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## Developments in Microwave photonics

# Integrated Microwave Photonics
## based on hybrid combination of $Si_3N_4$-based-TriPleX and InP PICs

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(online)

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# Our Mission

- LioniX International is a leading global provider of customized microsystem solutions, in particular integrated photonics-based, in scalable production volumes

**Why**

- Applying disruptive technologies to solve major societal challenges

**Integrated Photonics is one of the key enablers**

# Scalable Production Volumes

The Gallery,
LioniX Int office and lab

The Gallery,
Cleanroom, PIC production

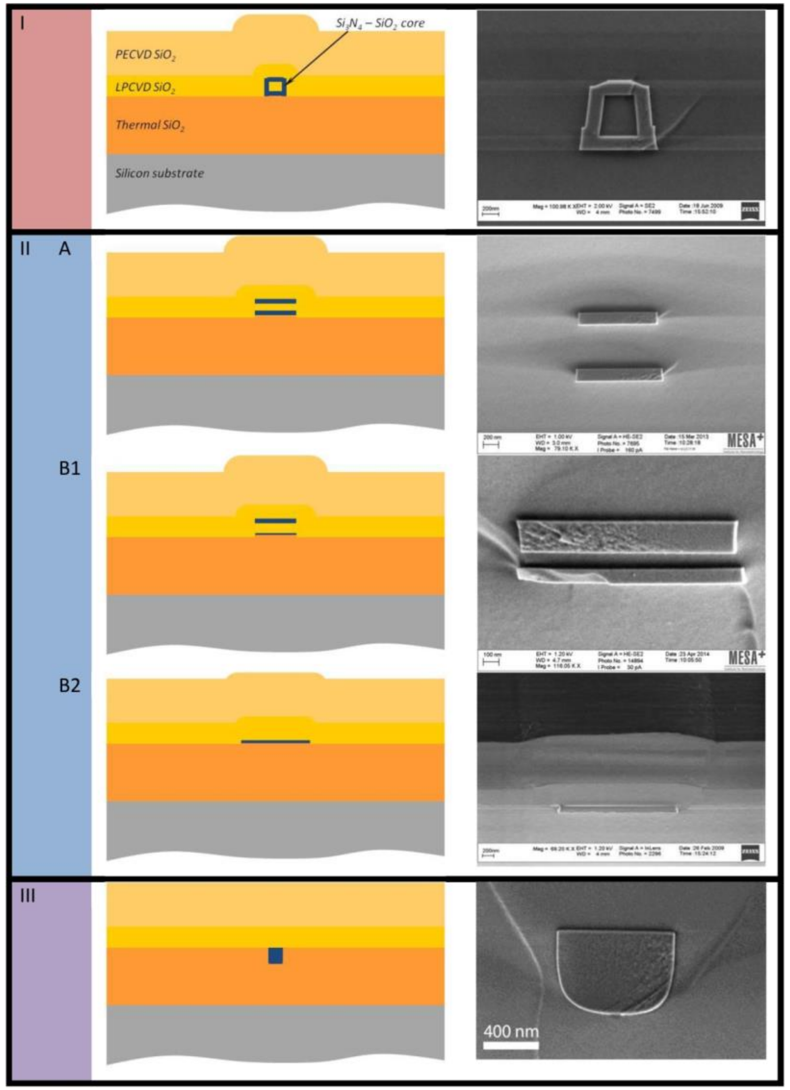
High Tech Factory,
PHIX assembling & packaging Fab

Magic Micro and KANC
Cleanroom, PIC production

**Magic Micro / KANC**
**Seoul,**
**South Korea**

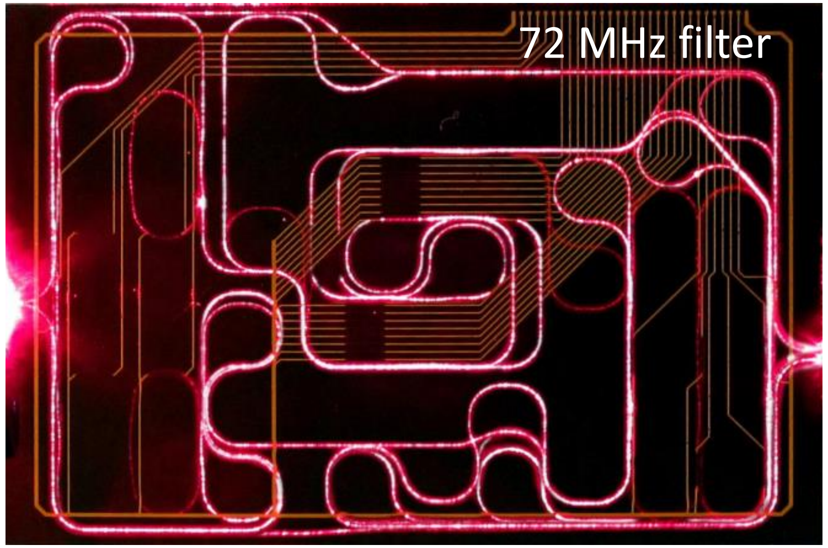
**LioniX International**
**Enschede,**
**The Netherlands**

# TriPleX$^{TM}$: Some Geometries…



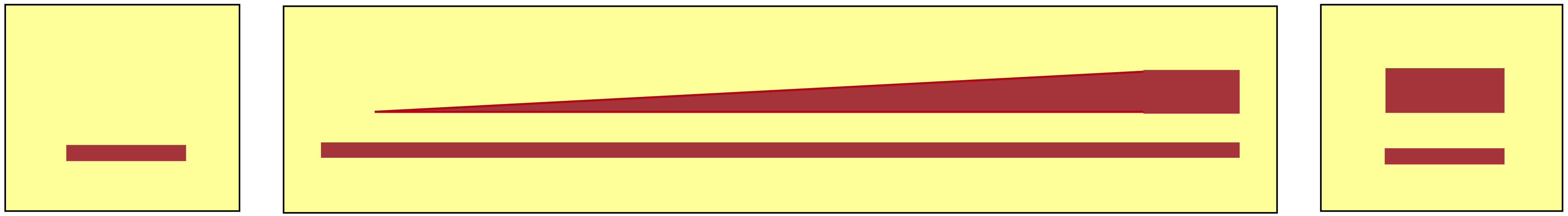
- Core $Si_3N_4$ and Cladding $SiO_2$
- High optical powers (watts)
- Low optical attenuation
  - 0.1 dB/cm high confinement
  - 0.001 dB/cm for low confinement
- Adjustable polarization properties
- Broad band (405nm-2350nm)
- Small footprint ($R_{bend}$ < 80 µm)
- Spot-size converters
  - Low coupling loss to SMF (<0.5 dB)
  - Low chip-to-chip coupling loss (< 1 dB)
- Silicon and glass compatible

**C. Taddei et al.," High-selectivity on-chip optical bandpass filter with sub-100-MHz flat-top and under-2 shape factor," IEEE PTL, 2019**



**C. Roeloffzen et al., "Low-Loss Si3N4 TriPleX Optical Waveguides: Technology and Applications Overview," IEEE JSTQE, 2018**

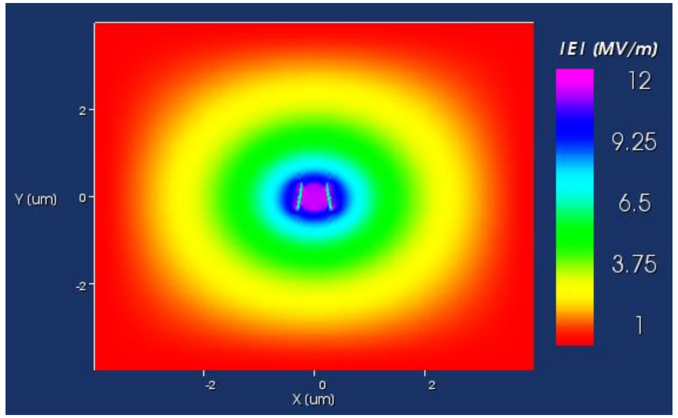
# Tapering: High ⇔ Low Index Waveguides

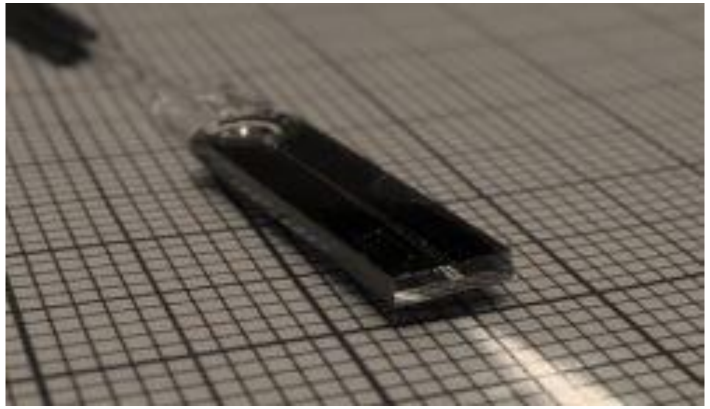


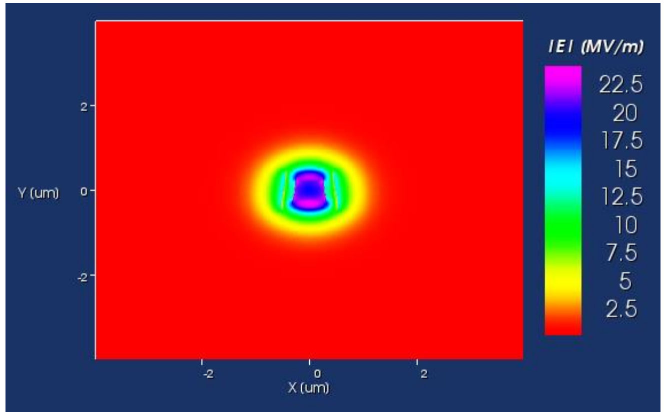
Low index contrast

Taper region

High index contrast

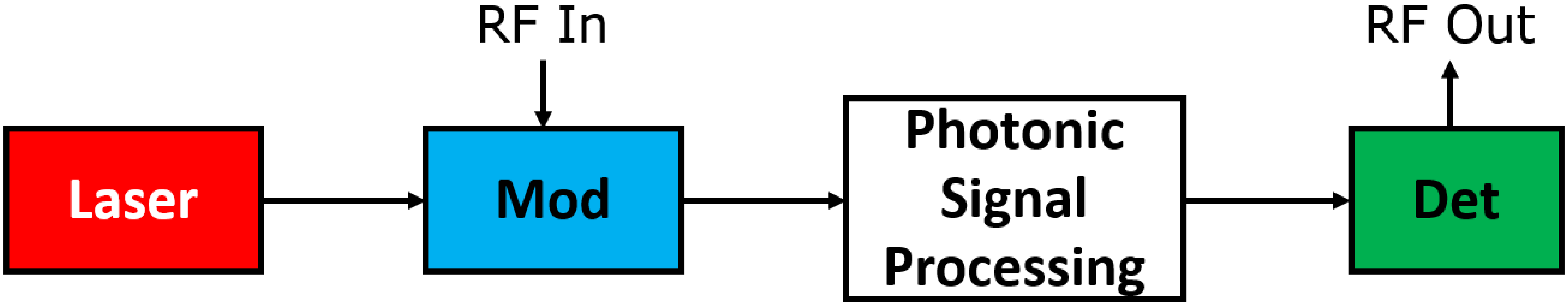






- Mode profiles from 1 µm - 10 µm
- Modefield conversion
- Pitch conversion by mask layout
- Low loss coupling to almost any external component, including SM fiber, InP and Si (SOI)

# Microwave Photonic Link (MPL)


RF In

Laser

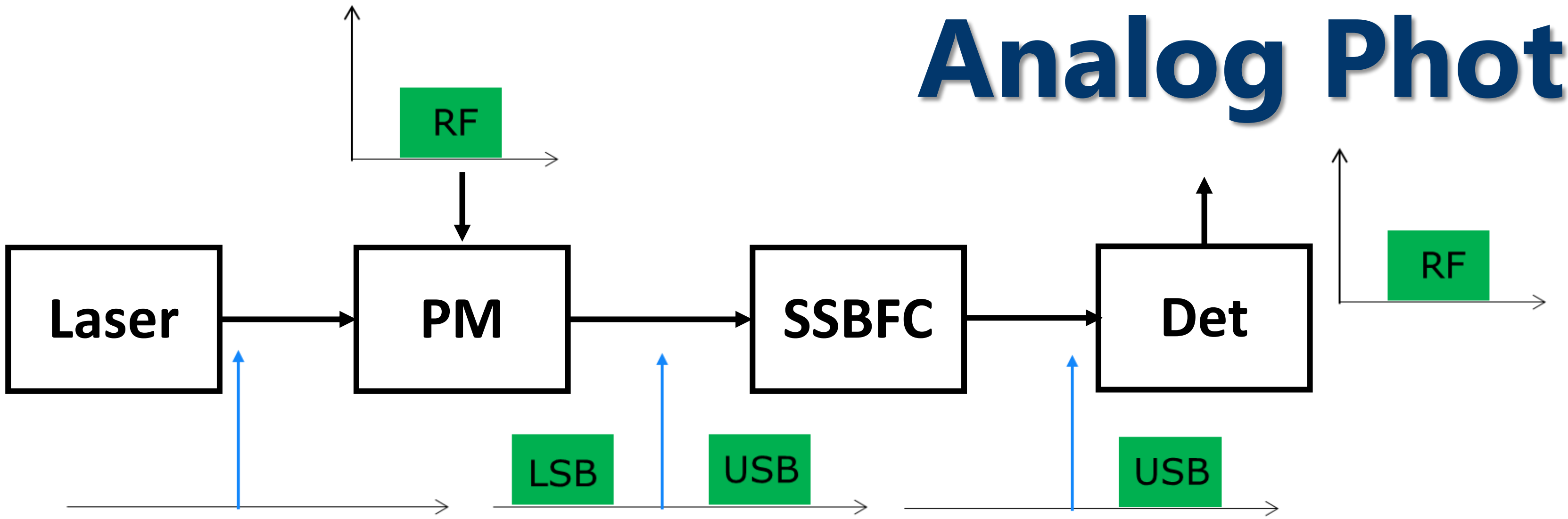
Mod

Photonic Signal Processing

Det

RF Out

# Analog Photonic Link



PM - SSBFC

$$G_{PM\_SSBFC} = \frac{P_{RF\_out}(t)}{P_{RF\_in}(t)} = \left(\frac{\pi R_{pd} P_l R}{2 L V_\pi}\right)^2 = \left(\frac{\pi I_{pd\_DC} R}{2 V_\pi}\right)^2$$

$$I_{pd\_DC}(t) = R_{pd} \frac{P_l}{L}$$

$P_l$ = Laser power (100 mW)
$V_\pi$ = half-wave voltage of the phase modulator (2 V)
$L$ = loss of the optical link (10 dB)
$R_{pd}$ = Responsivity of the photodiode (0.8 A/W)
$R$ = matching resistance (50 Ω)
$I_{pd\_DC}$ = Average photo current (8 mA)

