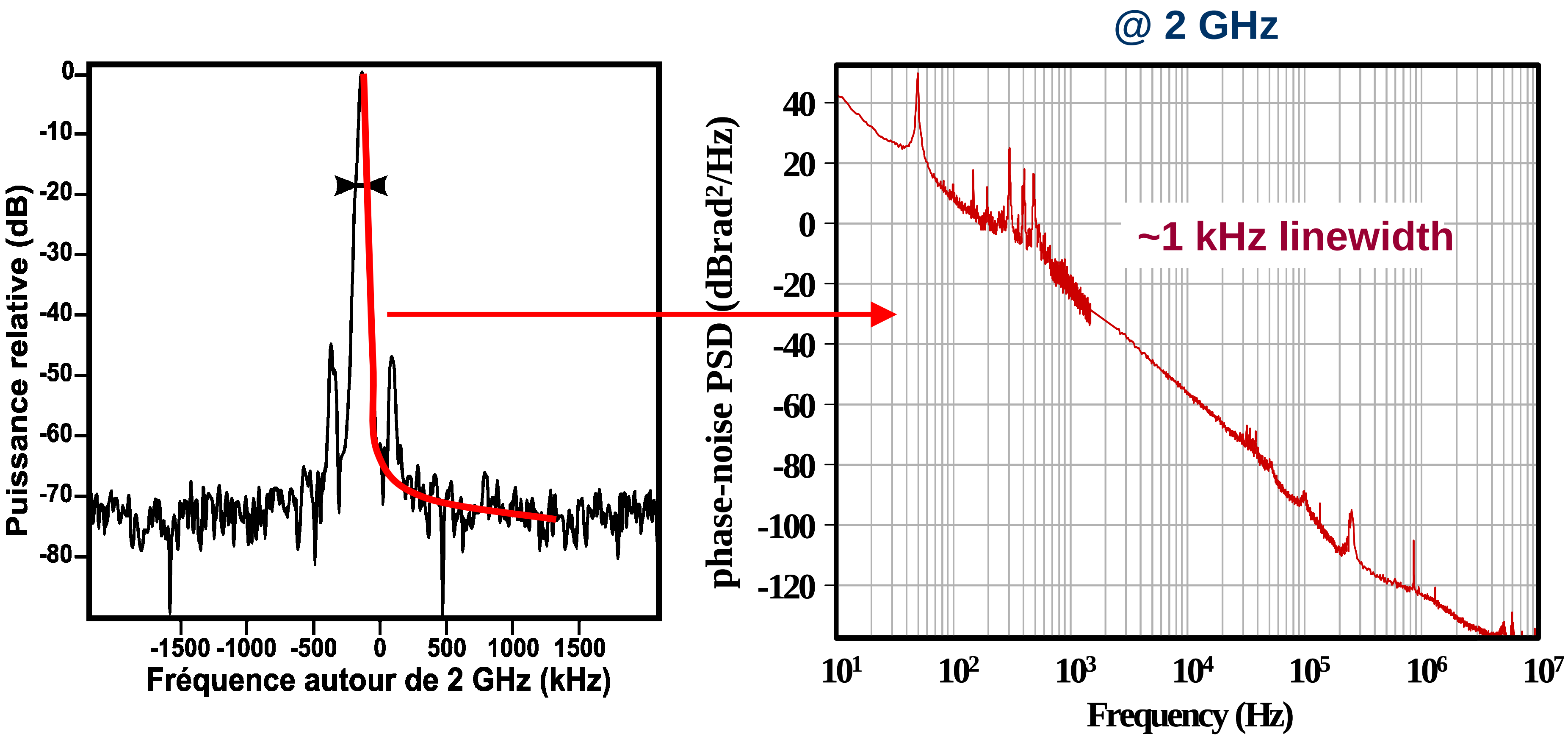
Electro-optic *Thermo-optic*



Alouini et al, IEEE PTL 13, 2001

Er:Yb:Glass two-frequency laser (DFL)

