High-Speed Plasmonic Modulators for Microwave Photonics

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[3] *University of Washington, Seattle, WA, USA*

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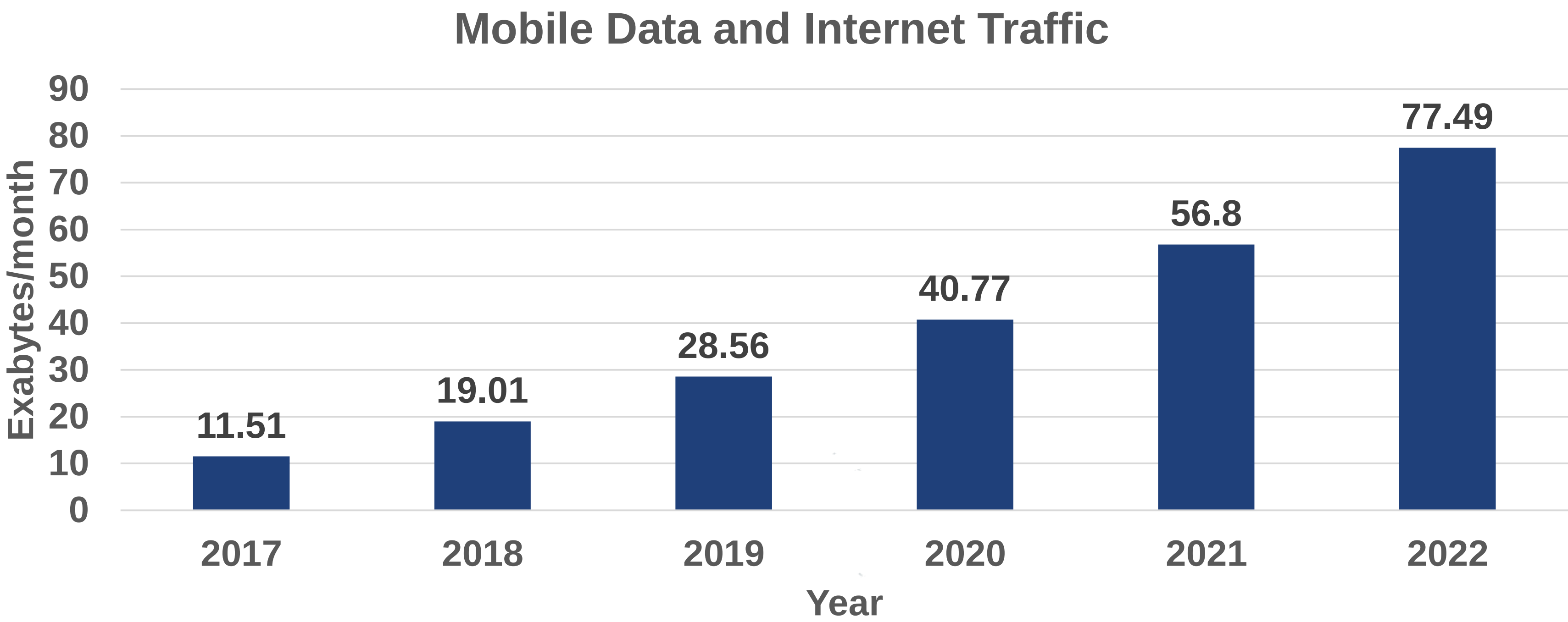
The Wireless Revolution



Source: Cisco Visual Networking Index: Forecast and Trends 2017-2022

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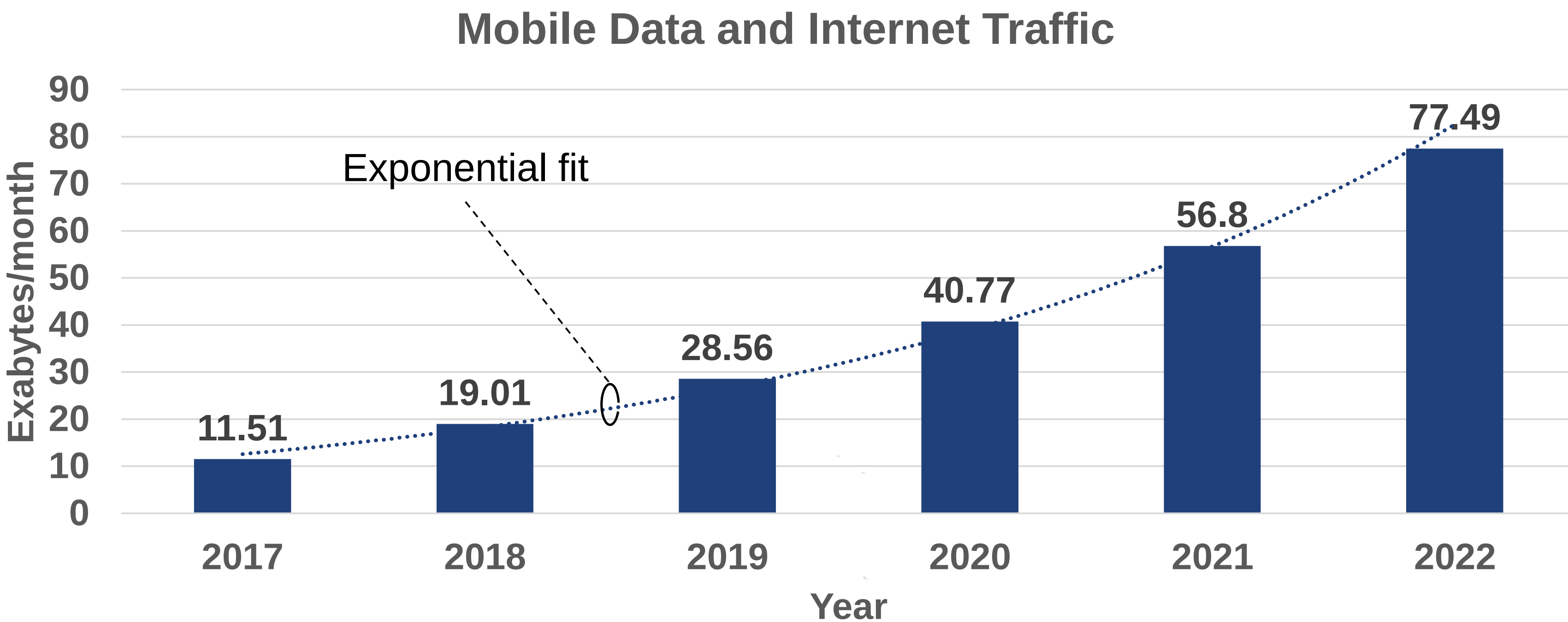
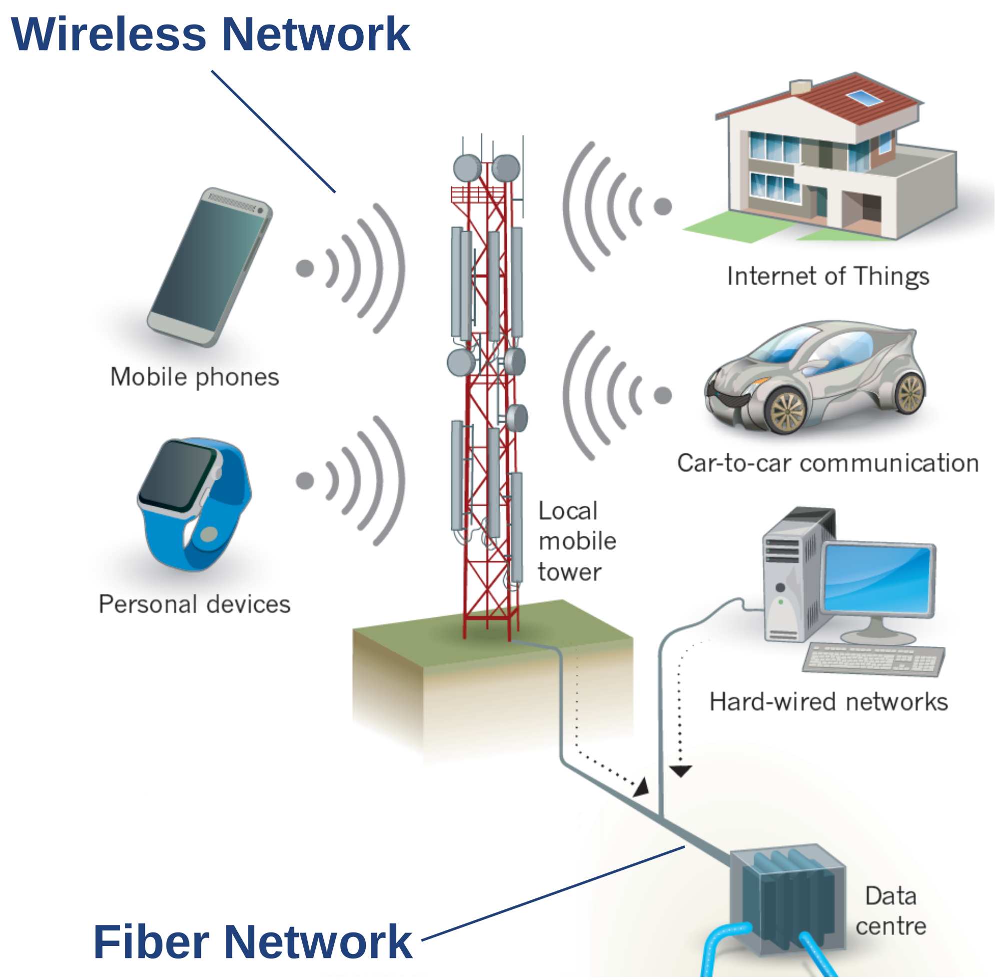