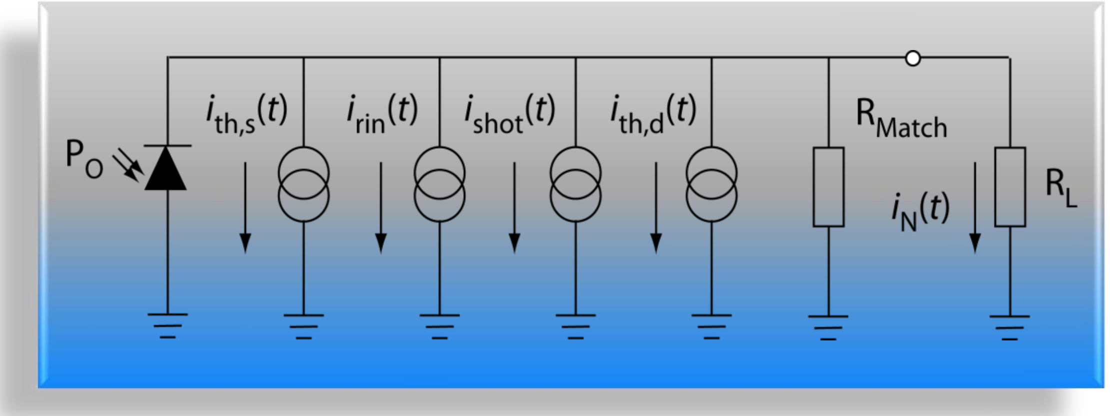
For given values: **$G$ = -10 dB**

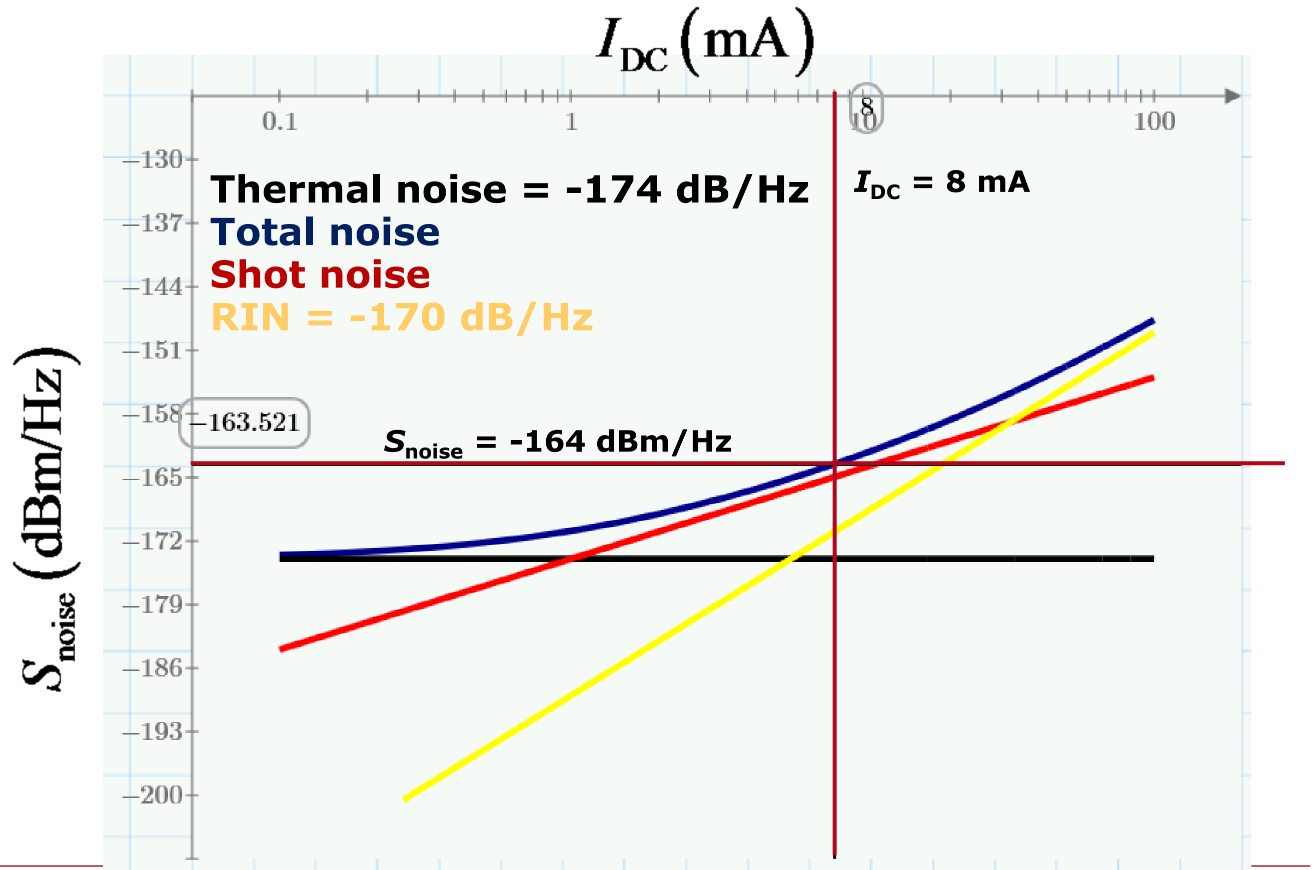
# Link Noise

B = noise bandwidth
k = Boltzmann constant (1.38·10-23)
T = temperature
q = electron charge
$r_{PD}$ = photodetector responsivity (A/W)
$I_{av}$ = average photocurrent
$P_{av}$= average received optical power
$R_L$ = load resistance (50 ohm)

- Thermal noise: $S_{th} = kTB$ (= -174 dBm + 10 log $B$ @ 290k)
- Shot noise → **proportional to optical power ($P_{opt}$)** : $S_{shot} = 2qI_{av}BR_L$
- Relative intensity noise (RIN) → **proportional to ($P_{opt}$)$^2$** : $S_{RIN} = 10^{\frac{RIN}{10}} I_{av}^2 B R_L$
- $P_{av} = {}^{I_{av}}/_{r_{PD}}$

Noise modeled as current sources





# Noise Figure

$$S_{\text{noise}} = S_{\text{th}} + \frac{1}{4}\left(S_{\text{shot}} + S_{\text{RIN}}\right)$$

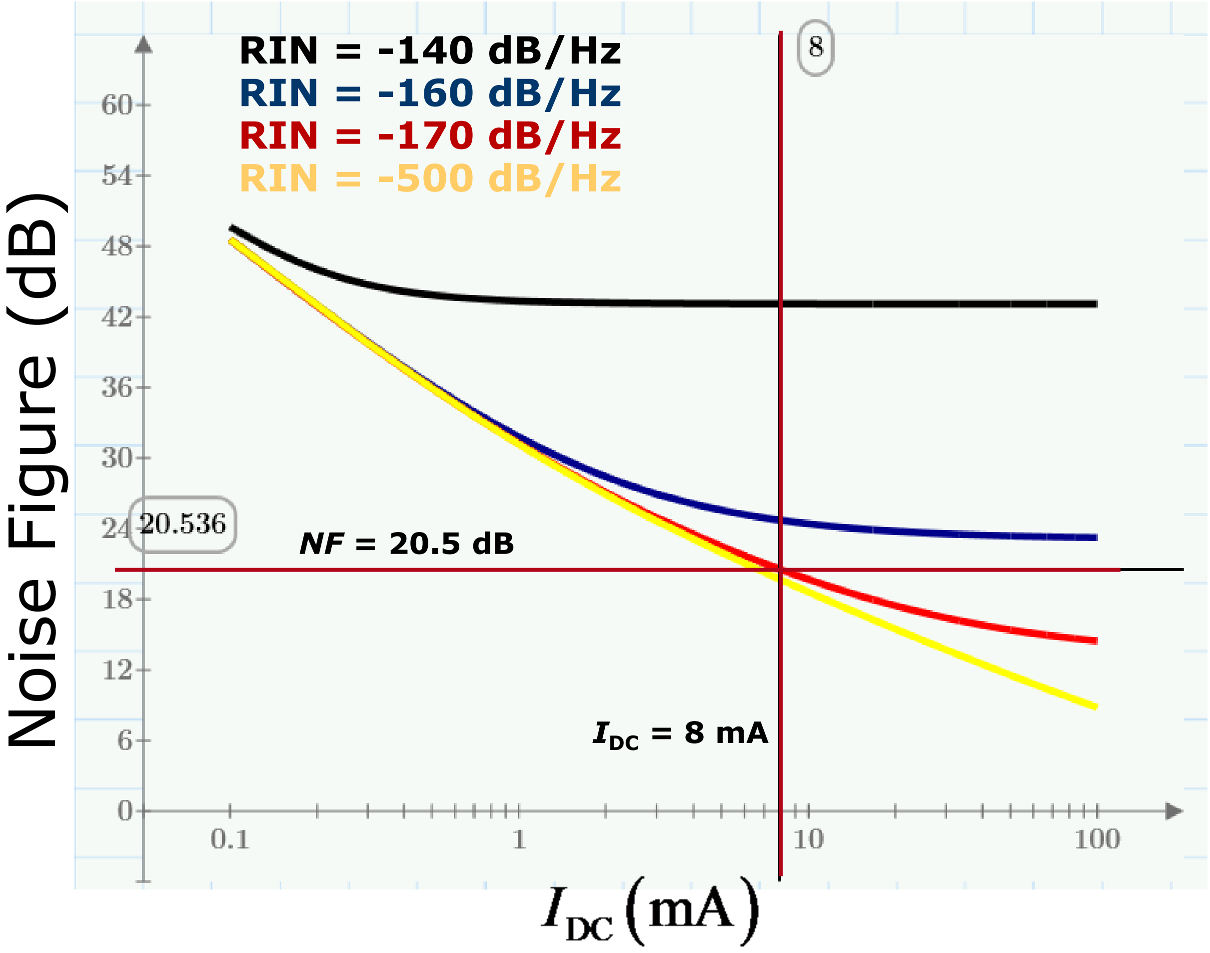
$$\text{NF} = 10\log_{10}\left(\frac{S_{\text{noise}}}{G_{\text{link}} k_{\text{B}} T B}\right)$$

$$\text{NF} = S_{\text{noise}}\left(\text{dBm/Hz}\right) - G_{\text{link}}\left(\text{dB}\right) + 174\ \text{dBm/Hz}$$

- High Noise Figure
- $I_{\text{DC}}$ ↑ → NF ↓ until RIN limitation
- Minimum NF depends on RIN

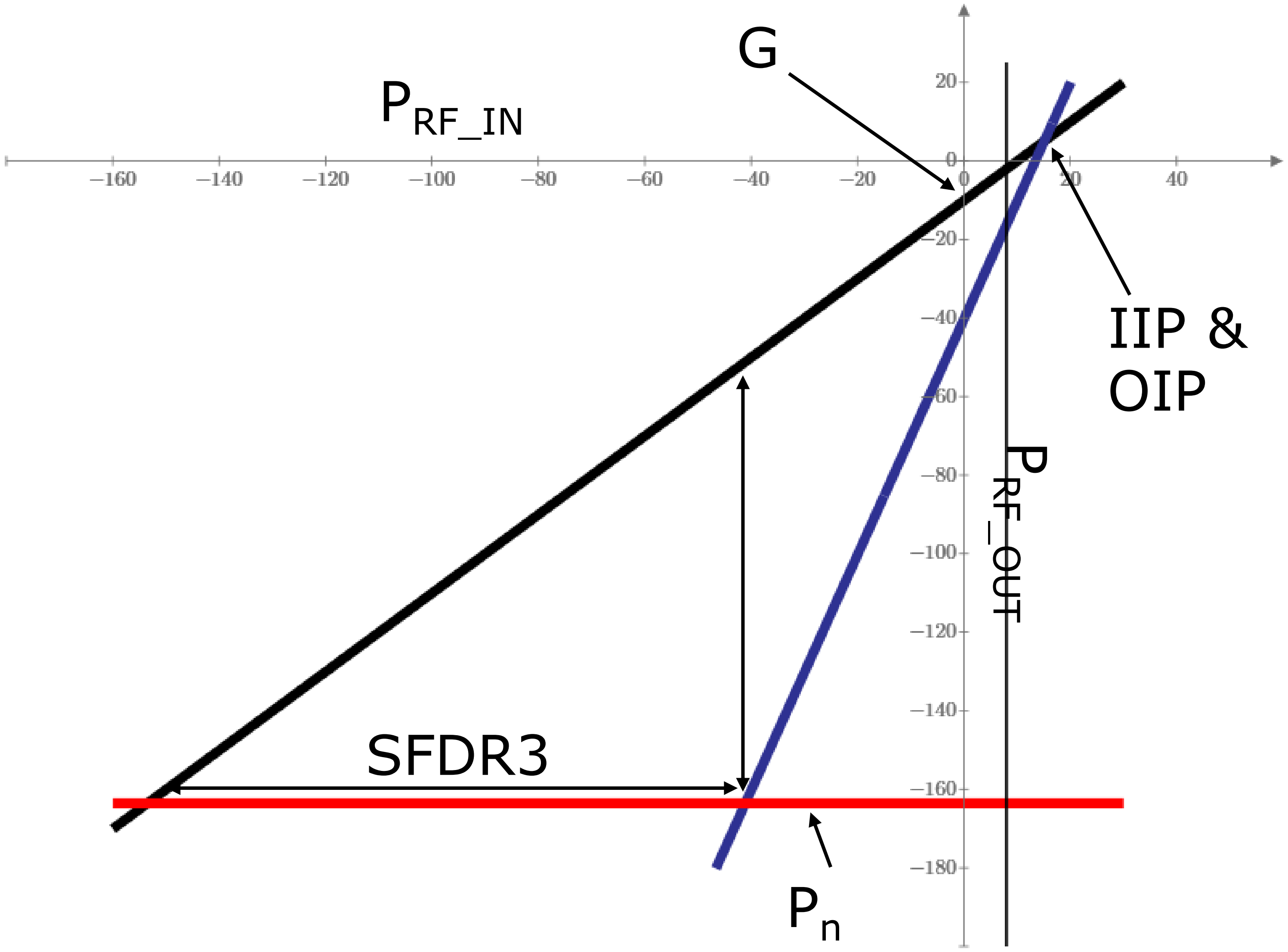
**$L_m$ = 10 dB** **$r_{\text{PD}}$ = 0.8 A/W**

**$V_\pi$ = 2 V** **$R_L$ = 50 Ω**



# Spurious-Free Dynamic Range

- PM-SSBFC
- Laser power = 100 mW
- Detected optical power = 10 dBm
- Photodiode current 8 mA (matched load)
- RIN = -170 dB / Hz
- $V_\pi$ = 2 V
- $P_{in\_1dB}$ = 6 dBm
- Gain = -10 dB ($P_{out}$ @ $P_{in}$ = 0 dBm)
- OIP3 = 5 dBm
- IIP3 = 15 dBm
- $P_n$ = -164 dBm/Hz
- NF = 20 dB
- SFDR3 = 112 dB·Hz$^{2/3}$



# Criteria: High Performance Photonic Link

## Multiple Indium Phosphide Chips

- **Gain**
  - High power laser (> 50 mW)
  - High power gain (> 100 mW)
  - Small linewidth (< 10 kHz)
  - Low RIN (-170 dBc / Hz)
- **Modulator**
  - Phase modulator
  - High speed (> 40 GHz)
  - Sensitive ($V_\pi$ < 3 V)
- **Detectors**
  - High speed (> 40 GHz)
  - Responsivity (> 0.6 A/W)
- Very low RF crosstalk required (< -70 dB)

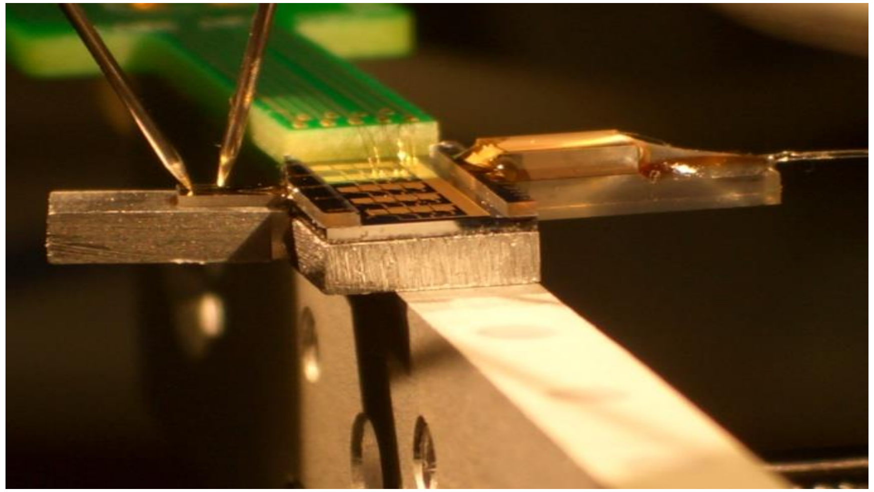
## TriPleX, Silicon Nitride chips

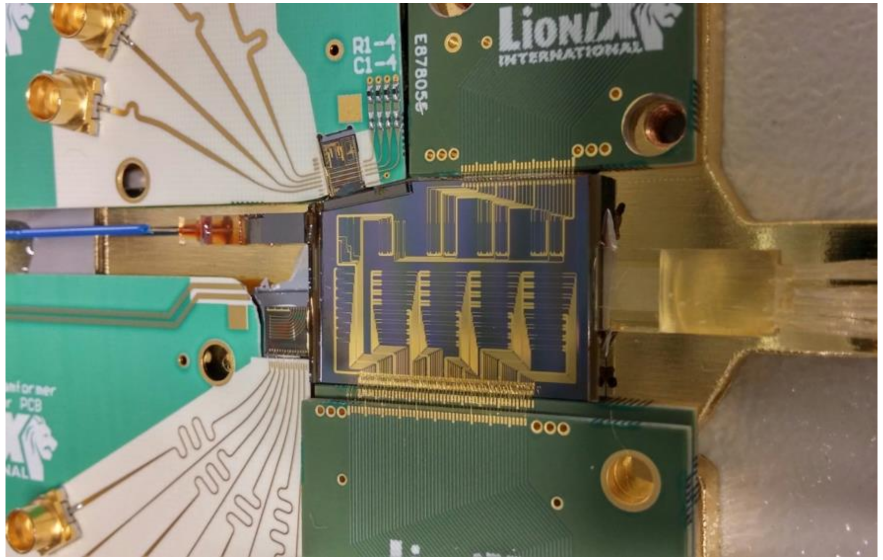
- Tunable mirror for laser
- Rectangular filter for SSBFC
- High contrast, low loss optical processing
- Spot size converters for low loss interfacing