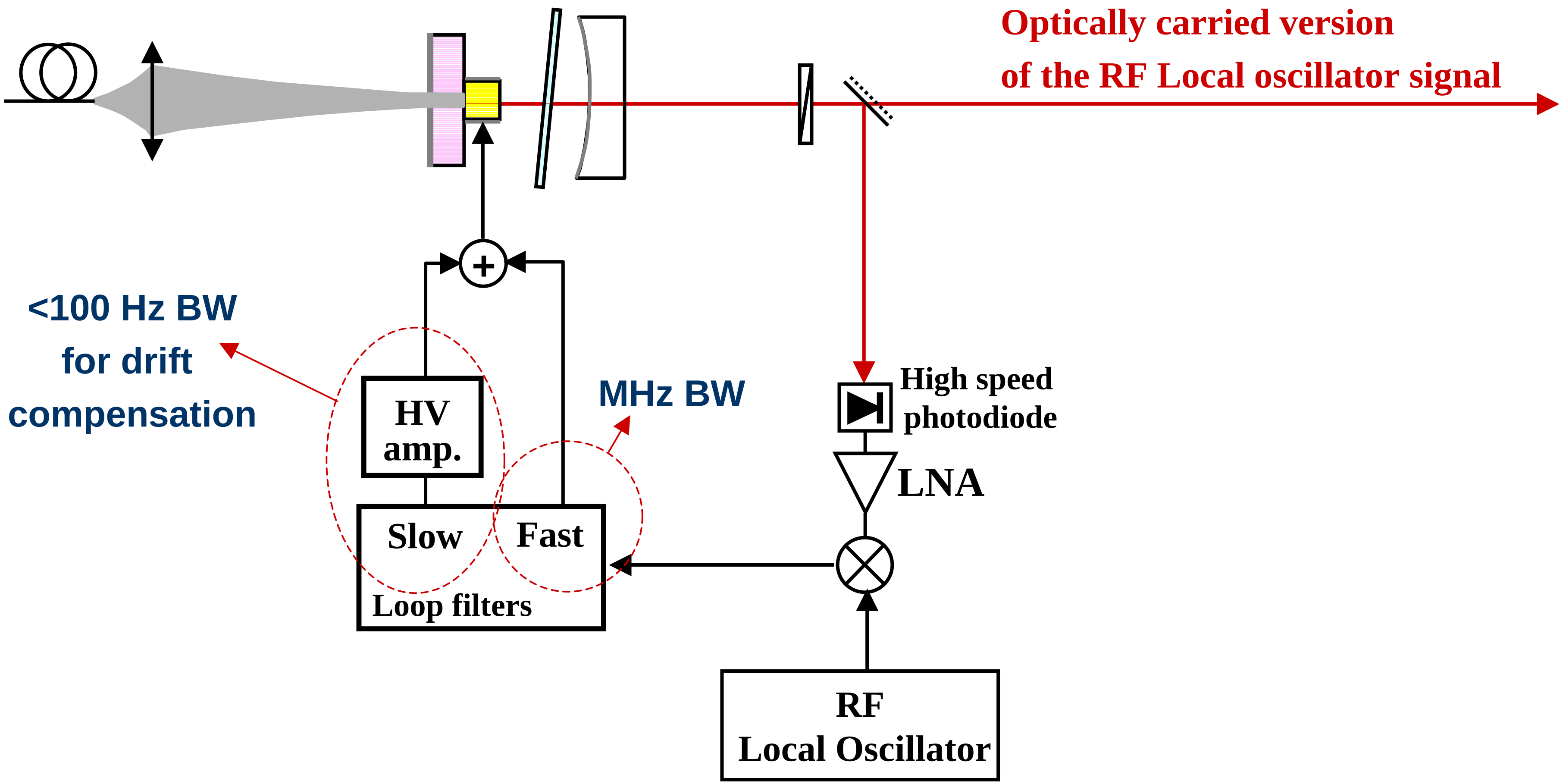
Phase noise of the free-running beatnote