- Mobile data traffic:
  - **Exponential growth** (2x as fast as fixed IP traffic)
  - 7x increase between 2017 and 2022

- Traffic from wireless/mobile devices: **71% of total IP traffic by 2022**

Source: Cisco Visual Networking Index: Forecast and Trends 2017-2022

The Bandwidth Bottleneck



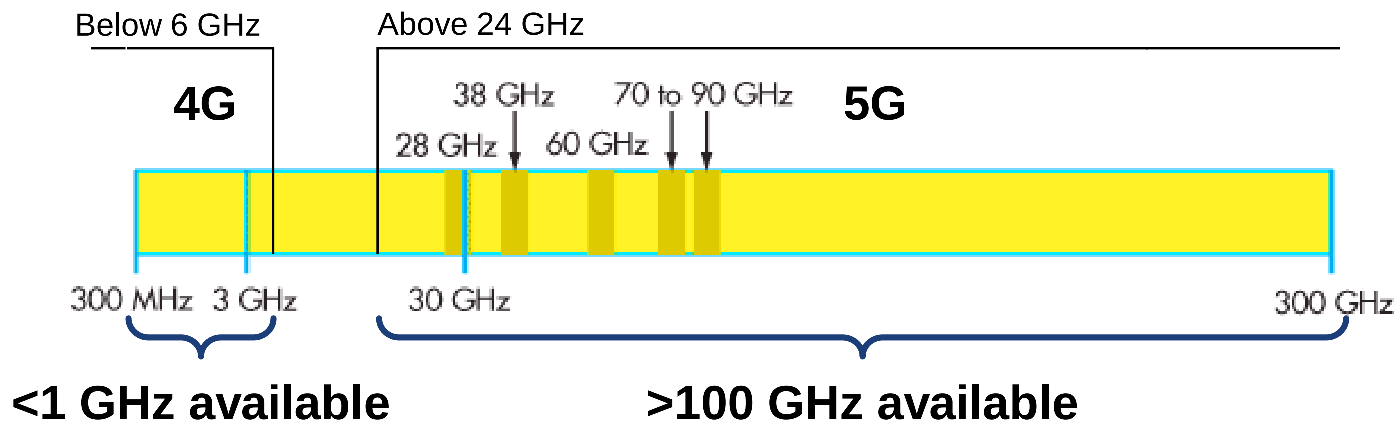
State-of-the-Art **(4G):**
up to 100 Mbit/s

↓

×100-1000
times capacity
demand **(5G):**
10s-100s Gbit/s

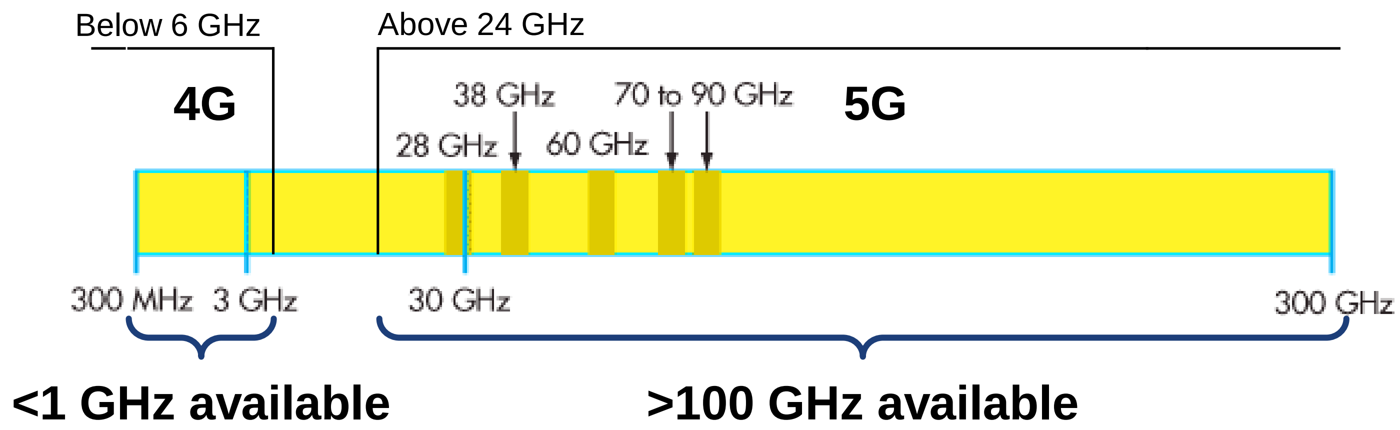
J. Hecht, Nature 536, 2016

The Millimeter-Wave Spectrum

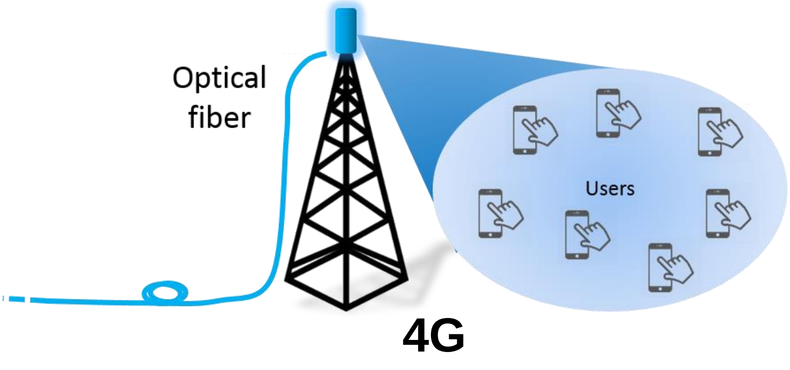


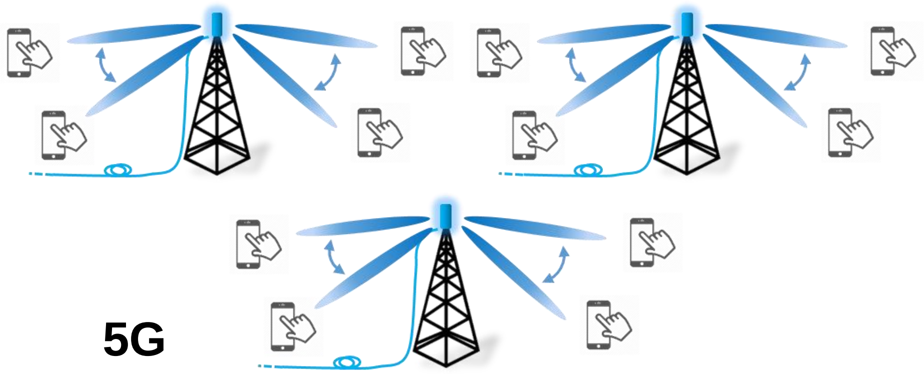
- *Opportunity*: >100 GHz bandwidth available

The Millimeter-Wave Spectrum



- *Opportunity*: >100 GHz bandwidth available
- *Challenge*: high loss (short range), sensitive to blockage
  - Many base stations needed (small cells)
  - Directive beams + direction control





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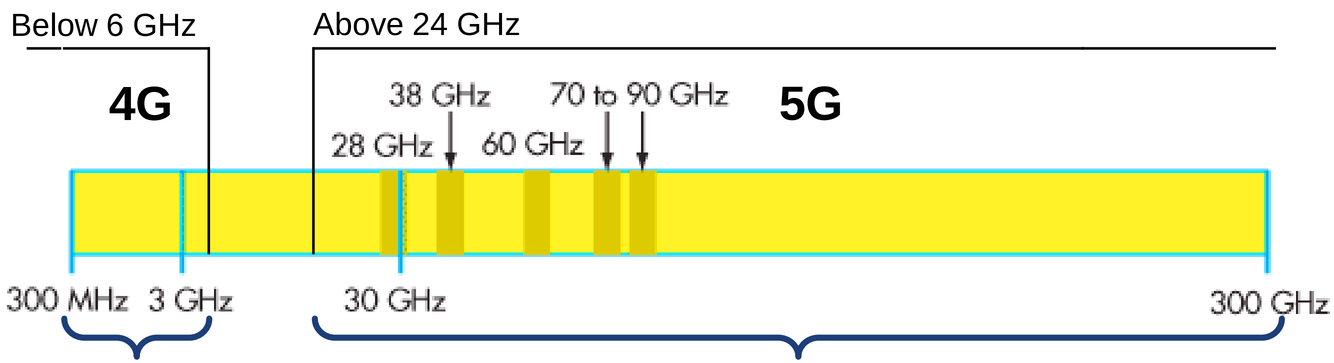