- **High integration density +**
- **Efficient, low-power tunability**
- **Drives Co$t Down**

# Hybrid Photonic Integrated Circuits

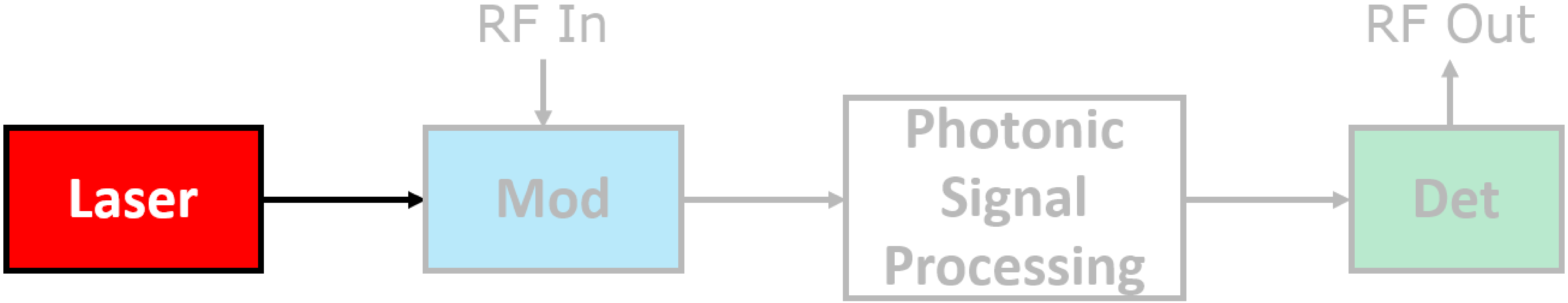
- **TriPleX ($Si_3N_4$)**
  - ✓ Ultra low loss (<0.1 dB/cm)
  - ✓ Applicable in almost all interesting wavelength regions
  - ✓ Reliable actuators (heaters, strain-based: PZT)
  - × But is not electro-optic, so lacks direct light generation, high speed modulation and detection
- **Hybrid integration TriPleX with InP yielding:**
  - ✓ Very high quality, widely tuneable lasers !
  - ✓ High speed modulation (E/O conversion)
  - ✓ High speed photodetection (O/E conversion)
  - ✓ Hybrid integration with other materials (AlGaAs, Si, etc.) was shown
  - ✓ Intrinsically stable, vibration insensitive



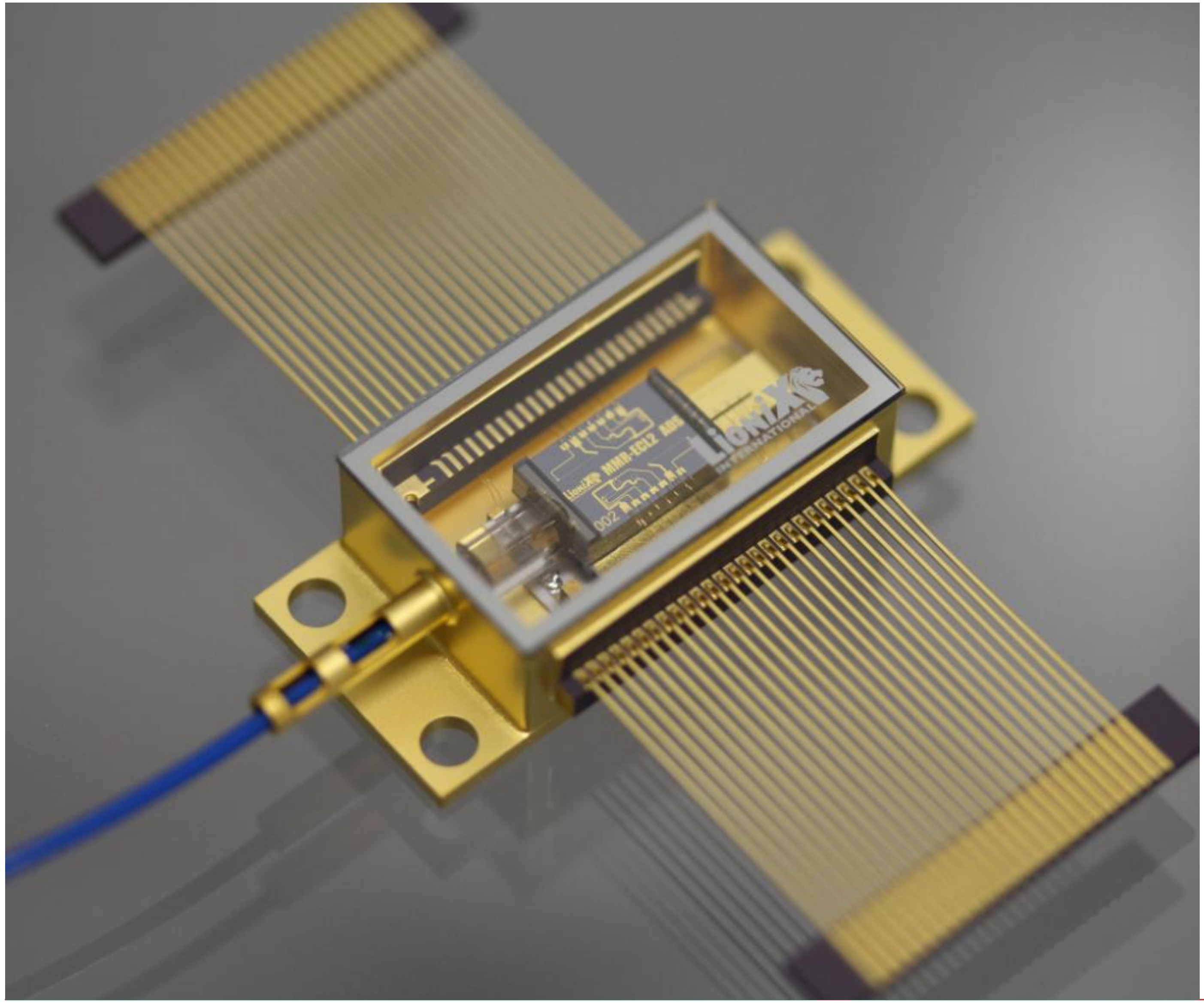


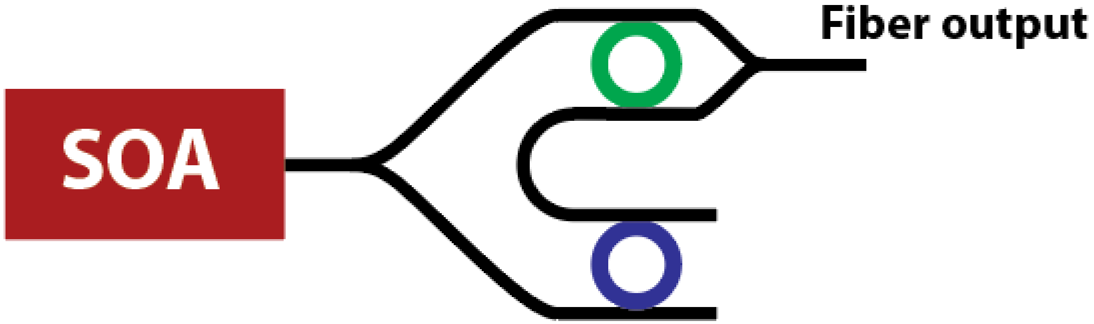
D. Marpaung et al., ” Integrated microwave photonics,” LPR, 2013