➔ Require stabilization for radar applications

THALES

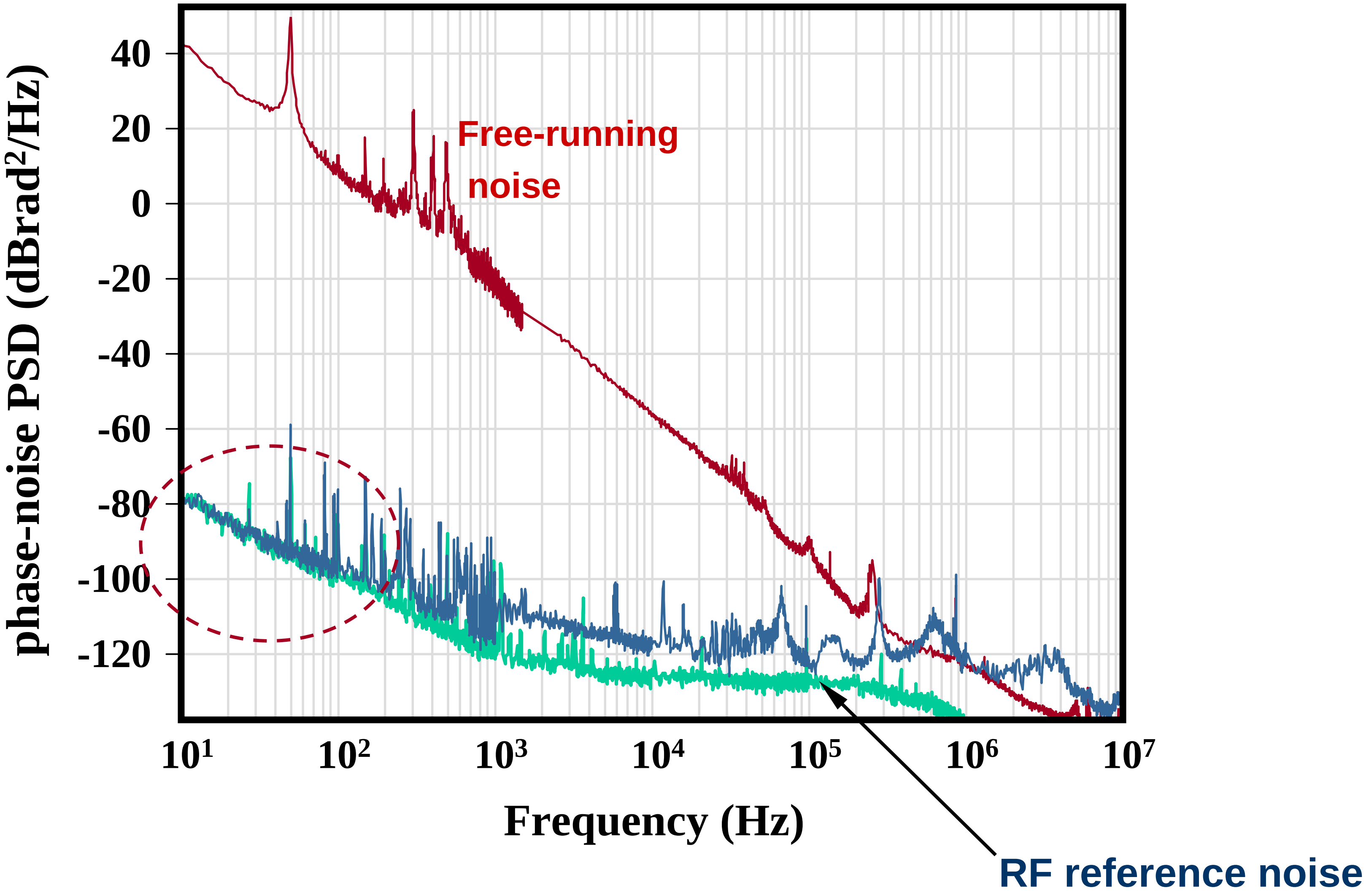
Optical Phase-Locked Loop (OPLL) stabilization