<1 GHz available

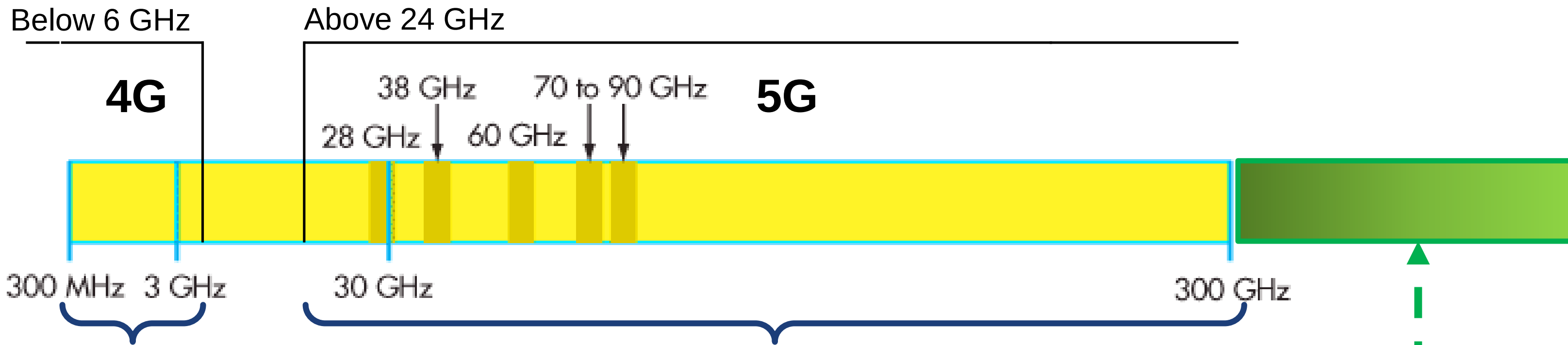
>100 GHz available

< 9 GHz contiguous

- *Opportunity*: >100 GHz bandwidth available
- *Challenge*: **contiguous bandwidth available < 9 GHz**
- > 100 Gbps difficult:
  - e.g. 512-QAM @ 1 Gbaud → 128 Gbps
    → Difficult to have long (~100s m) links

Seeds, A. J., et al. (2015). "TeraHertz Photonics for Wireless Communications." Journal of Lightwave Technology, 33(3): 579-587.

The Millimeter-Wave Spectrum



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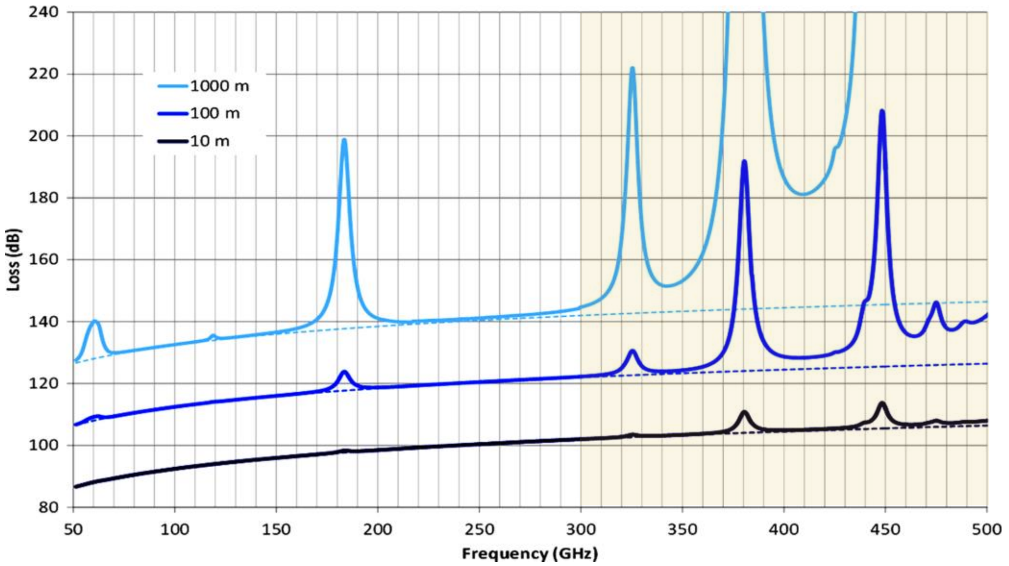
- **What's next?**

Seeds, A. J., et al. (2015). "TeraHertz Photonics for Wireless Communications." Journal of Lightwave Technology, 33(3): 579-587.

ETH zürich

Communications in the THz band (> 300 GHz)

- THz band (**300 GHz – 10 THz**) considered as the "**next frontier**" for the 100s Gbps data-rate target: extremely large BW available [1]

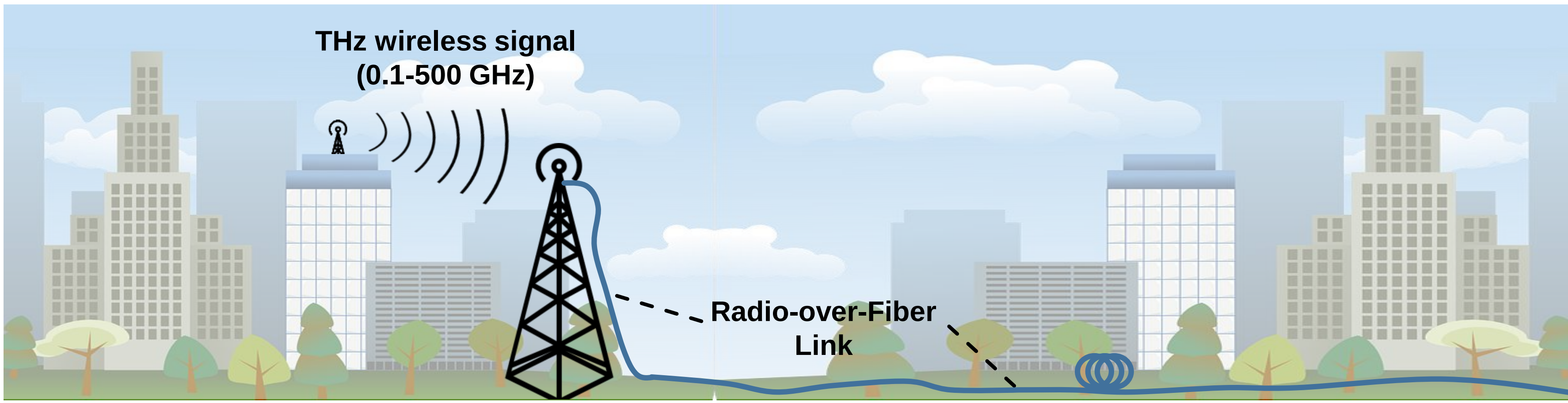


- Atmospheric absorption due to H_2O vapor
- Spectral windows exist between 200 GHz and 450 GHz

[1] S. Jia, X. Pang, O. Ozolins et al., "0.4 THz Photonic-Wireless Link With 106 Gb/s Single Channel Bitrate," Journal of Lightwave Technology, 36(2), 610-616 (2018).
[2] Seeds, A. J., et al. (2015). "TeraHertz Photonics for Wireless Communications." Journal of Lightwave Technology, 33(3): 579-587.