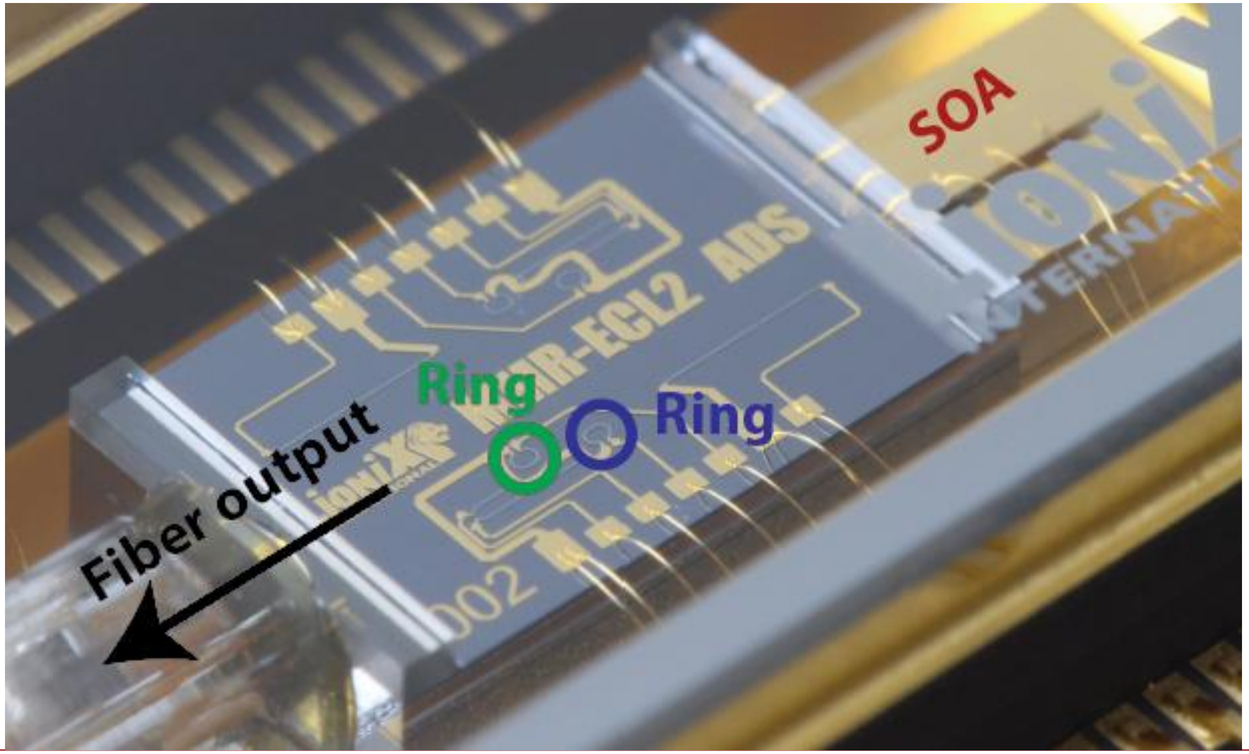
# MPL: Laser



# Laser Assembly



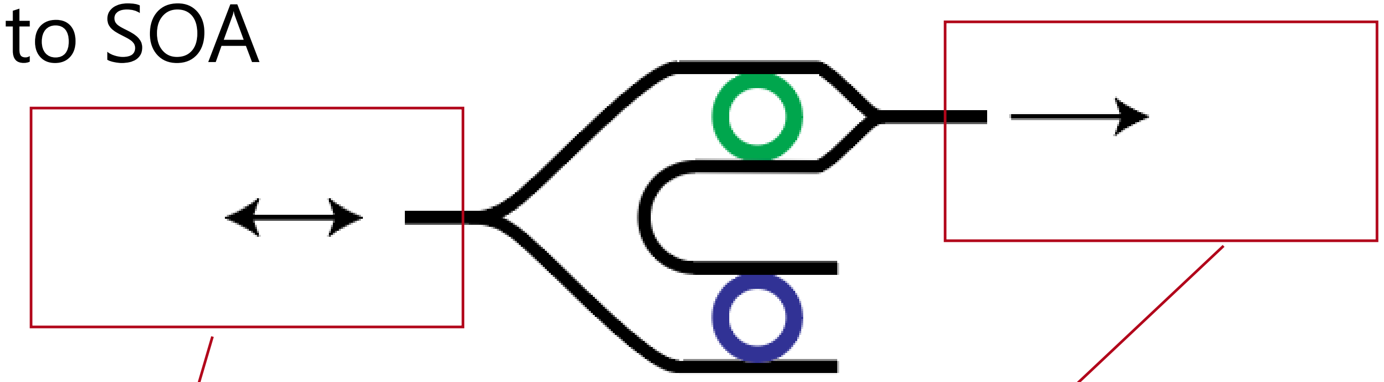


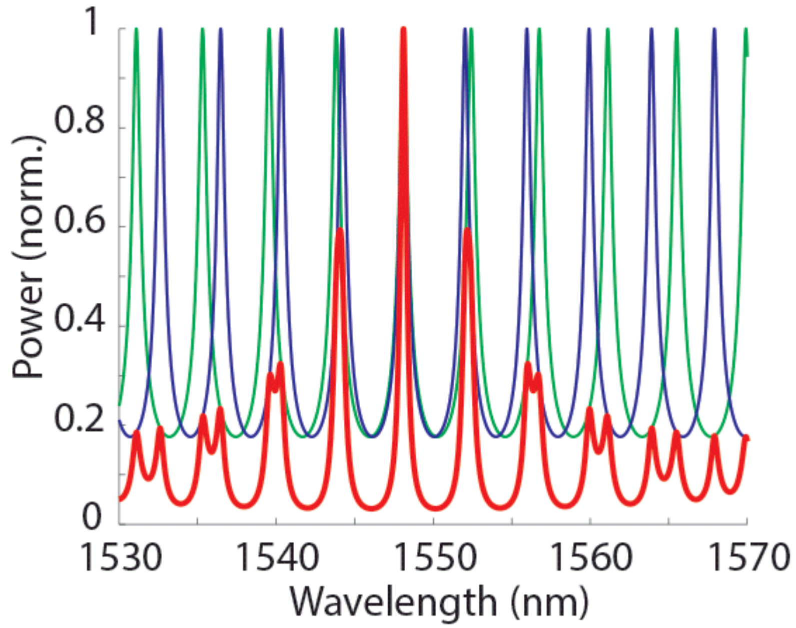


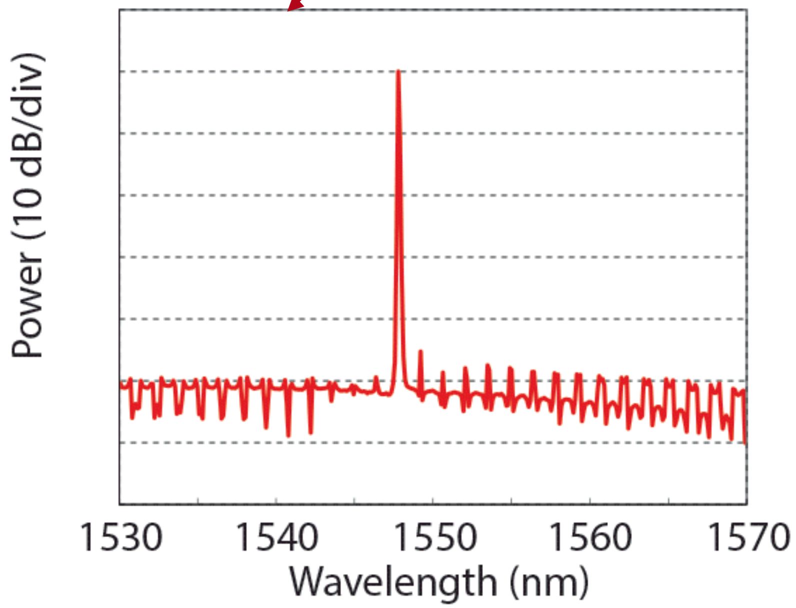
# Laser Working Principle

- Double ring reflector, attach to SOA

Heating 1 ring
Causes spectrum
to hop across
wavelengths

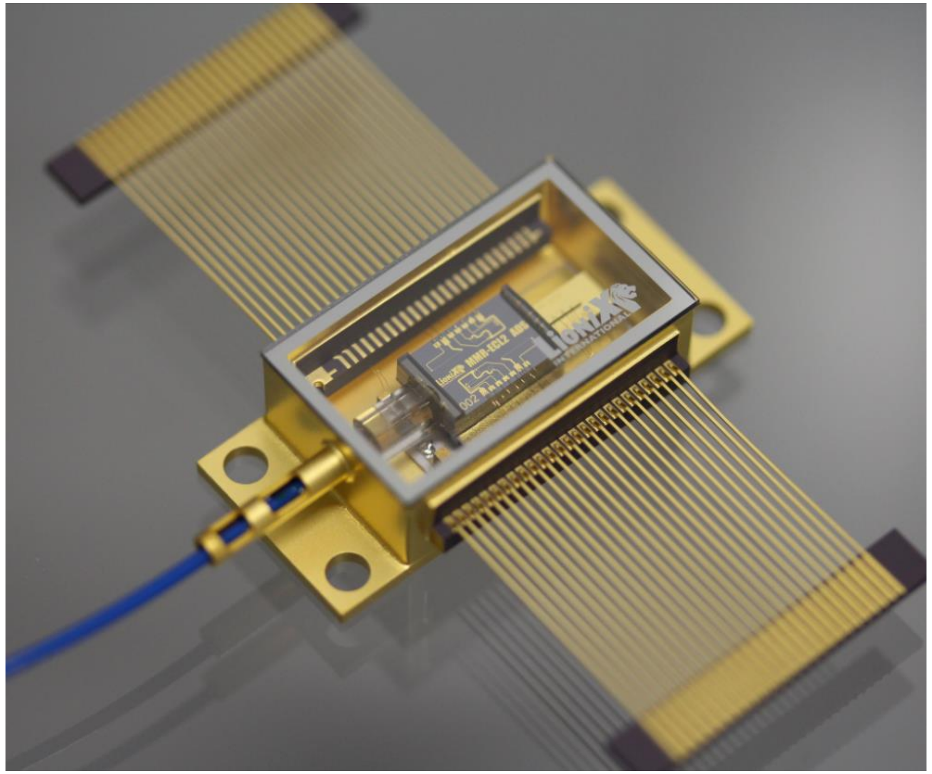






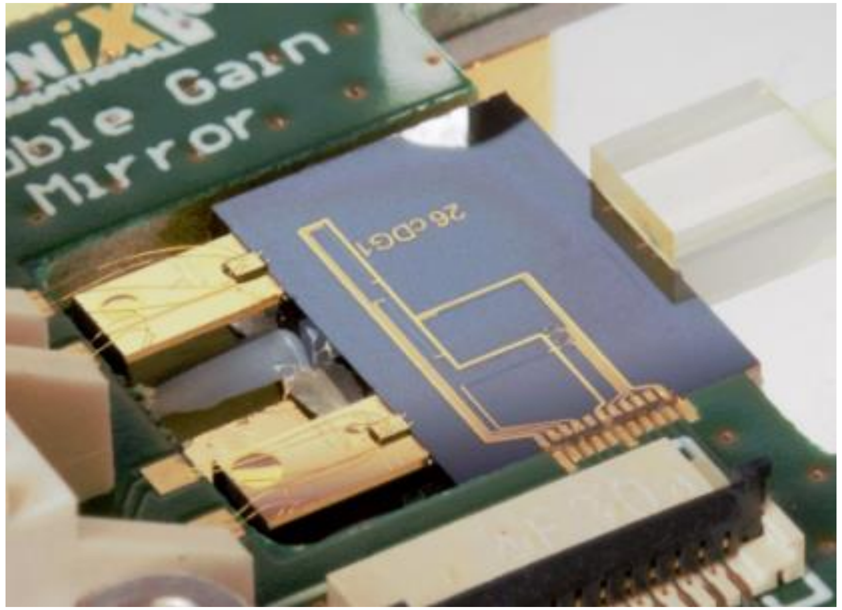
# Typical Specifications

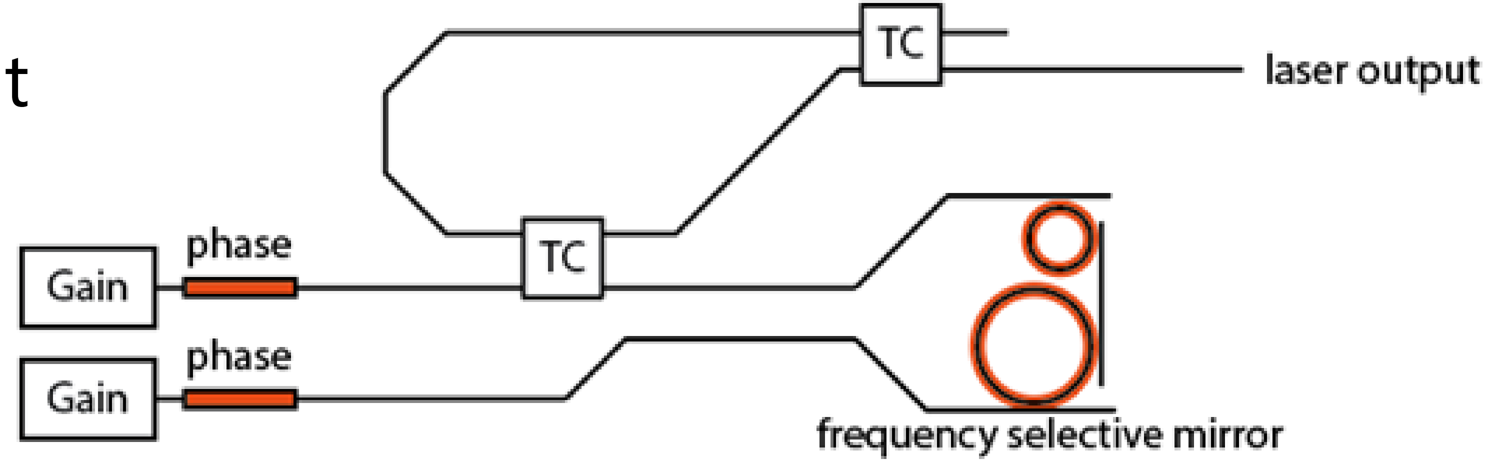
- Output power > 17 dBm (50 mW)
  - Maximum power 20 dBm (100 mW)
- Linewidth <1 kHz
- Wavelength tuning over c-band
  - 80-100 nm tuning range available
- Millisecond switching speed
  - 0.5 ms wavelength-to-wavelength switching
- SMSR > 40 dB
- RIN < -170 dBc/Hz
- Mode-hop free tuning range 0.2 nm



# Dual Gain Laser

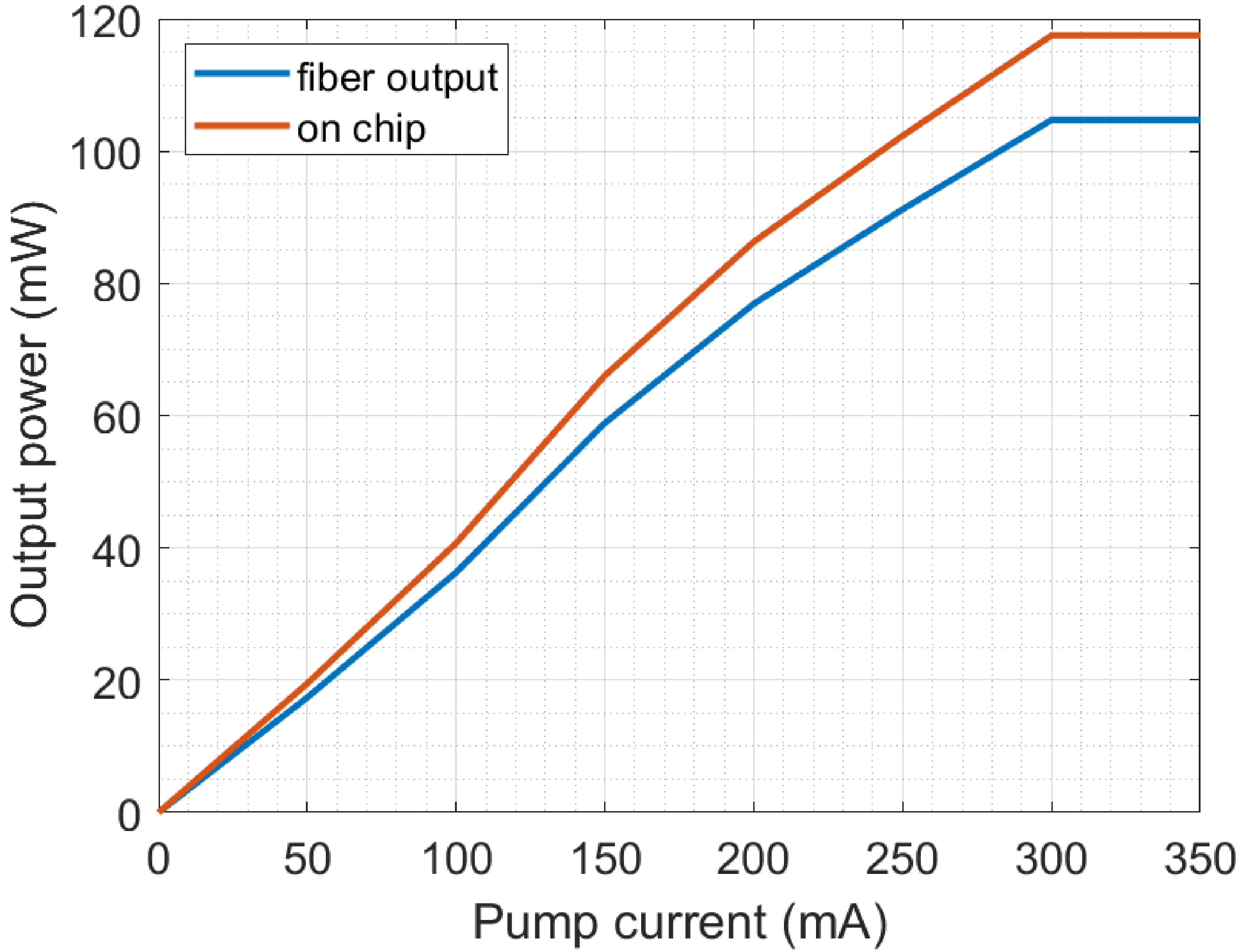
- Use two InP gain sections sharing a cavity to increase power
  - But maintaining single gain properties
- Output coupling controlled by tunable coupler (TC)
- Output coherently combined
- Highest output power achieved at 80% output coupling





# Output Power 100 mW!

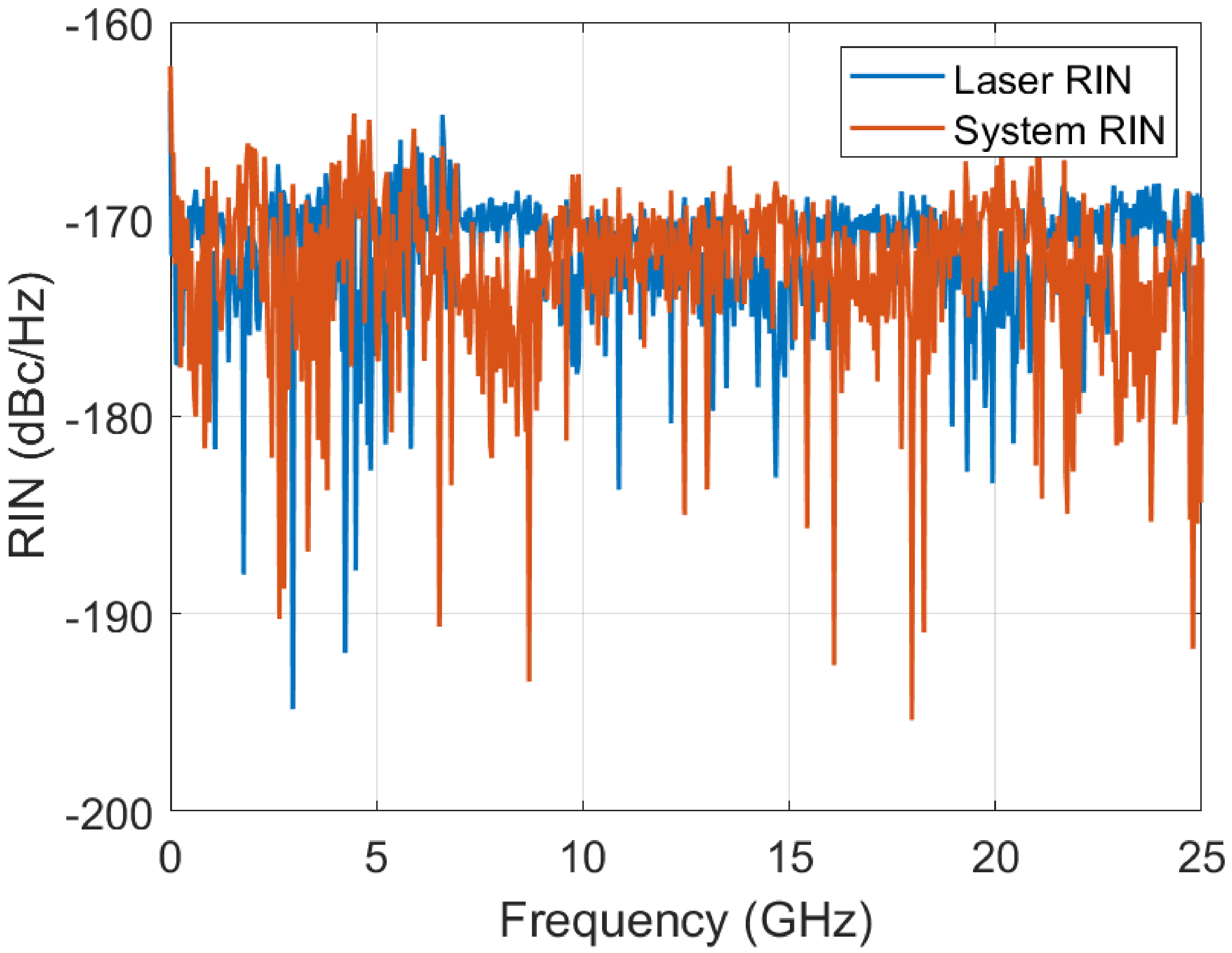
- Output power: >100 mW (20 dBm); 117 mW on chip
- Laser was in single mode
- Side-mode-suppression ratio > 50 dB
- Gain saturation begins above 300 mA
- Improved thermal conductivity will increase the output power even more



J. Epping et al., “High power integrated laser for microwave photonics,” OFC, 2020

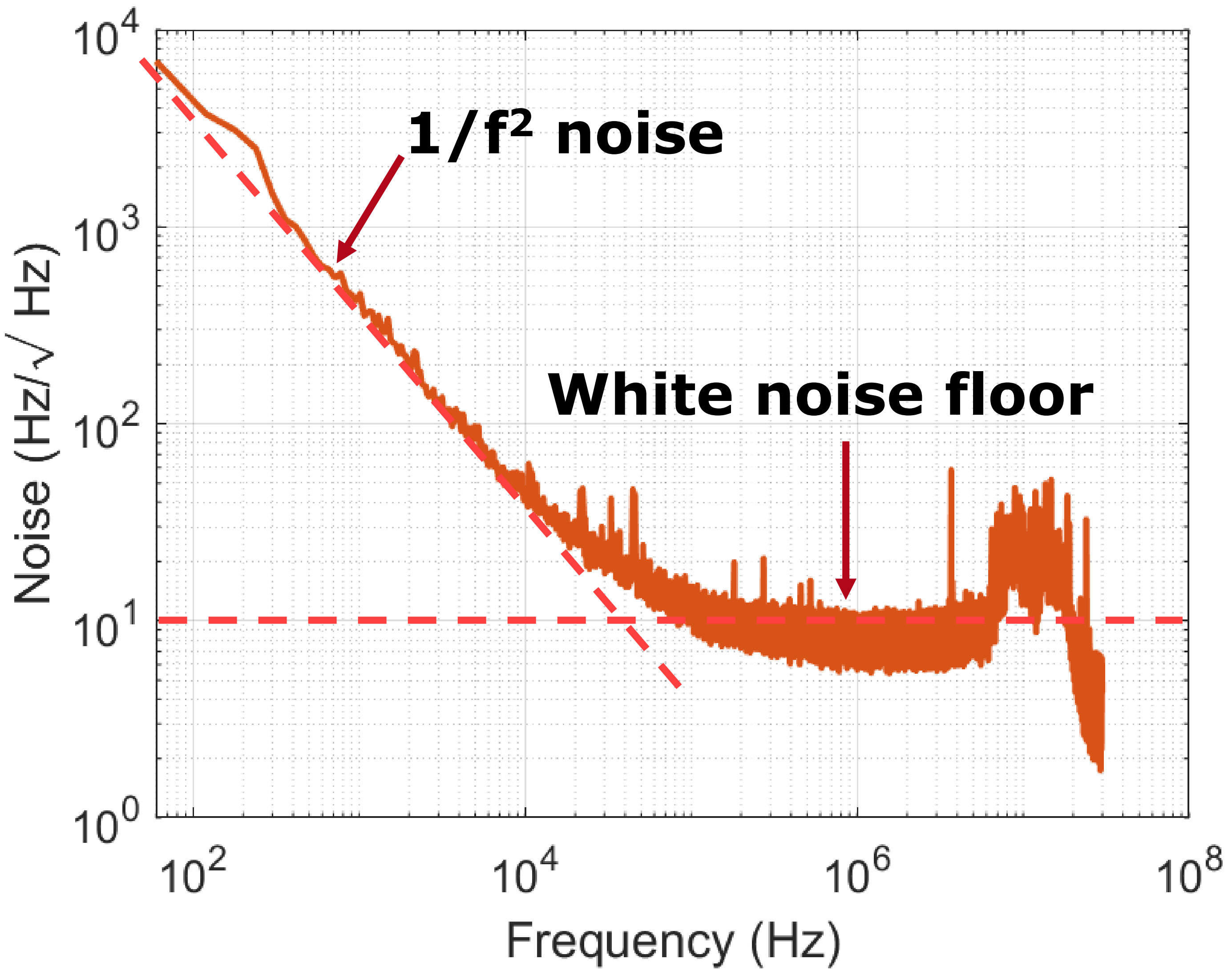
# Low Relative Intensity Noise

- Low relative intensity noise (RIN) is crucial microwave photonic links
- RIN results in signal noise
- Low RIN achieved
  - Measurement limited