THALES

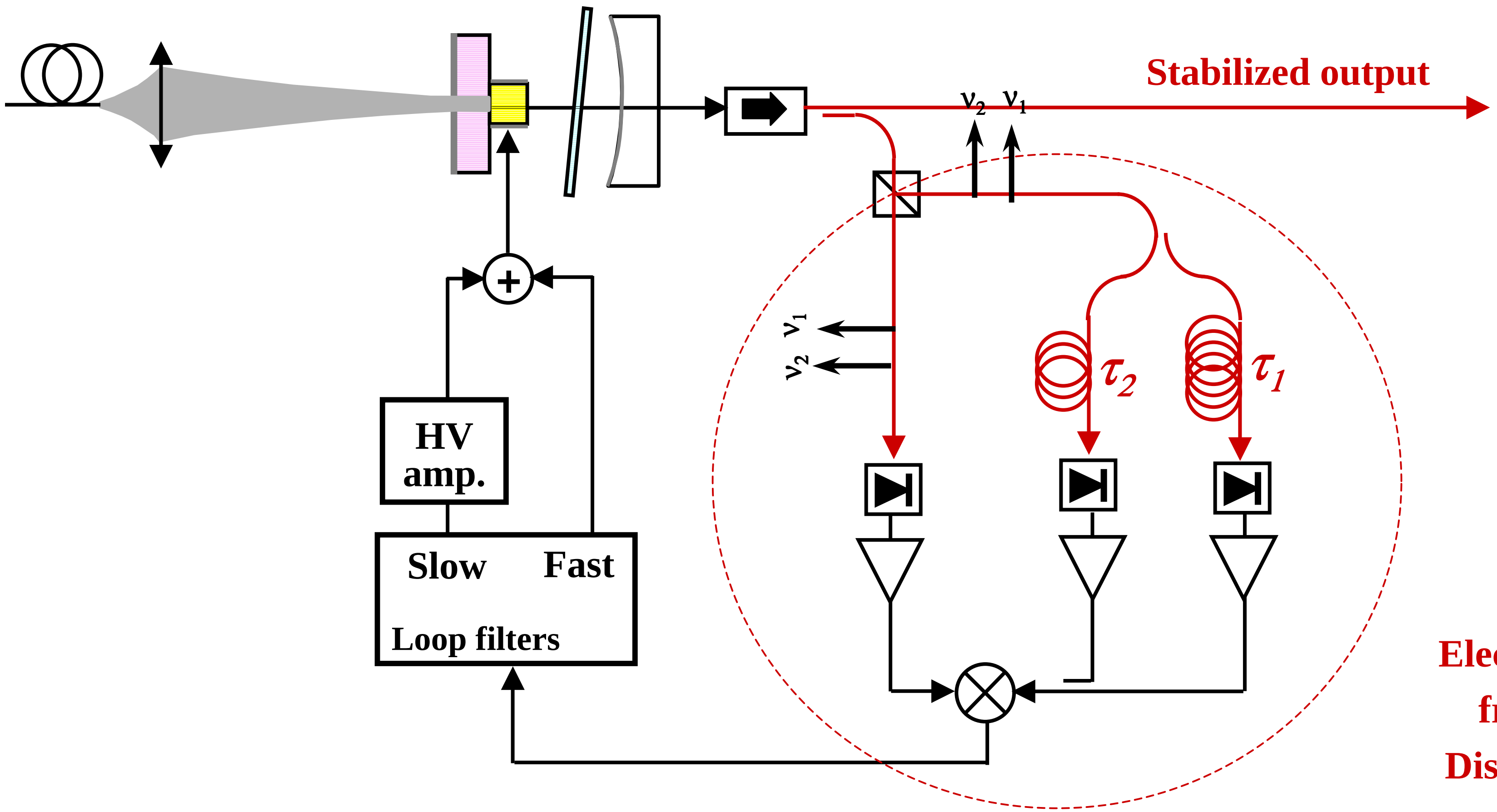
DFL stabilization with an Optical Phase-Locked-Loop (OPLL)