Communications in the THz band (> 300 GHz)

- A possible scenario



- THz wireless signals received by an **antenna**
- Converted to the optical domain
- Transported over an **analog radio-over-fiber link**

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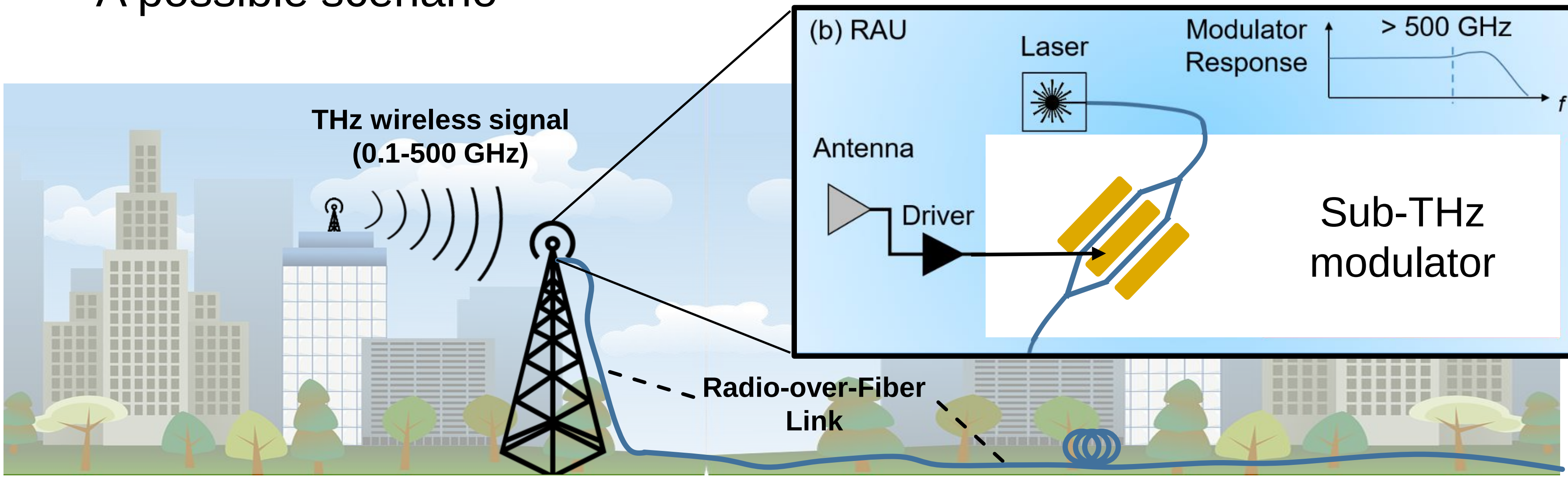
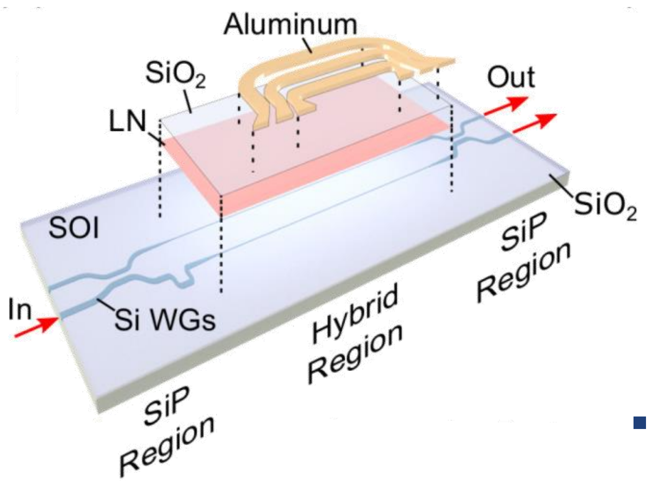


- THz wireless signals received by an **antenna**
- Converted to the optical domain
- Transported over an **analog radio-over-fiber link**
- Need of modulator with:
  (1) **sub-THz bandwidth**, (2) **high linearity**, (3) **high-power handling**

State-of-the-Art Modulators

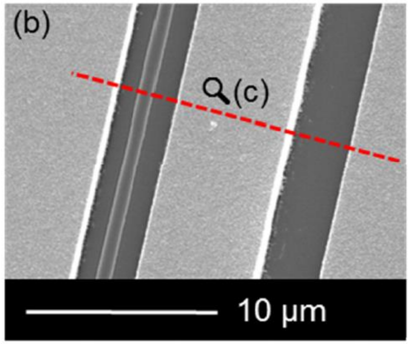
- Very recently: impressive progress in $LiNbO_3$ modulators

UCSD, Sandia



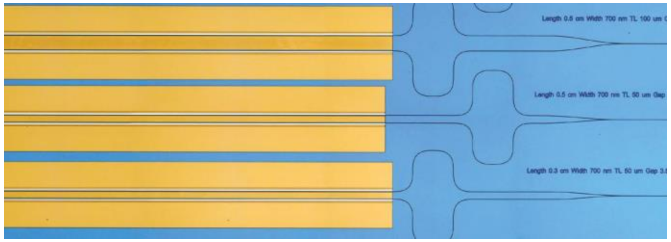
- Oxide-bonding thin-film $LiNbO_3$ on SiP chip
- BW_{3dB} > 106 GHz

Uni. Delaware



- Crystal ion sliced $LiNbO_3$
- $V_{\pi,DC}$ = 3.8 V·cm

Harvard



- $LiNbO_3$ on Si
- Length 20 mm
- IL = 0.5 dB
- BW_{3dB} = 40 GHz and V_π = 1.4 V
- BW_{3dB} = 100 GHz and V_π = 2.4 V

[1] P. O. Weigel, J. Zhao, K. Fang et al., Optics Express, 26(18), 23728-23739 (2018).
[2] A. J. Mercante, S. Shi, P. Yao et al., Optics Express, 26(11), 14810-14816 (2018).
[3] C. Wang, M. Zhang, X. Chen et al., Nature, 562(7725), 101-104 (2018).

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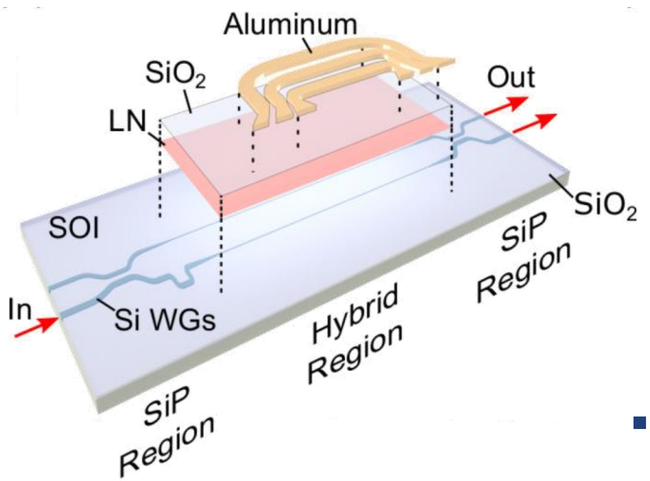

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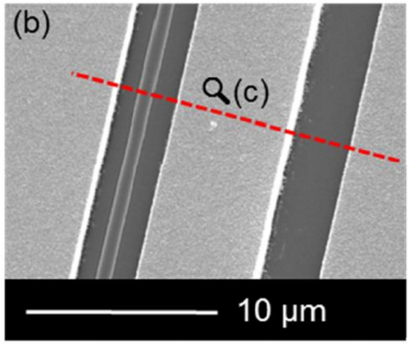

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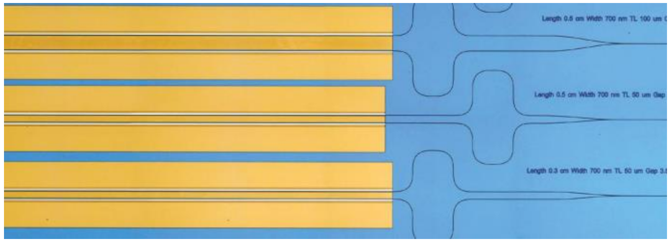

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A modulator ***simultaneously*** displaying sub-THz frequency responses, high power handling and high linearity is needed

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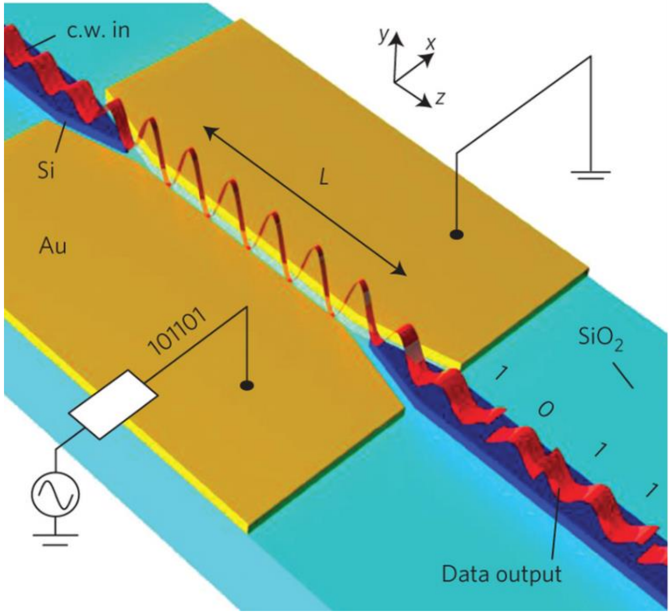
Plasmonic Modulators