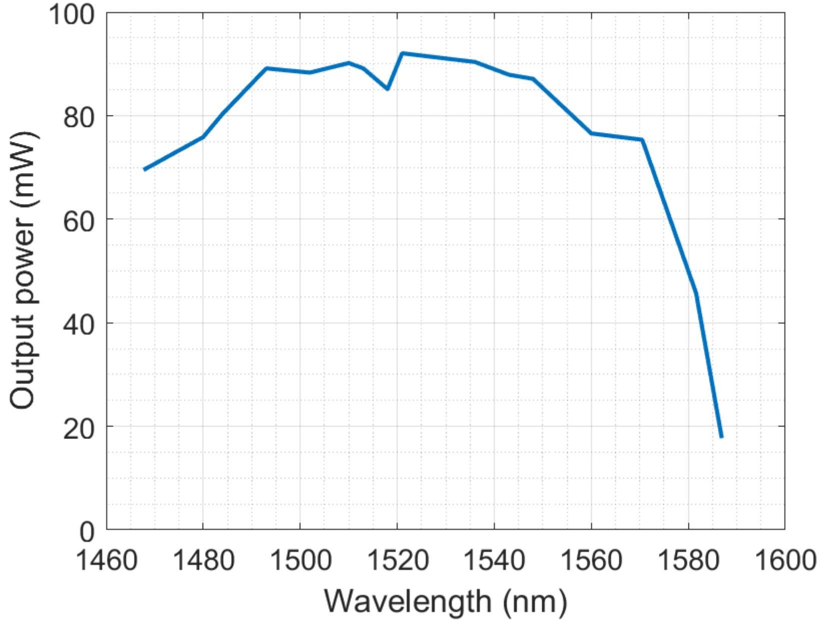
# Low Frequency Noise

- White noise floor (NF) gives intrinsic linewidth:
  - ○ Linewidth ≈ π*(NF)$^2$ ≈ 320 Hz
- Noise at higher frequencies are measurement artifacts.
- Propagation losses: 0.08 dB/cm

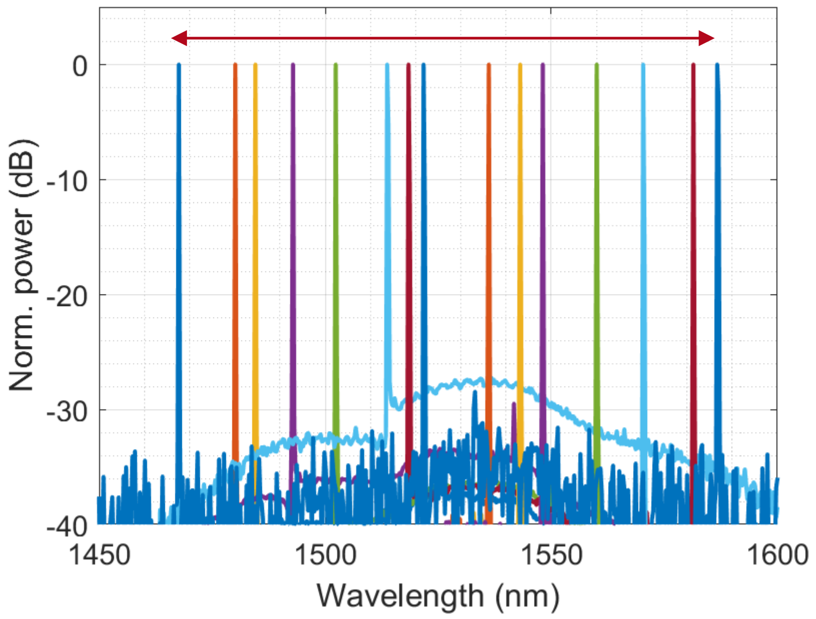


# Large Tuning Range

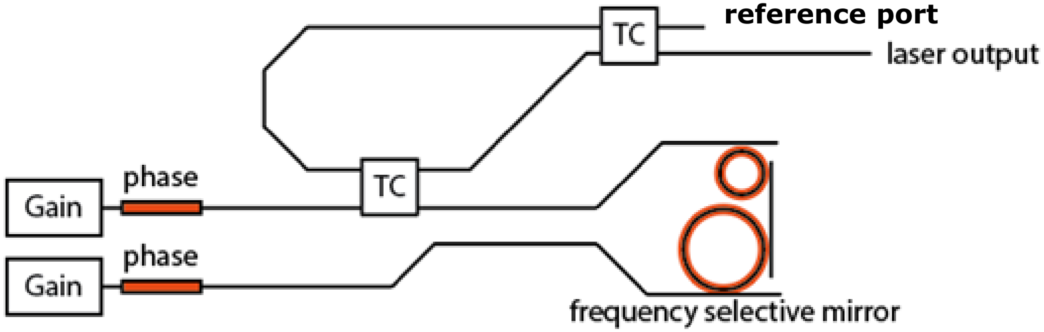
## Output power @ laser output



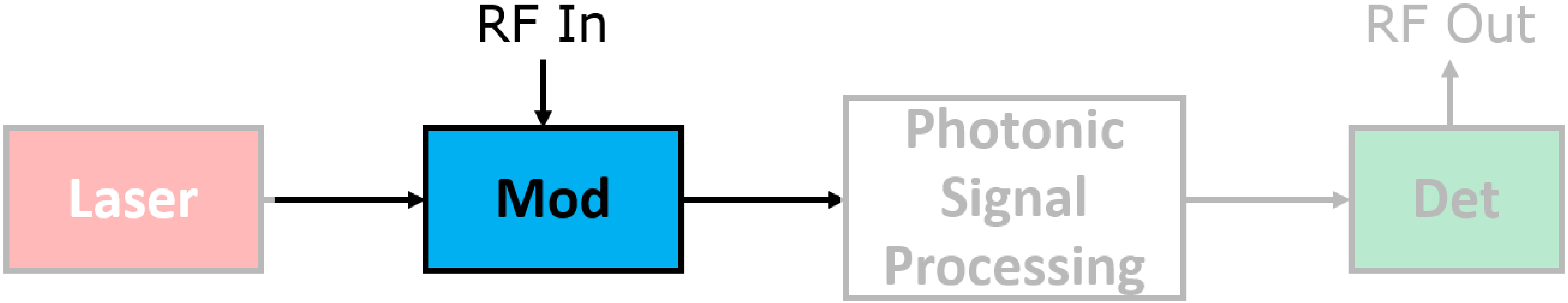
## Spectrum @ reference port



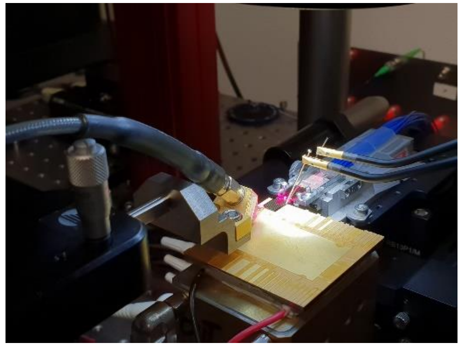
- Total tuning range is 119 nm!!!
- 100 nm tuning range within -1dB power drop
- Tunable output coupler increases tuning range by shifting the gain spectrum

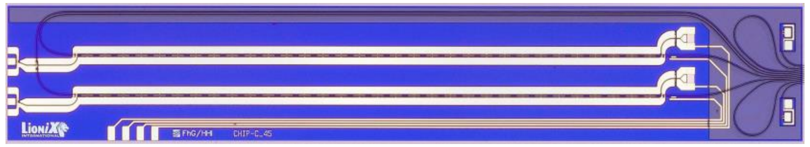


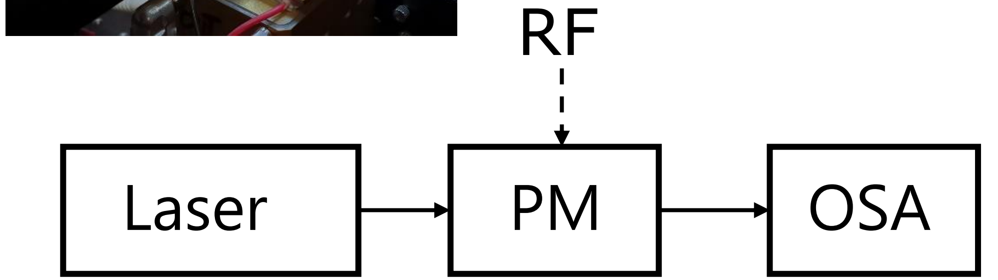
# MPL: Phase Modulator



# InP Modulator (E/O conversion)







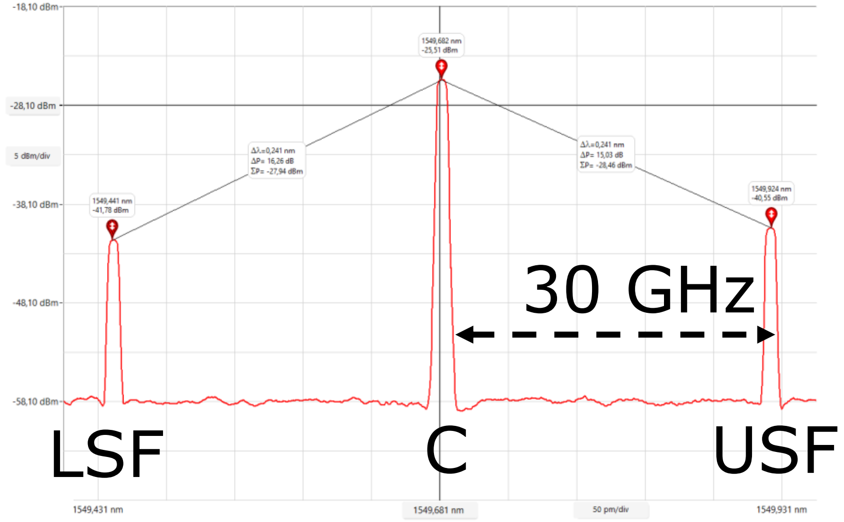
| Freq (GHz) | ΔP (dB) | m | $V_\pi$ (V) |
|---|---|---|---|
| 5 | 10.2 | 0.5907 | 1.68 |
| 10 | 10.9 | 0.5485 | 1.80 |
| 20 | 13.2 | 0.4275 | 2.30 |
| 30 | 15.6 | 0.3275 | 3.00 |

VERY GOOD !

Increase RF power until sidebands are as high as the carrier.

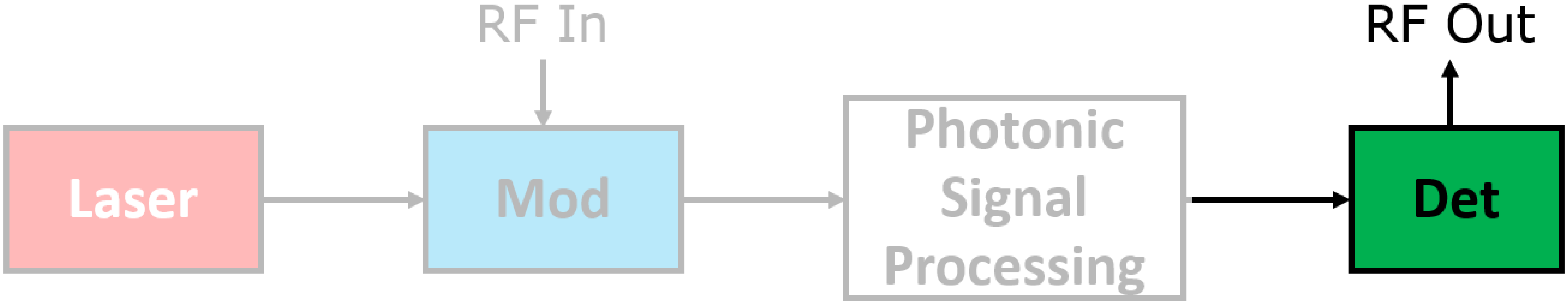
Calculate $V_\pi$ using: $$V_\pi = \frac{V_m}{0.457}$$