Phase noise of the stabilized beatnote



THALES

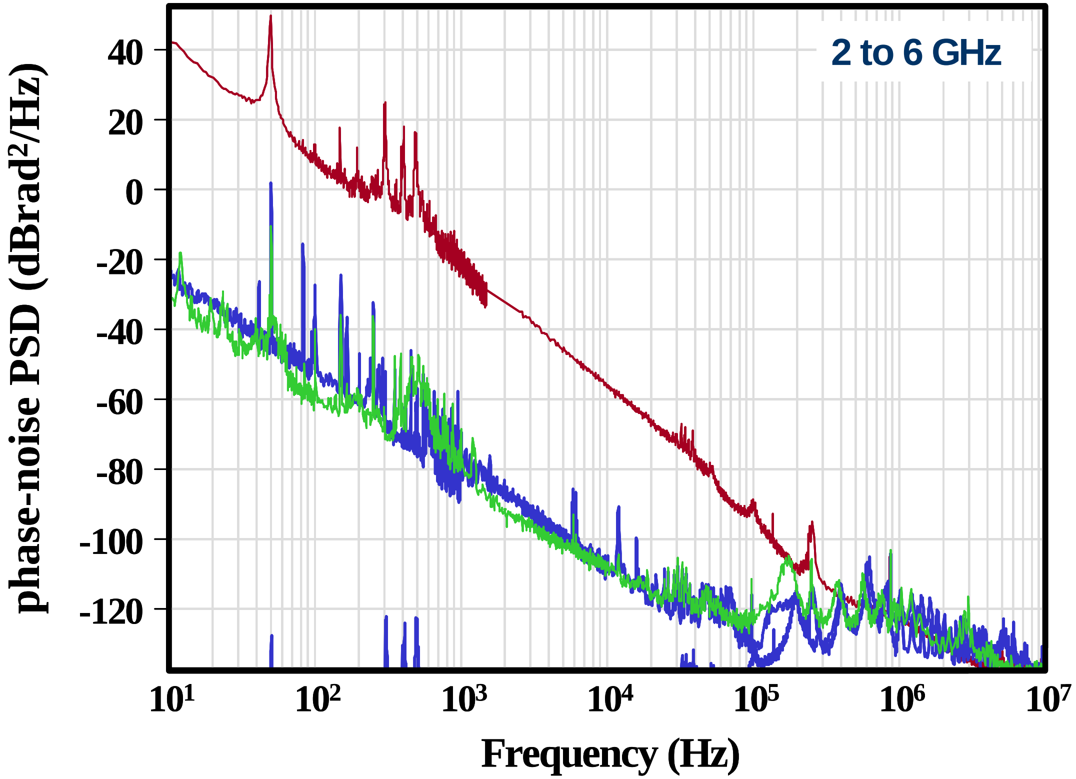
Stabilization combining two delays



Electro-optical frequency Discriminator (EOFD)

THALES

Phase noise of the stabilized beatnote : 1000 + 100 meters long fibers



➔ **both low and high frequency phase noise are reduced, detection + electronic noises are still limiting**

- **Theoretical limit is fixed by the shot noise level at detection and the amount of delay :**
- **Low noise, widely tunable, high frequency oscillators for radar applications**

$$S_\varphi = \frac{2e}{I_{phot}\pi^2\tau^2 f^2}, \qquad f \ll 1/\tau$$

-150 dBrad²/Hz @10 kHz

(1 km long fiber and 10 mA photocurrent I_{phot})

- **Optical technology offers :**
  - Potential for reducing mass and volume (e.g. the good performance of optical fiber as transmission medium regarding weight, volume and loss can implement compact optically-based TTD beamfoming structures).
  - Antenna remoting
  - Advance functionality (processing of different types of signals, wideband, multibeam, reconfigurable)
  - Different approaches to optical beamforming that can be combined to perform the most suitable optical architecture regarding the application targeted

- **New approaches for time delay implementation under studies will offer in the future a higher level of integration**