$$\Delta\varphi = k_0 \cdot \Delta n_{\text{eff}} \cdot L$$



- Compact (**<25 µm-long**) [1, 2]
- High-speed (**>325 GHz**) [3]
- Operation:
  - Light from input waveguide excites a ***surface plasmon polariton*** **(SPP)**
  - SPPs: **electromagnetic surface waves** propagating at **dielectric-metal interfaces**
  - **Nonlinear material** in the slot: refractive index changes via **Pockels effect**:

$$\Delta n = \frac{1}{2} r_{33} n^3 U / w_{\text{gap}}$$

NLM electro-optic coefficient

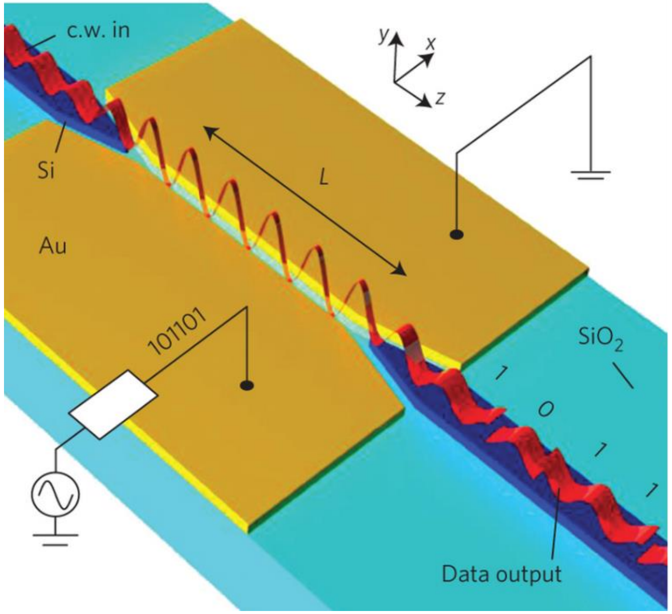
modulating voltage

slot width

[1] S. A. Maier, *Plasmonics: Fundamentals and applications. Academic Press, 2007.*
[2] *A. Melikyan et al., "High-speed plasmonic phase modulators," Nat. Photon., vol. 8, no. 3, pp. 229-233, 2014.*
[3] *S. Ummethala, T. Harter, K. Köhnle et al., "Terahertz-to-Optical Conversion Using a Plasmonic Modulator," OSA Technical Digest (online). STu3D.4*

Plasmonic Modulators

$$\Delta\varphi = k_0 \cdot \Delta n_{\text{eff}} \cdot L$$



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How can they be *compact* and *fast*, at the same time?

Plasmonic Modulators

Compact

- Efficient electro-optic (Pockels) effect
- Narrow slot
  → Perfect overlap of opt. and el. fields
  → Plasmonic slow-down effect

Fast

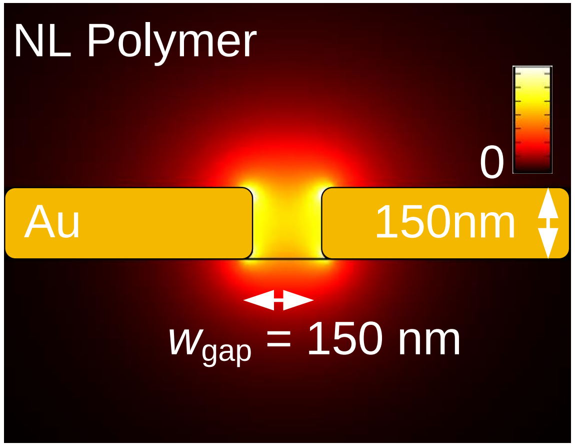
- Instantaneous Pockels effect
- Small RC-time constant → THz bandwidth

Energy-efficient

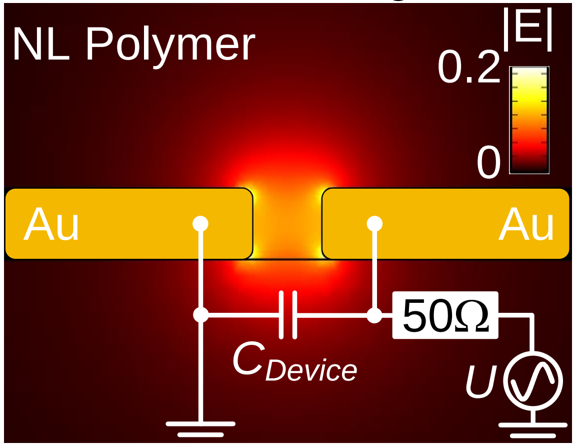
- Small V_π (~3 V) & small capacitance

Disadvantage: High losses (0.5 dB/µm)