Where: $$V_m = \sqrt{2P_{RF}R}$$

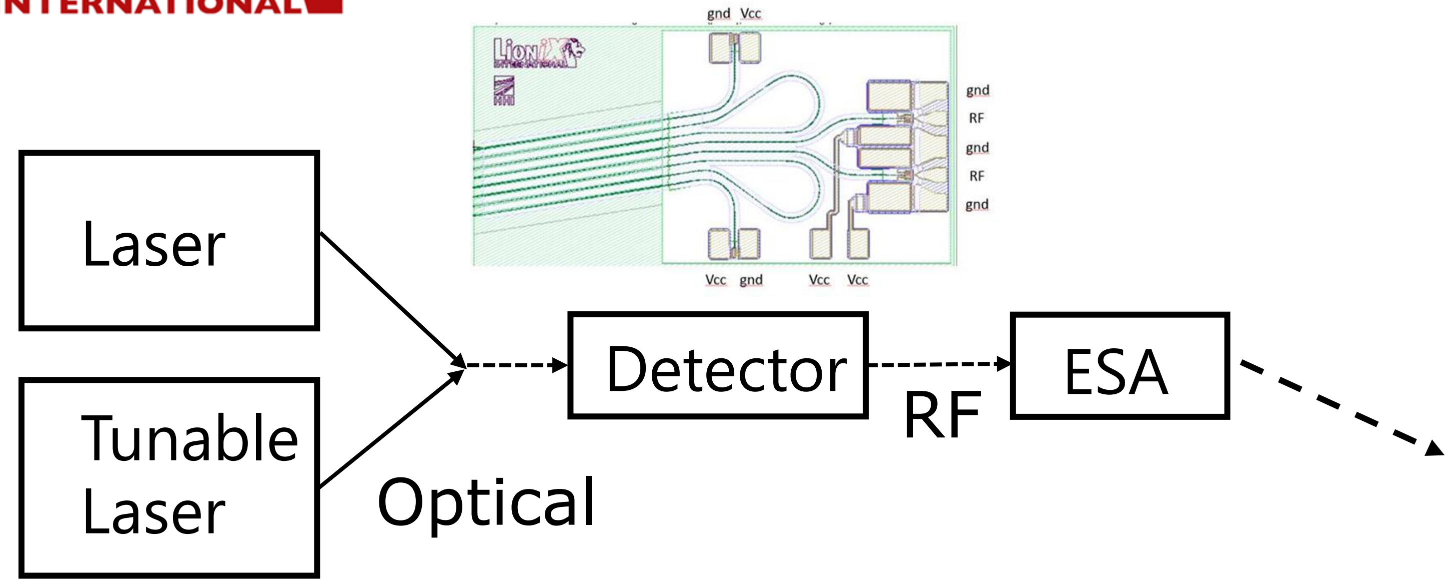


**Optical spectrum analysis method (Yongqiang Shi et al., IEEE JLT 21 (10), 2003)**

# MPL: Photodiode



# Detector Responsivity / Slope



Laser

Tunable Laser

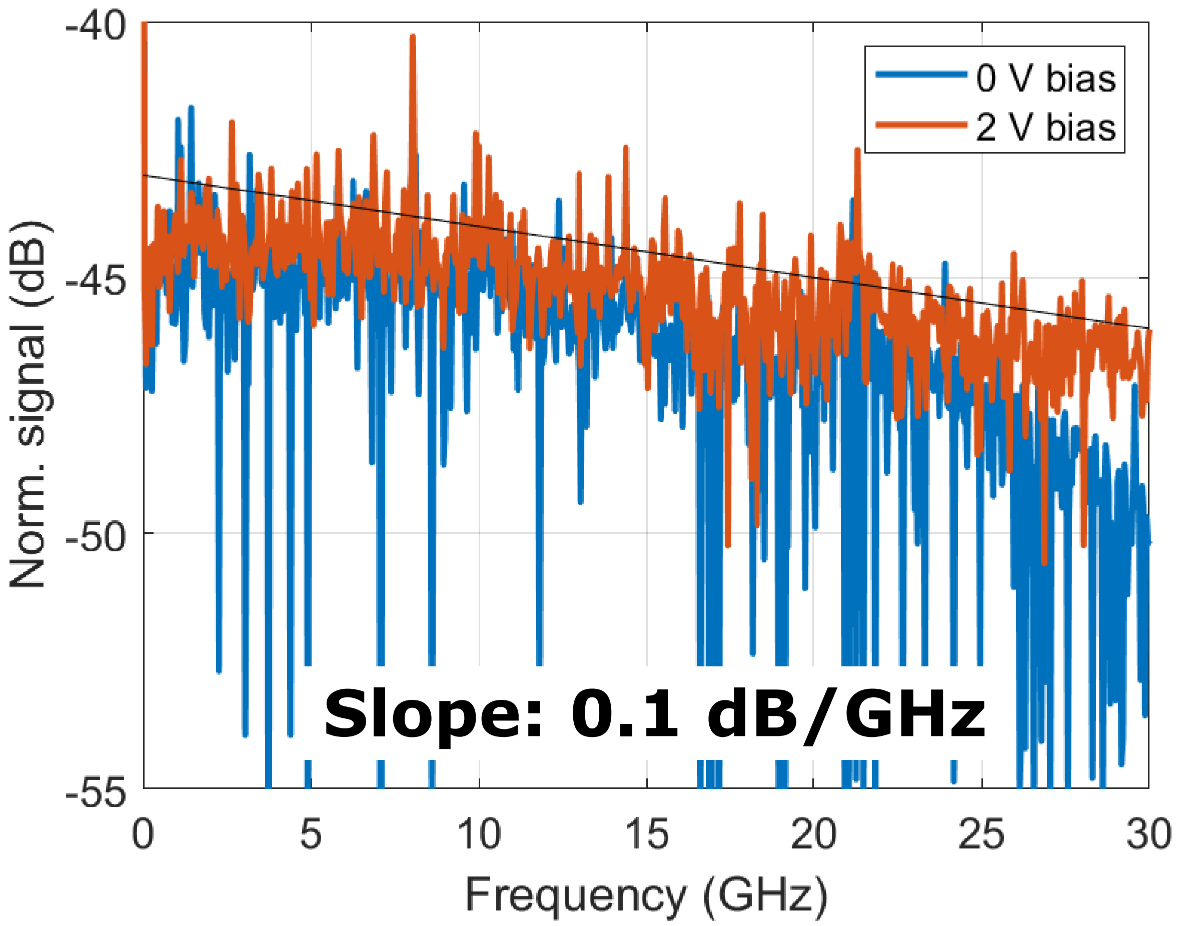
Optical

Detector

RF

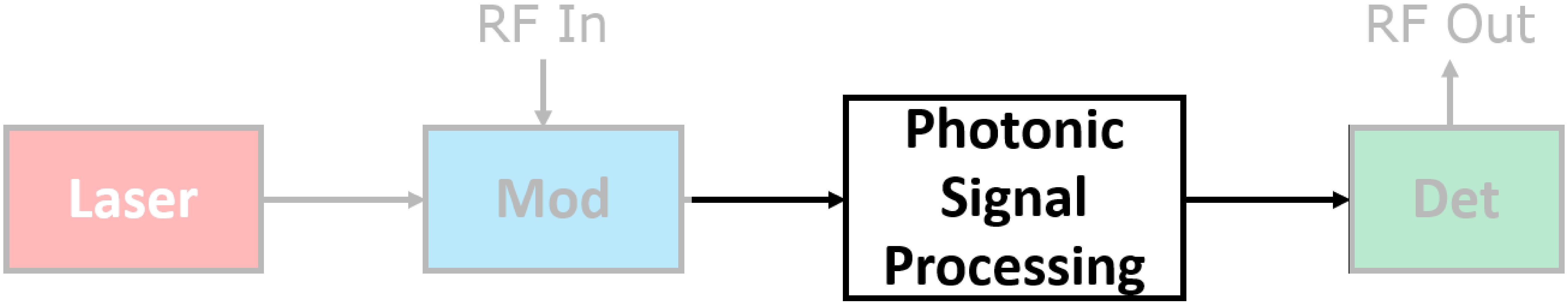
ESA

- ✓ High speed: > 40 GHz
- ✓ Responsivity > 0.8 A/W
- ✓ Internal Matching and biasing network

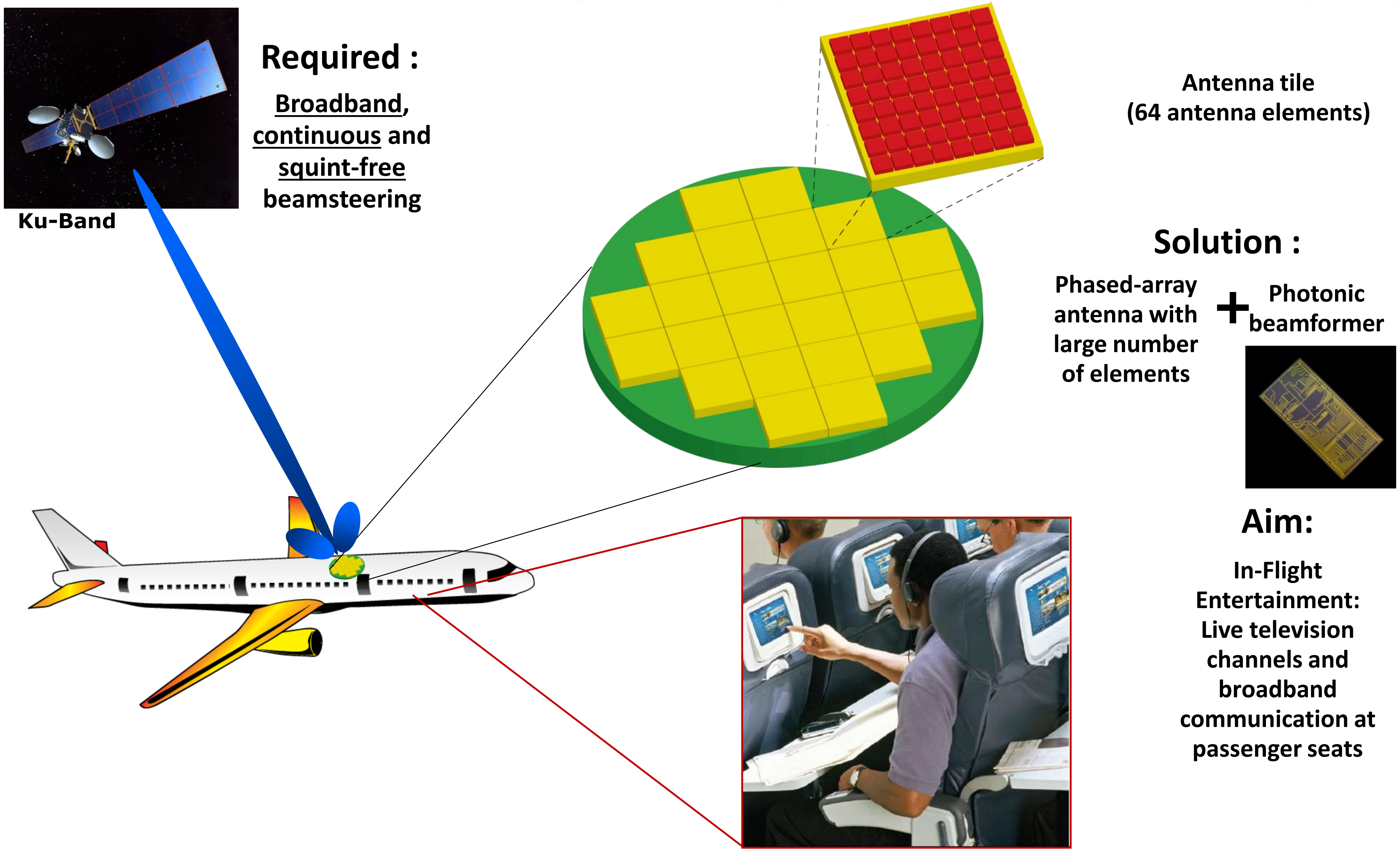


**Slope: 0.1 dB/GHz**

# MPL: Signal Processing



# Smart antenna for Satcom



**Required :**

Broadband,
continuous and
squint-free
beamsteering

**To Receive :**
Data & Digital
video
broadcasting
via satellite
(DVB-S) signal

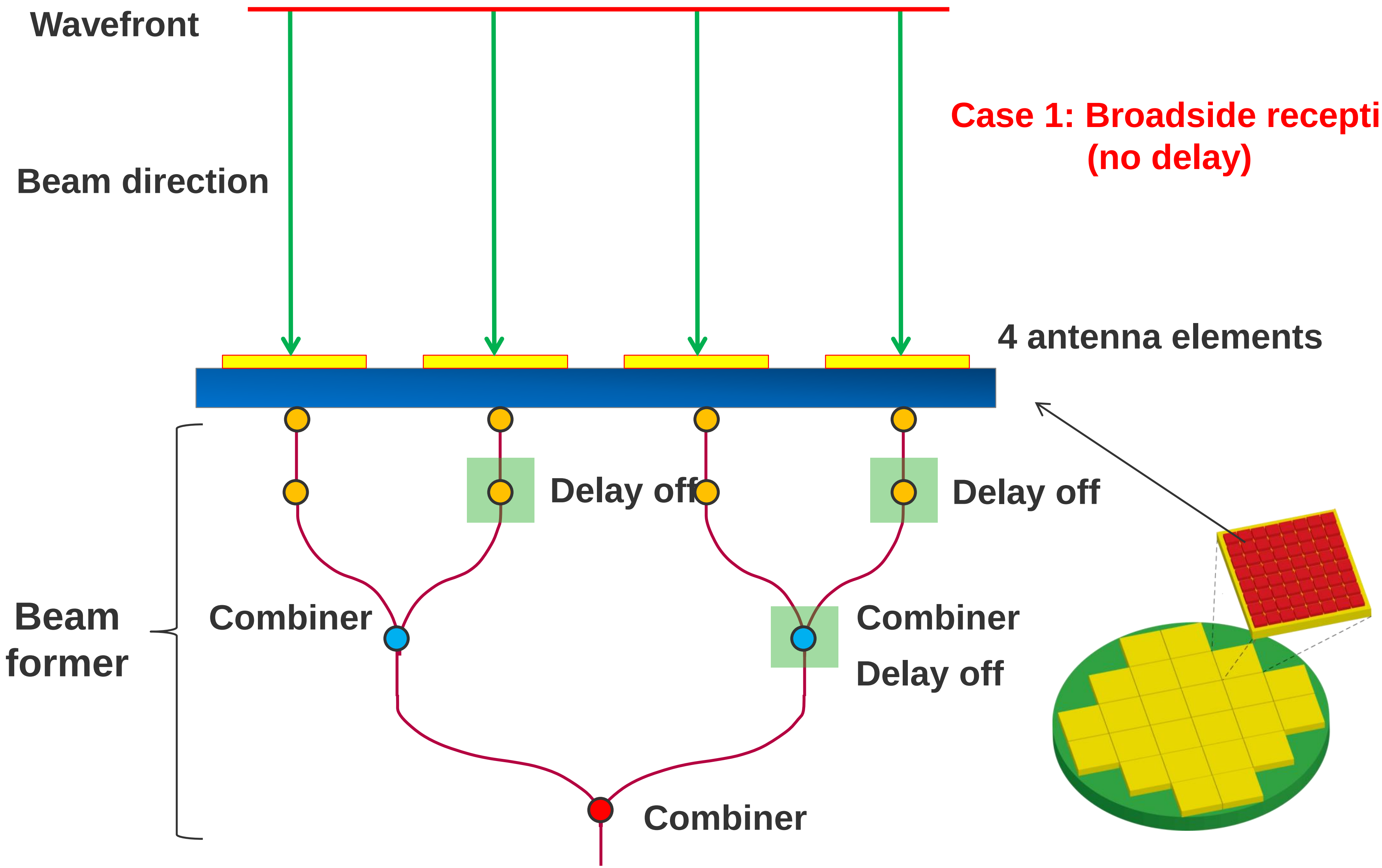
**Solution :**

Phased-array antenna with large number of elements + Photonic beamformer

**Aim:**

In-Flight Entertainment: Live television channels and broadband communication at passenger seats

# Optical Beamforming Network



Wavefront

Beam direction

Case 1: Broadside reception
(no delay)

4 antenna elements

Delay off

Delay off

Beam
former

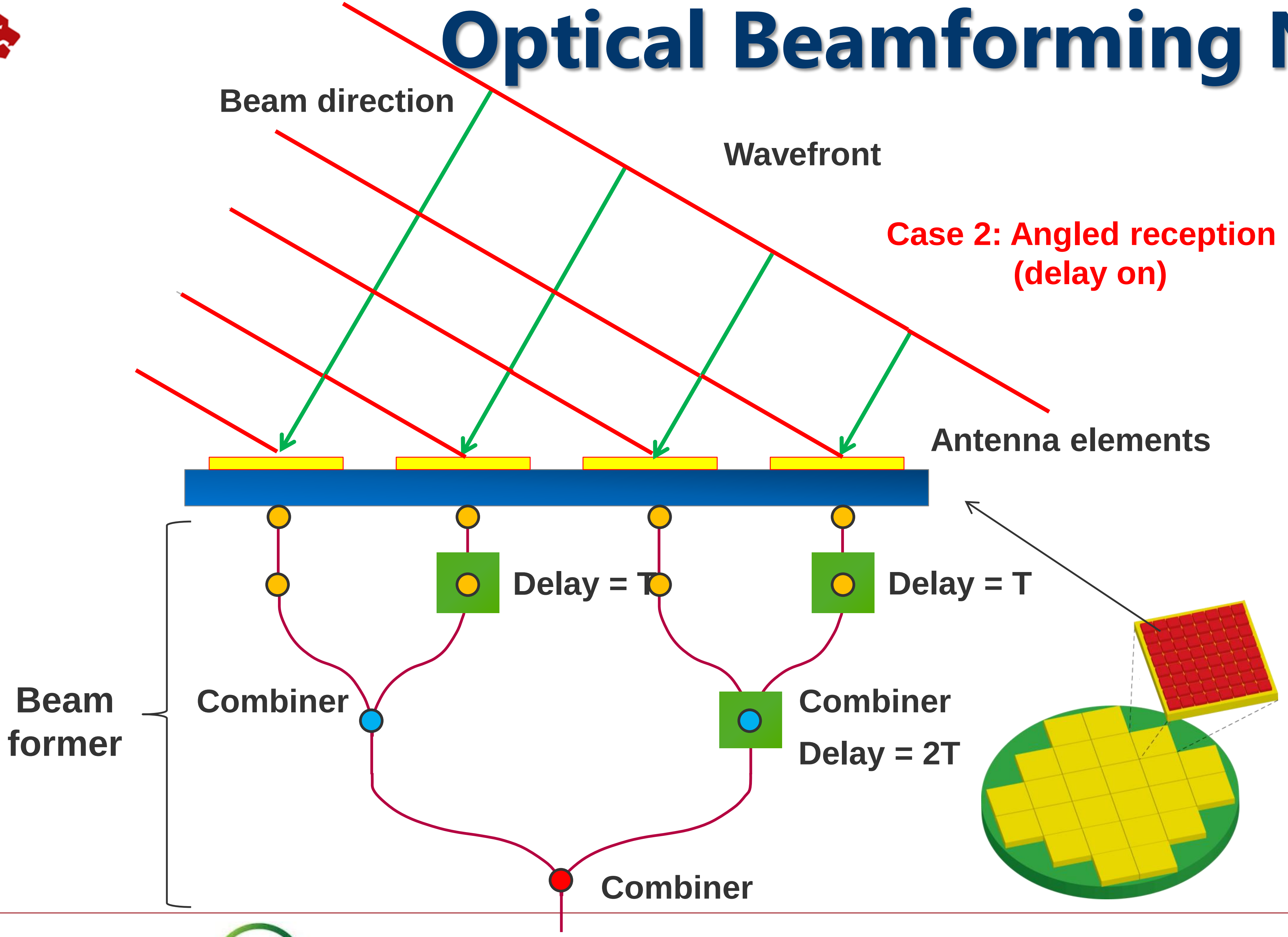
Combiner

Combiner

Delay off

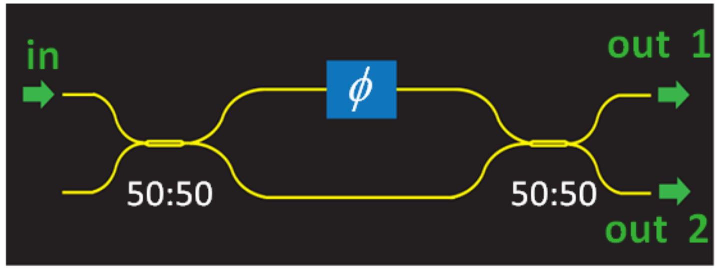
Combiner

# Optical Beamforming Network

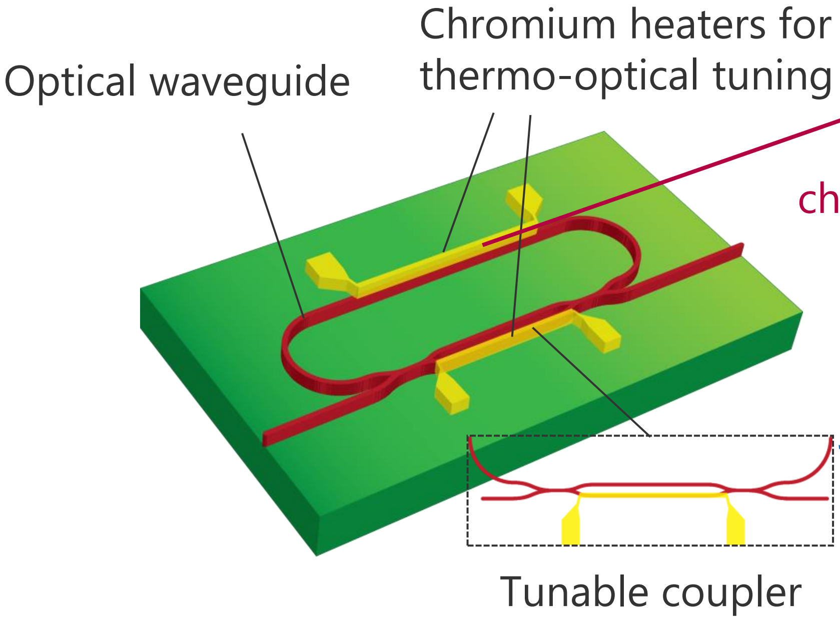


# True Time Delay via Optical Ring Resonator

**Combiners: Tunable MZI coupler**



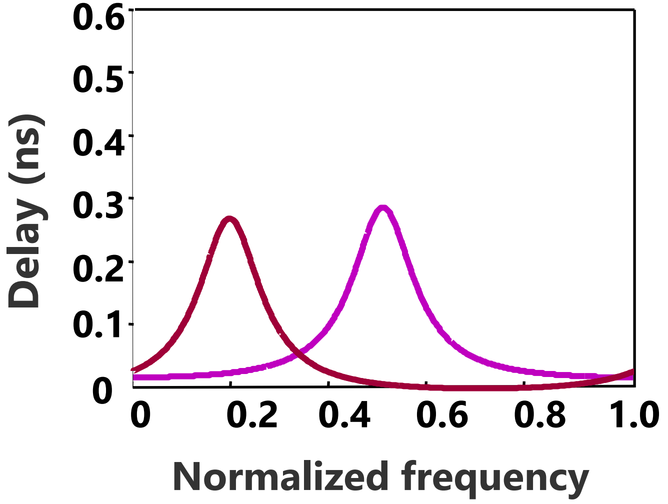
**Delay element: Optical ring resonator**

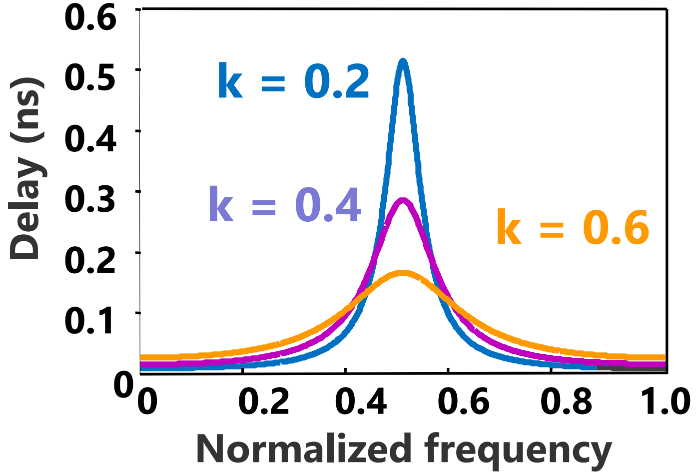


Phase shifter to change the resonance frequency

Tunable coupler to change the coupling to the ring

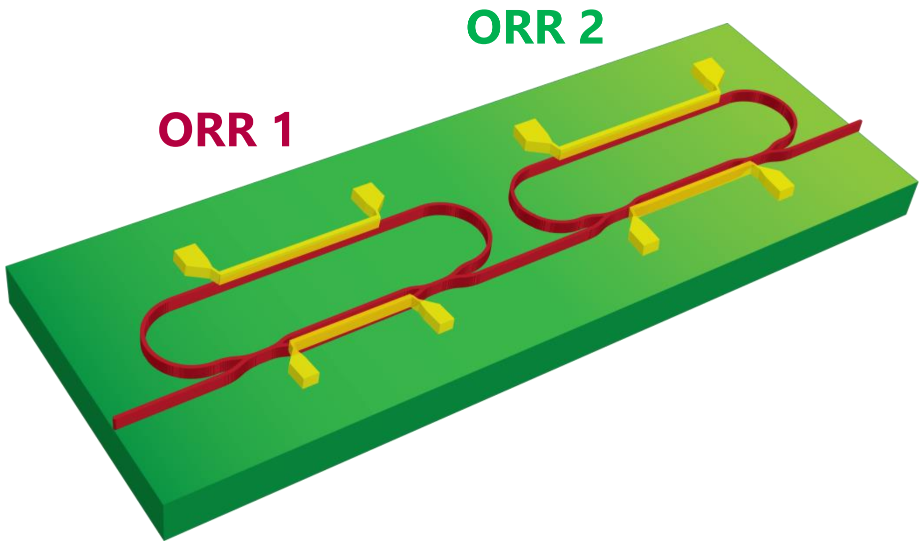
**If the directional couplers are 50:50, by changing *f* (thermo–optic tuning) the optical power at the complementary outputs can be tuned from 0 to 100%**

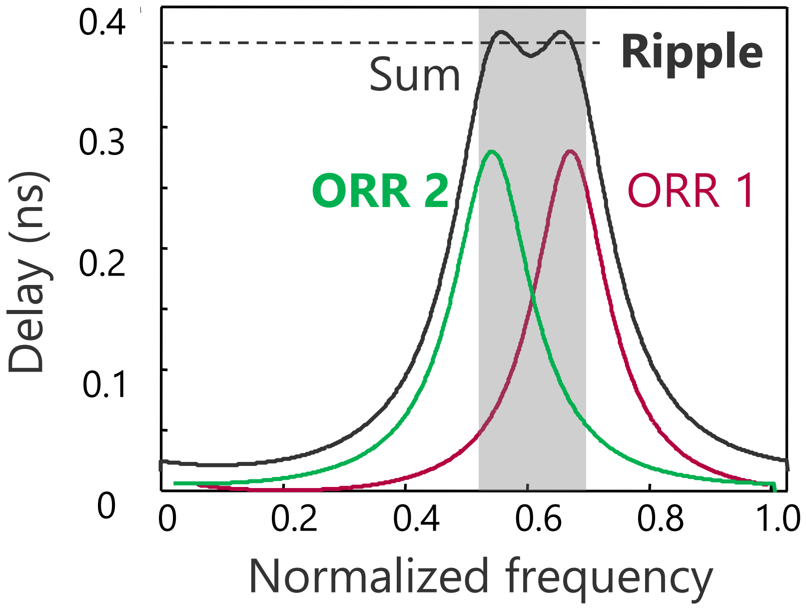




# Optical Ring Resonator

- Single ORR provides tunable delay, but it is band limited
- Trade-off between maximum delay and delay bandwidth
- Solution→ cascade more than one ORRs

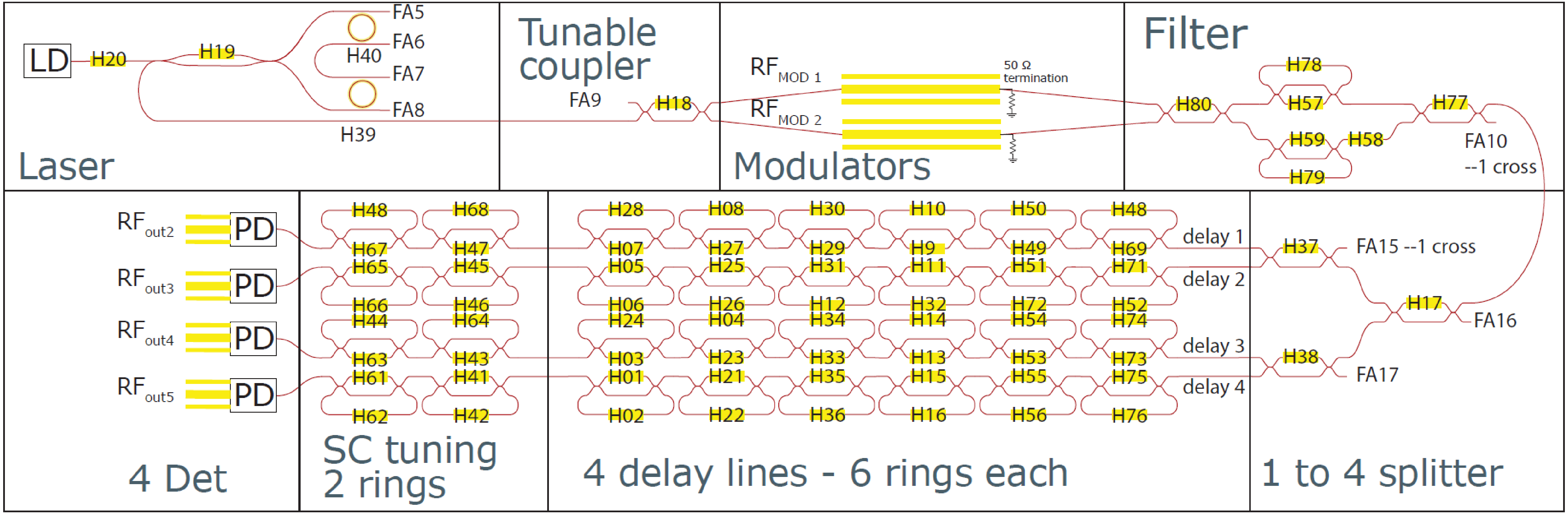




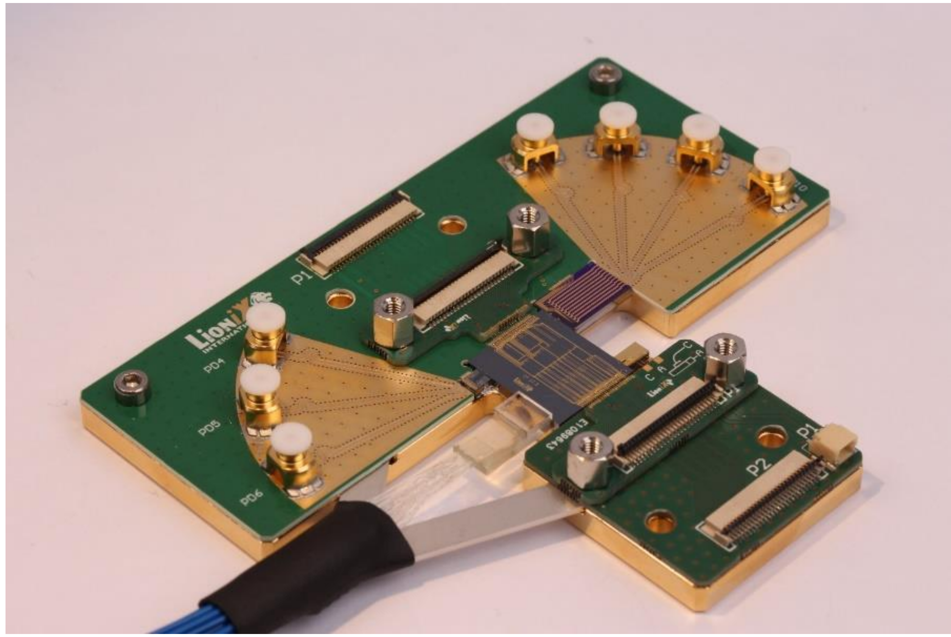
- More ORRs cascaded → more bandwidth but more ripple
- Trade-off between bandwidth, the number of ORR and the delay ripple

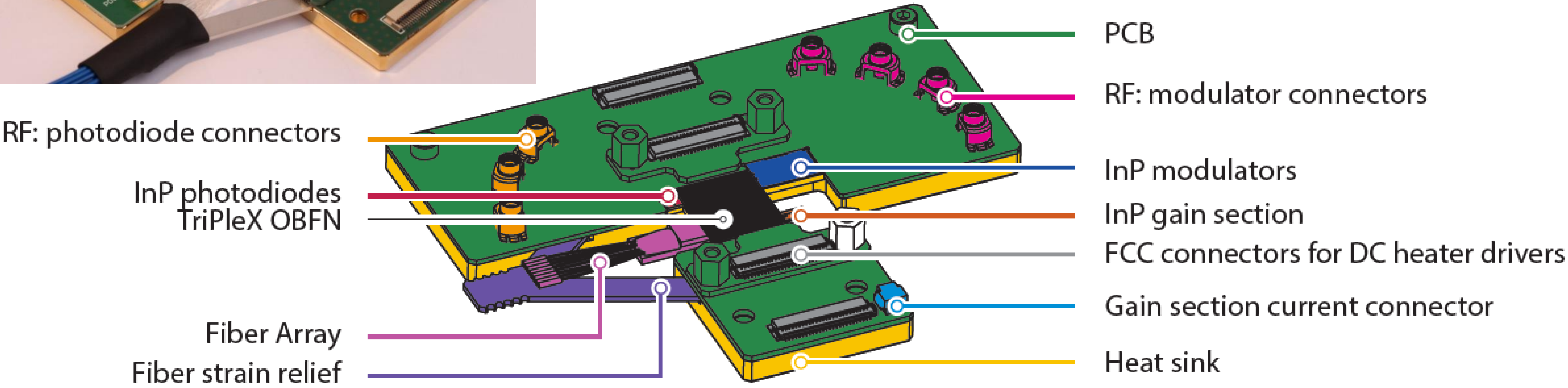
**Next step: to arrange the combiners and the ORRs to make a beamformer**