193 THz Carrier

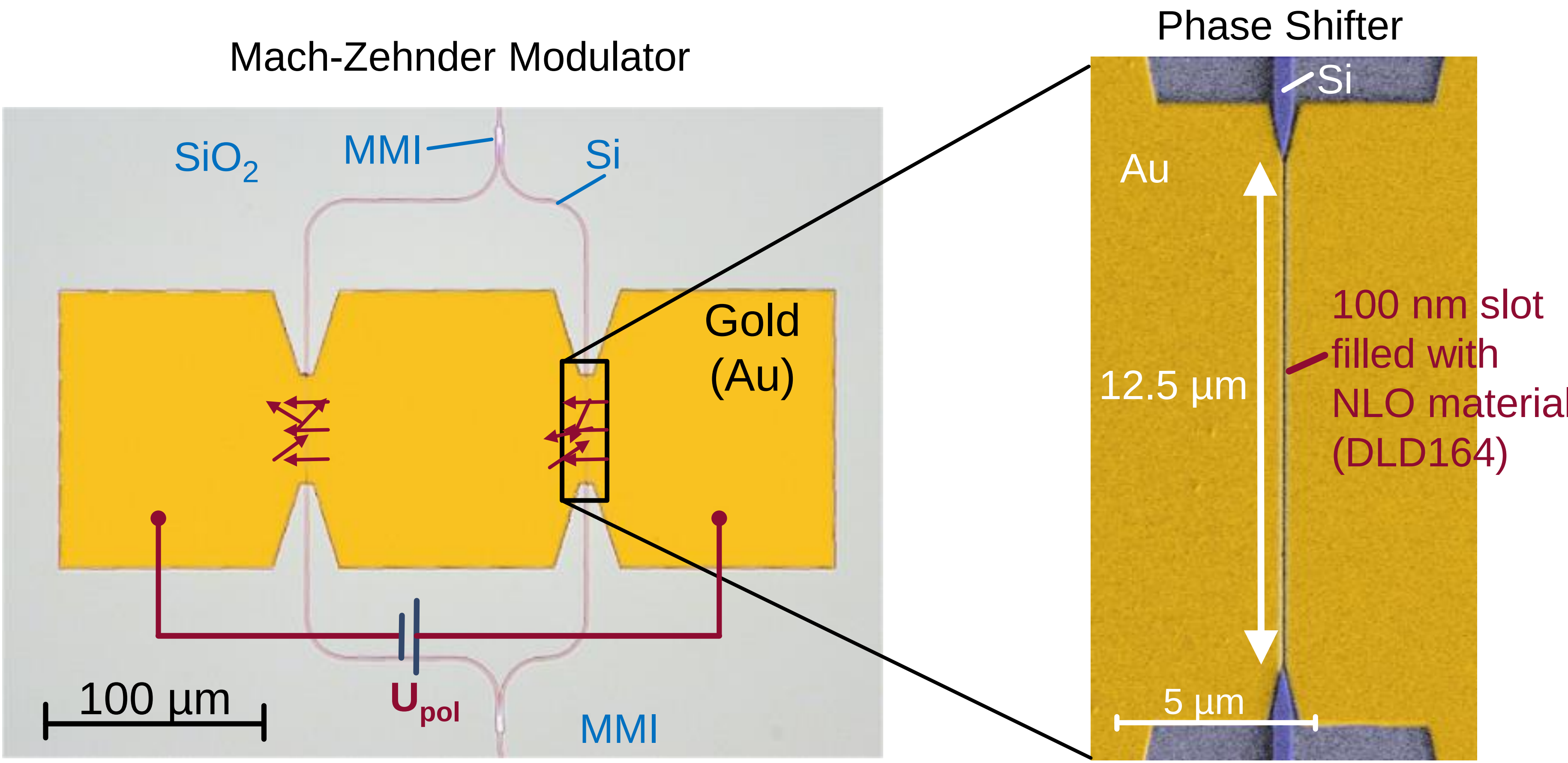


40 GHz RF Signal



C. Haffner et al., Proc. IEEE, 104: 2379 (2016)
W. Heni et al., JLT 34, 2 (2016)

Photonic-Plasmonic Mach-Zehnder Modulator



C. Haffner et al., Proc. IEEE, 104: 2379 (2016)
W. Heni et al., JLT 34, 2 (2016)

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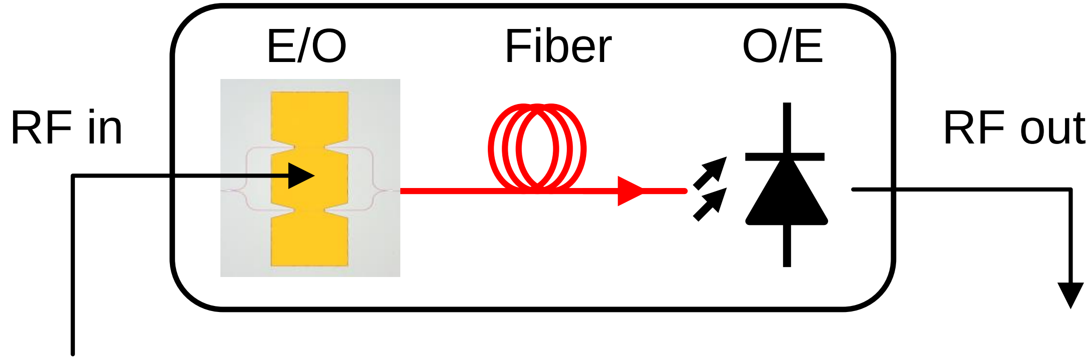
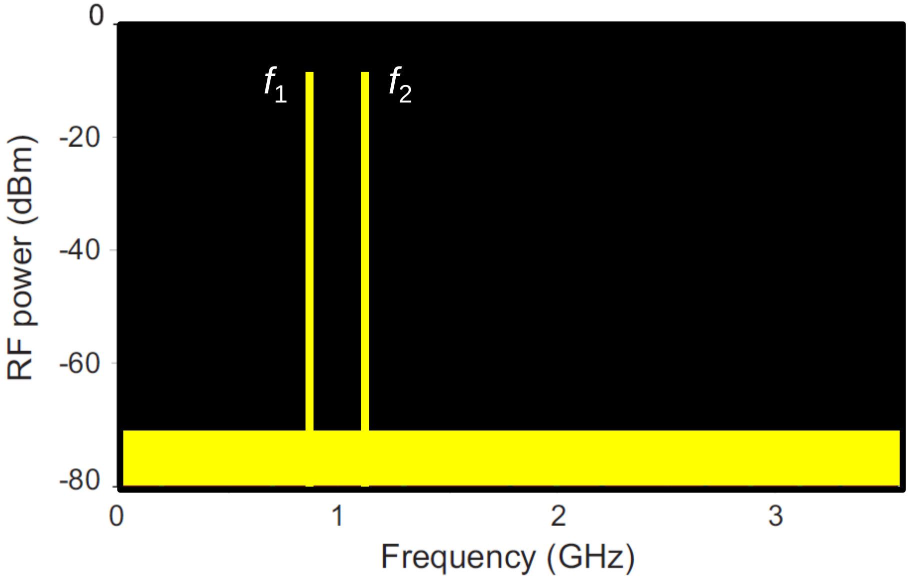
Two-tone test



Input Spectrum



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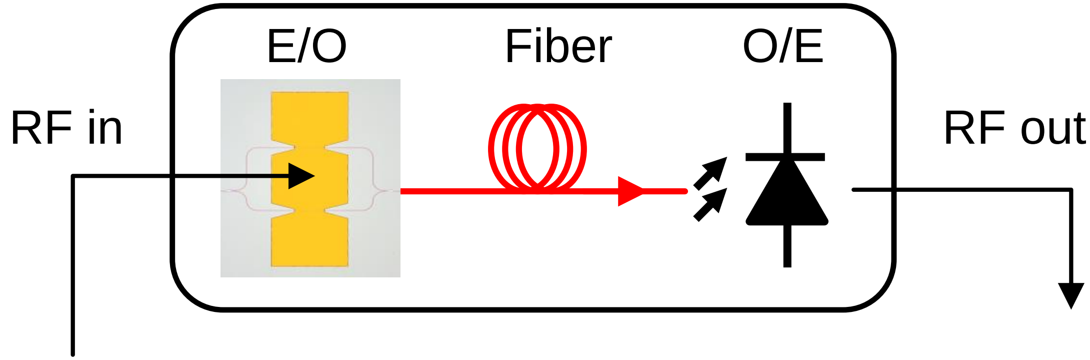

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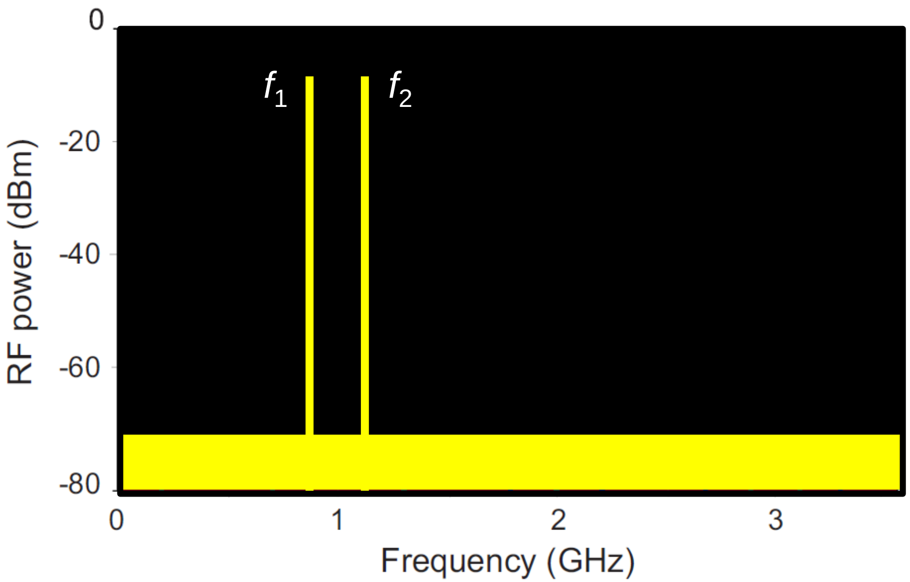
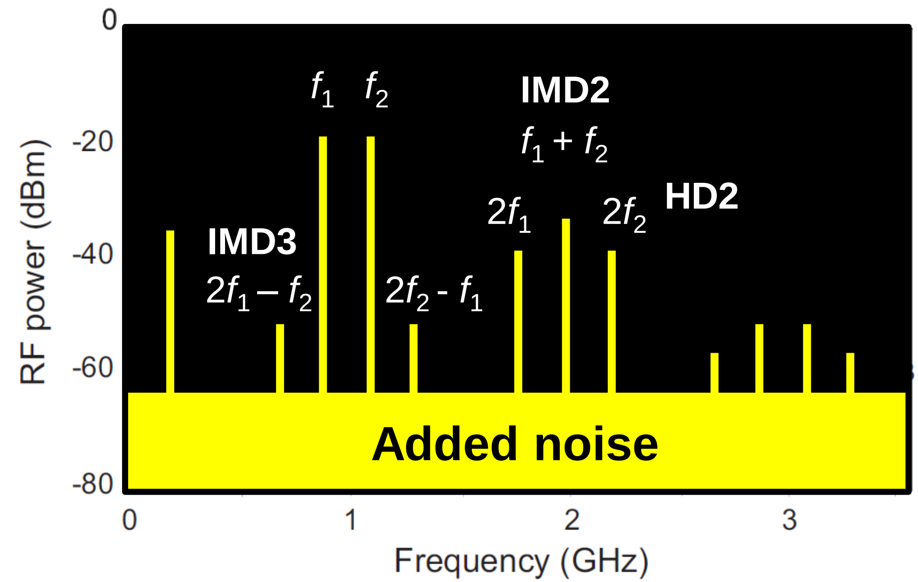