# 1xN Optical Beamforming Network

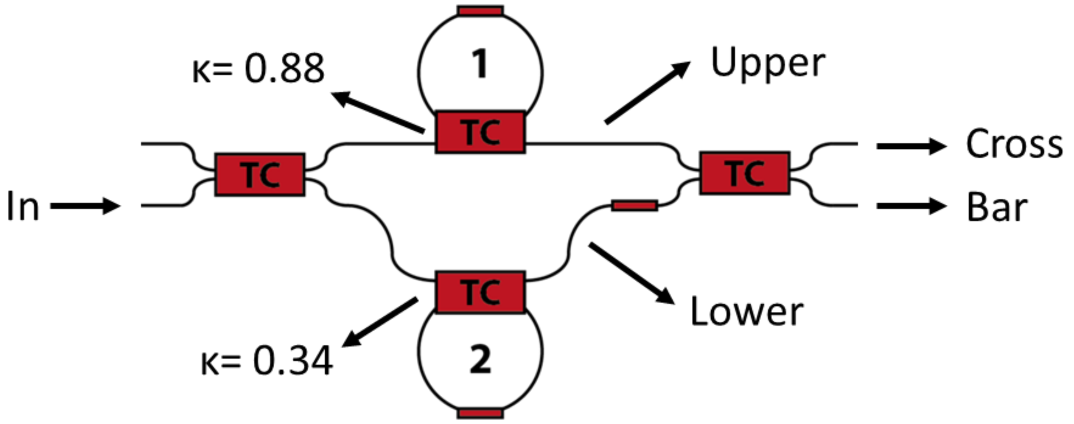


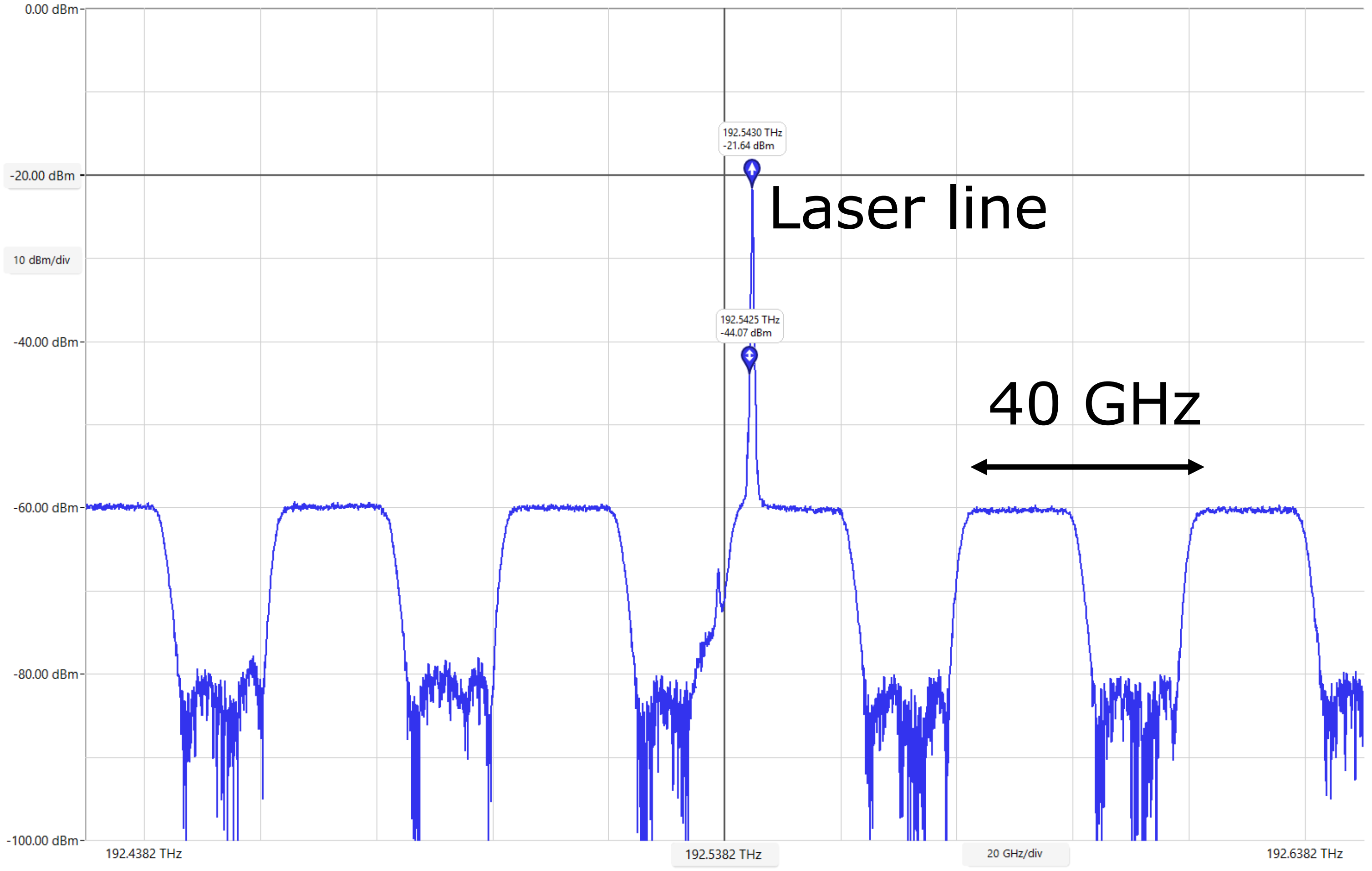
# iMWP Hybrid InP-TriPleX Assembly





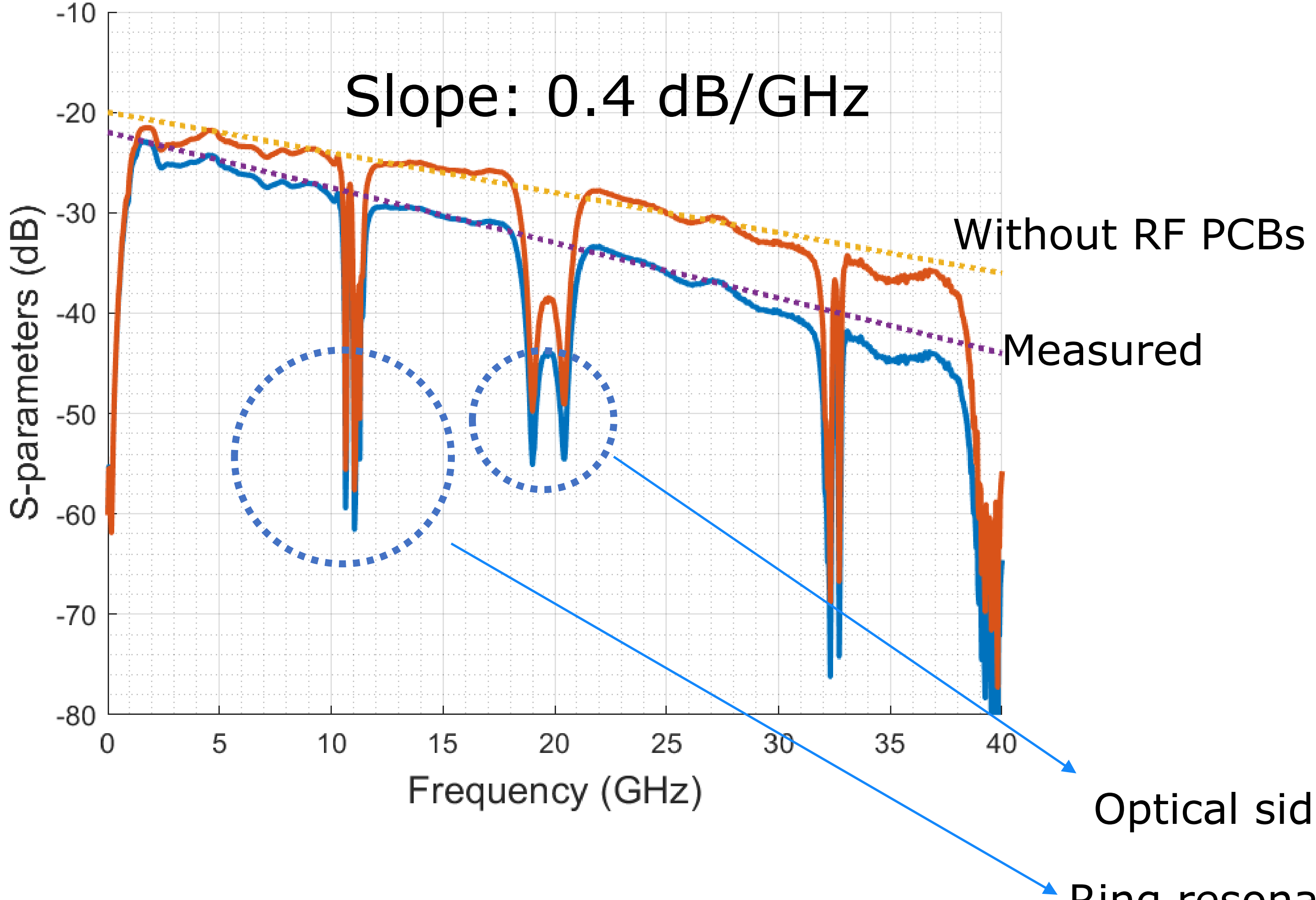
# TriPleX- Filter for SSBFC Processing





- Flat filter response
- Passband loss < 0.2 dB
- > 20 dB stopband rejection
- Carrier in the passband
- USB in the passband
- LSB in the stopband

# RF Link Gain



Optical side band filter

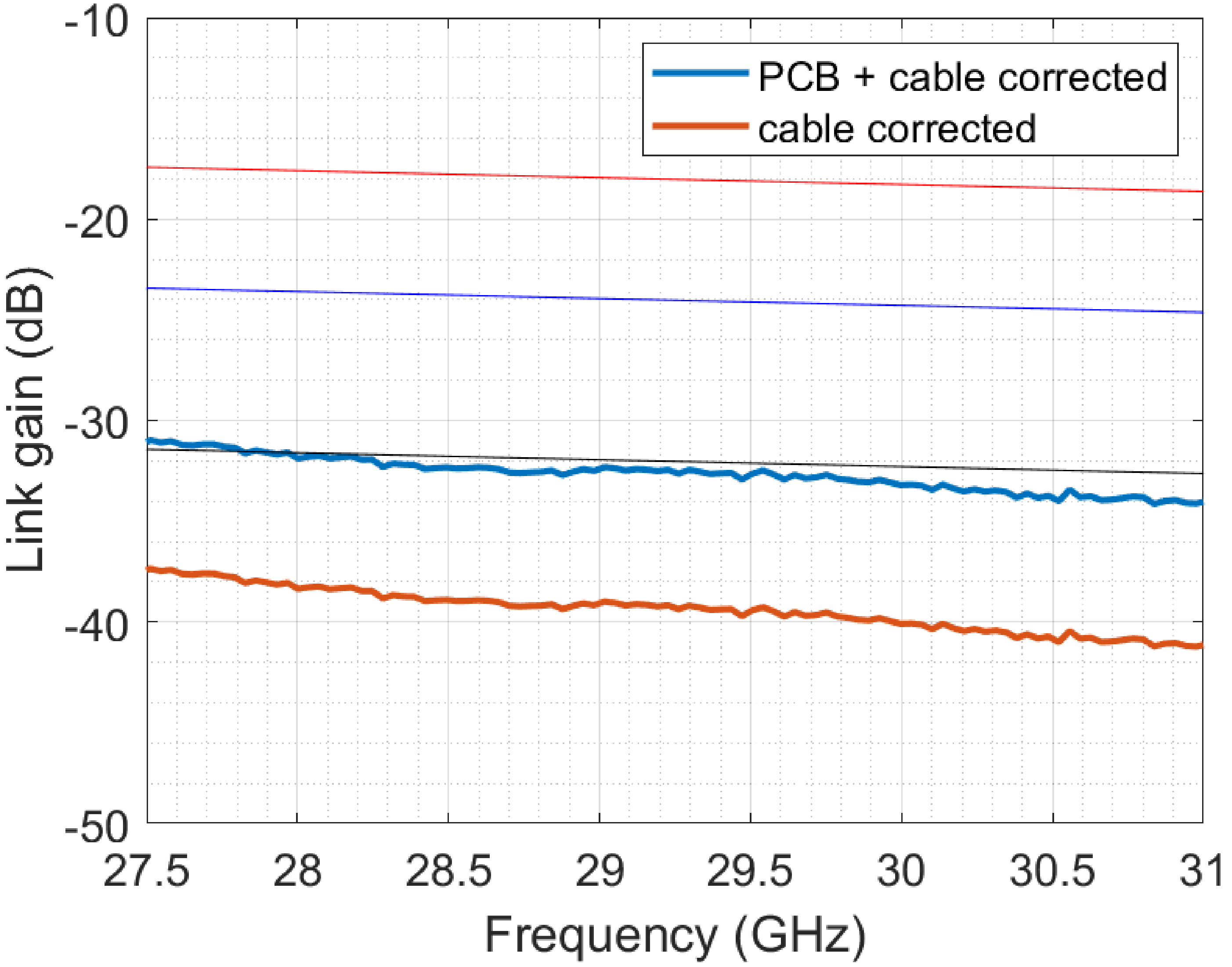
Ring resonators

$I_{PD\_DC} = 3.8$ mA

| | Freq<br>(GHz) | G<br>(dB) | $V_\pi$<br>(V) |
|---|---|---|---|
| Measured | 5 | -22 | 4.0 |
| | 10 | -24 | 4.7 |
| | 20 | -28 | 7.7 |
| | 30 | -32 | 11.8 |
| | | | |
| Expected | 30 | -20 ← | 3 |
| | 20 | -17.7 ← | 2.3 |

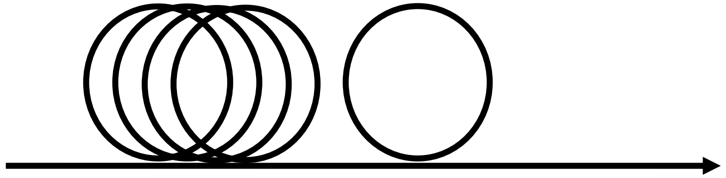
**Reduced link gain is a cause by modulator saturation and detector saturation**

# Amplitude Uniformity at 29 GHz

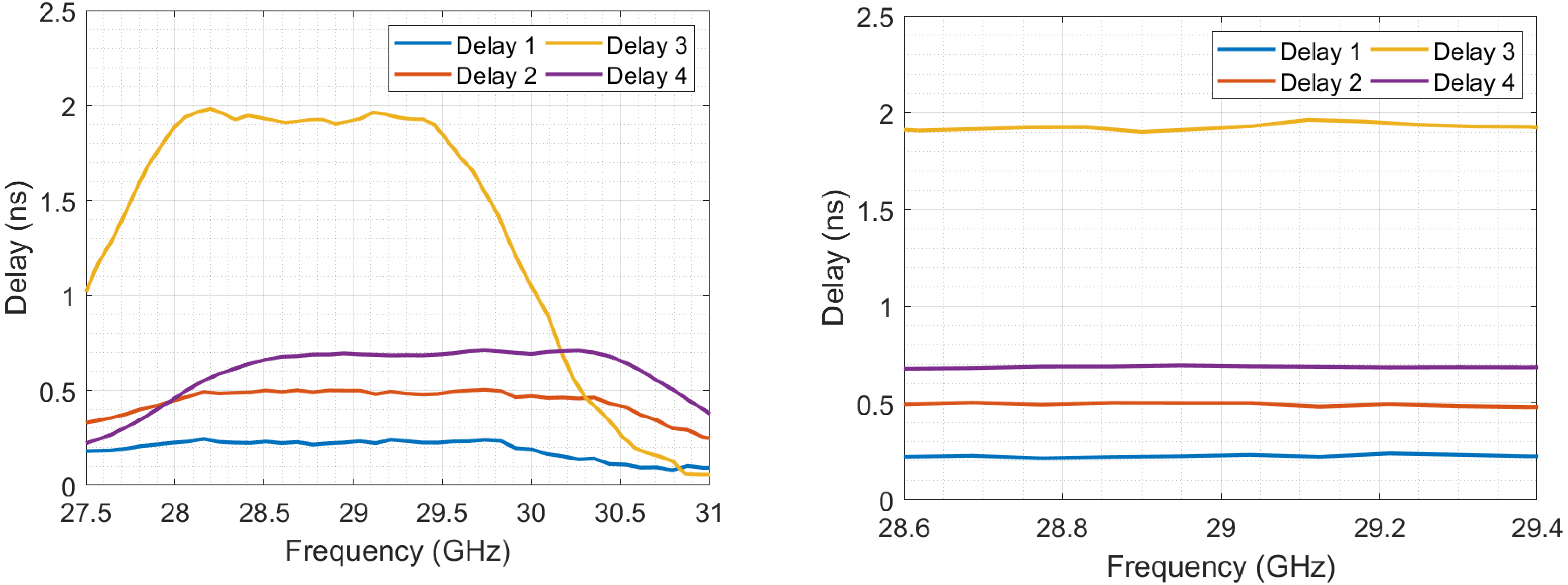


< 1.8 dB over 3.5 GHz
(PCBs + PM + DET)

# Tunable Delays



6 ring resonators



Tunable delay: 0 – 2 ns (= 60 cm)

Variation < 20 ps in 800 MHz

# iMWP a Disruption in RF Technology !!

- **Vision:** Towards iMWP (10-300 GHz, Phase Shifting, True Time Delay, Multi-beam, Combining, Splitting, Filtering, RF-in, RF-out)

- RF-Photonic integration is imperative to yield a reliable beamformer
  - **TriPleX™ $Si_3N_4/SiO_2$** waveguide technology enables low loss, compact, stable, mass producible MWP signal processors
  - InP enables integration of **detectors**, light sources, **narrow-band lasers** and **high-speed modulators**

- **Next step:** High optical power modulators with in-line optical amplification (with SOA) c.g.h.roeloffzen@lionix-int.com