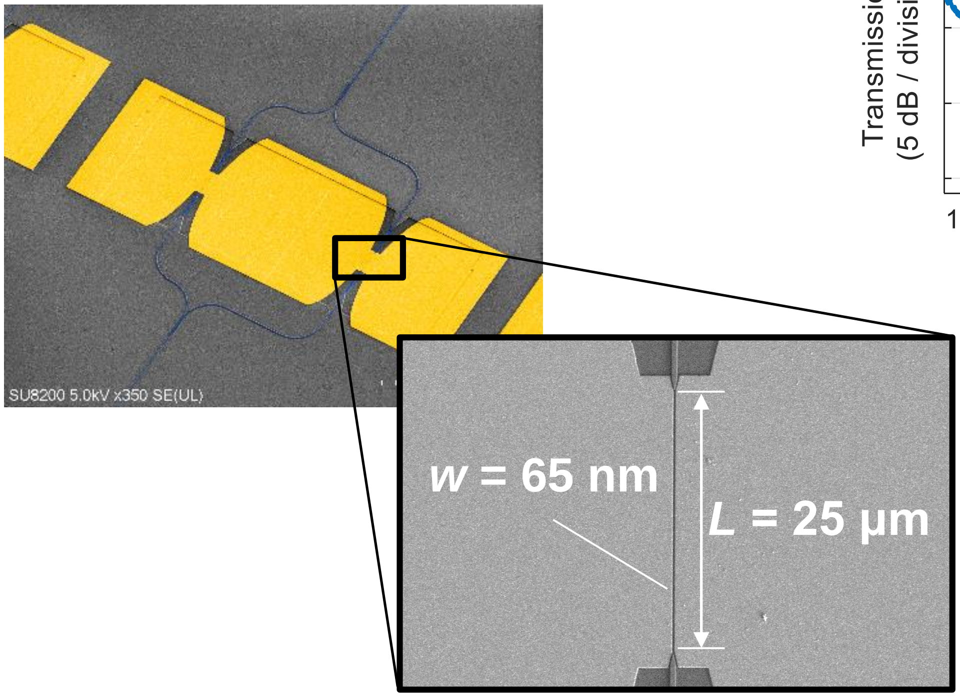
Output Spectrum

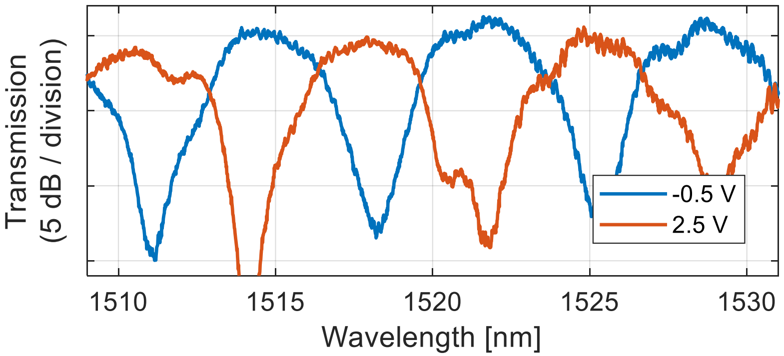


IMD: Intermodulation Distortions
HD: Harmonic Distortions

Plasmonic MZM: Linearity Tests

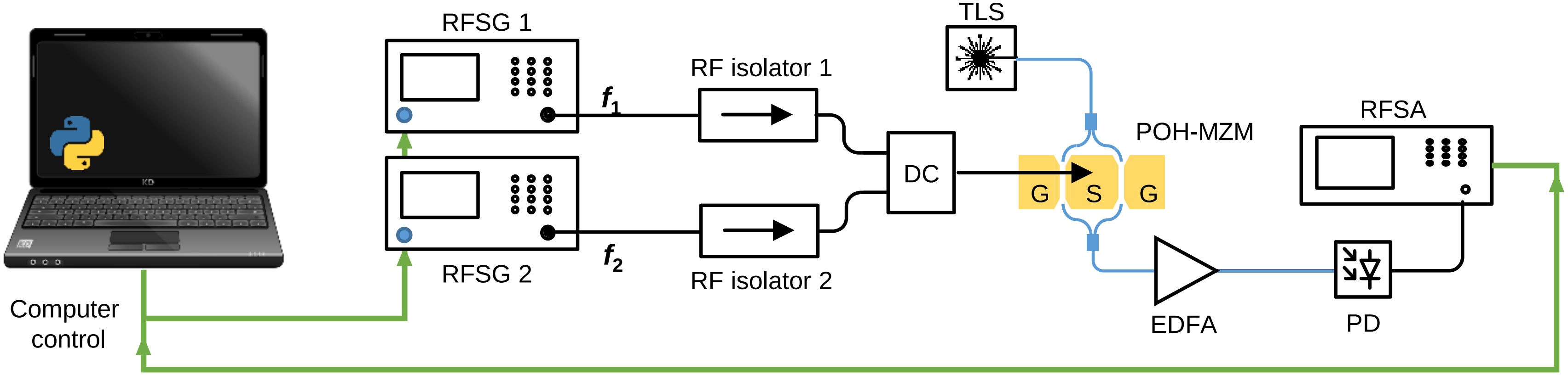
- Device under test: 25 µm-long, 65 nm wide slot
- $V_\pi \approx 3$ V





Plasmonic MZM: Linearity Tests

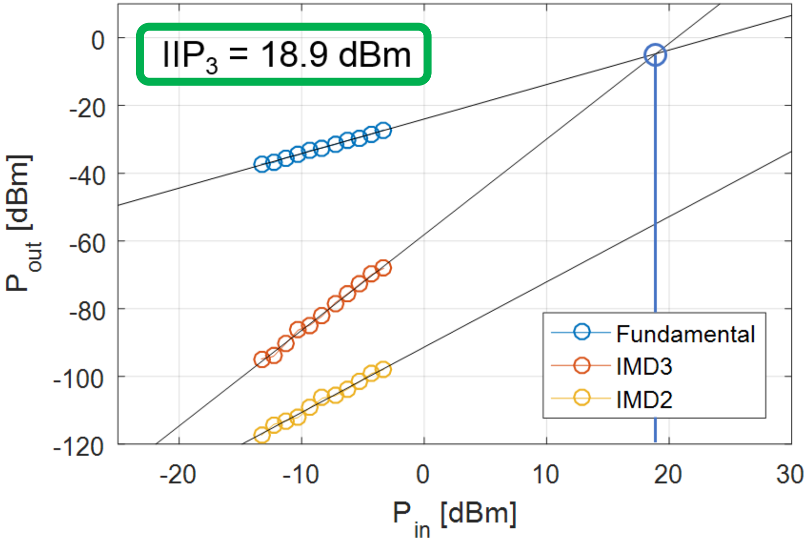
- Two-tone-test at 21 GHz ± 1 kHz
- Computer-controlled experimental setup
- High power handling photodetector (100 mW, BW_{3dB} = 18 GHz)



Plasmonic MZM: Linearity Tests

- Power sweep: -13.3 dBm to -3.3 dBm
- Second-order (IMD2) and third-order (IMD3) intermodulation distortions

Plasmonic modulator
$V_{\pi,\,DC} \approx 3$ V



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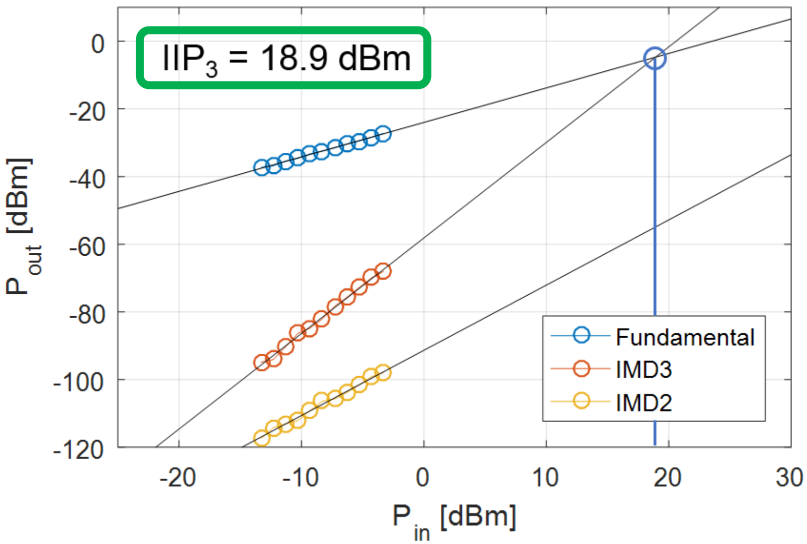
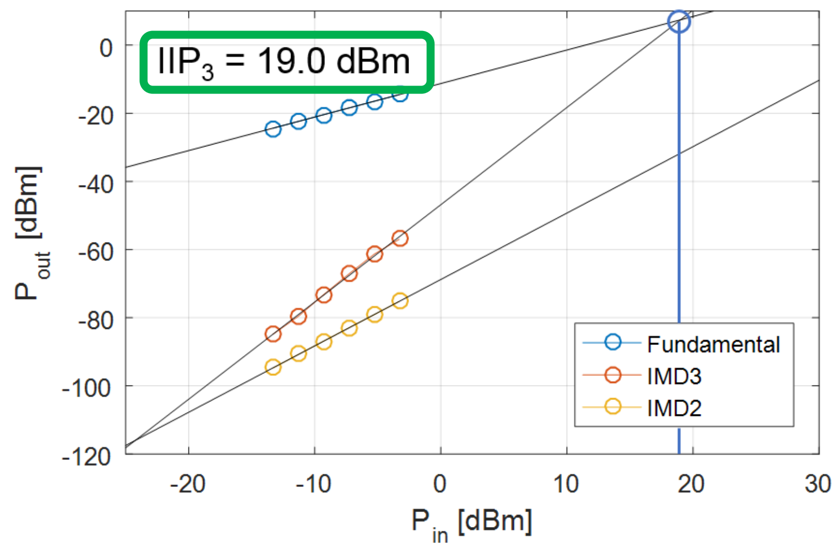


GaAs MZM (u^2t)
***V*$_{\pi, RF}$ = 3 V @ 20 Gbps PRBS**



M. Burla et al., "500 GHz plasmonic Mach-Zehnder modulators for sub-THz microwave photonics," APL Photonics, 4 (2019). (Featured Article)

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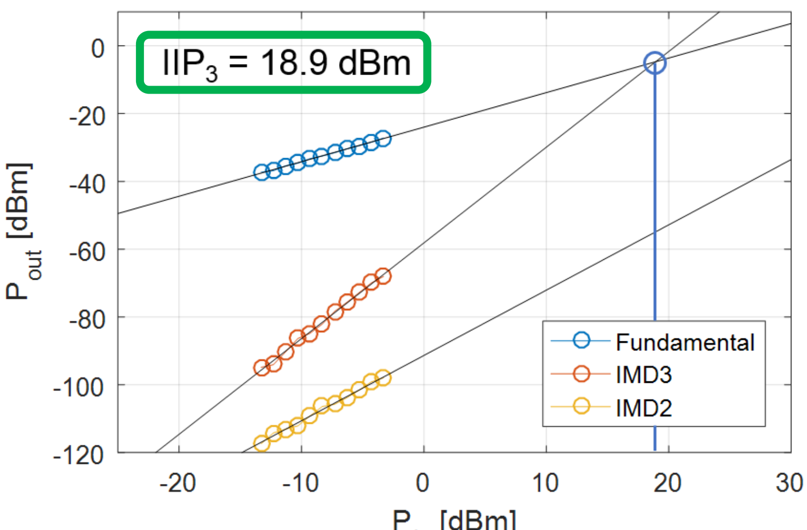

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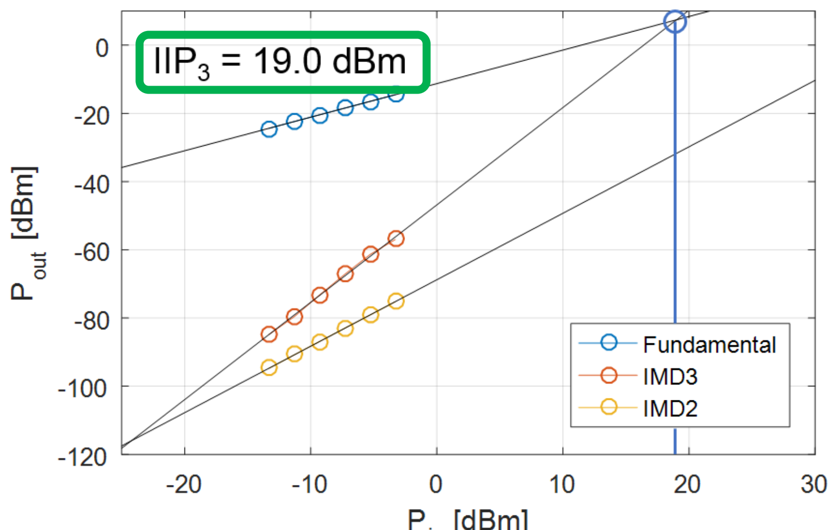

Plasmonic modulators are as linear as the best commercial ones

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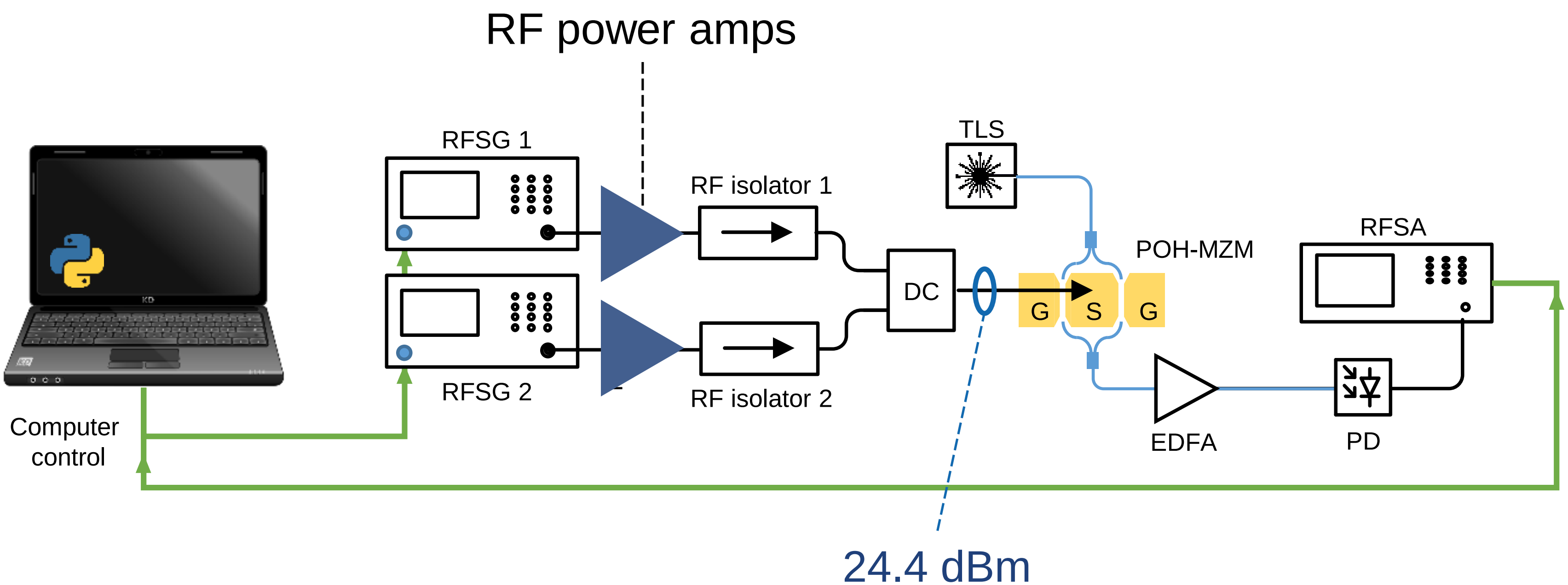
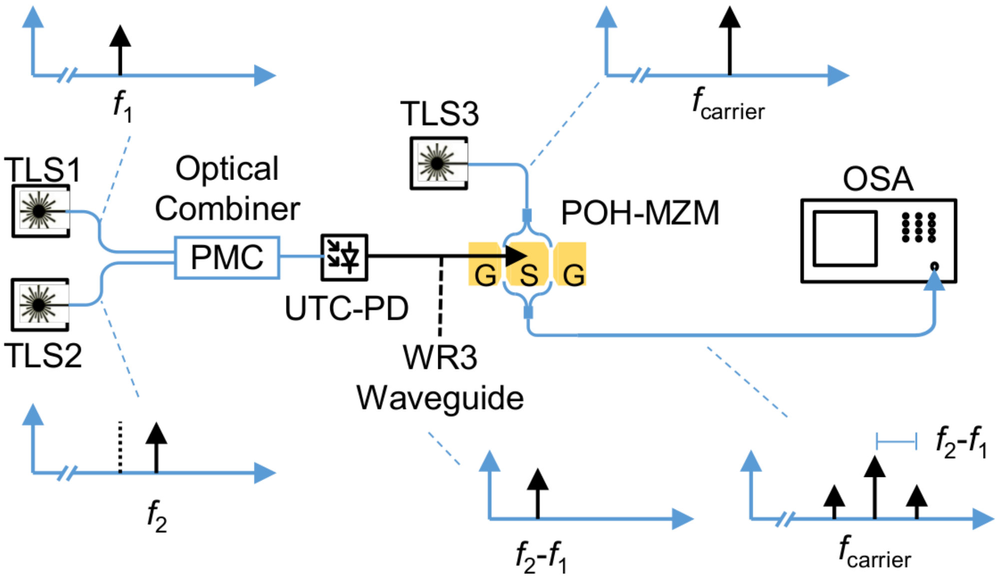
Plasmonic MZM: Power Handling

- Adding two power amplifiers (PA)
- 24.4 dBm (18.1 $V_{p\text{-}p}$) total RF power @ MZM input (limited by RF PAs)
- No degradation observed



Pushing up the speed

- Use of two tunable laser sources and a UTC-PD (270-370 GHz) to generate sub-THz waves



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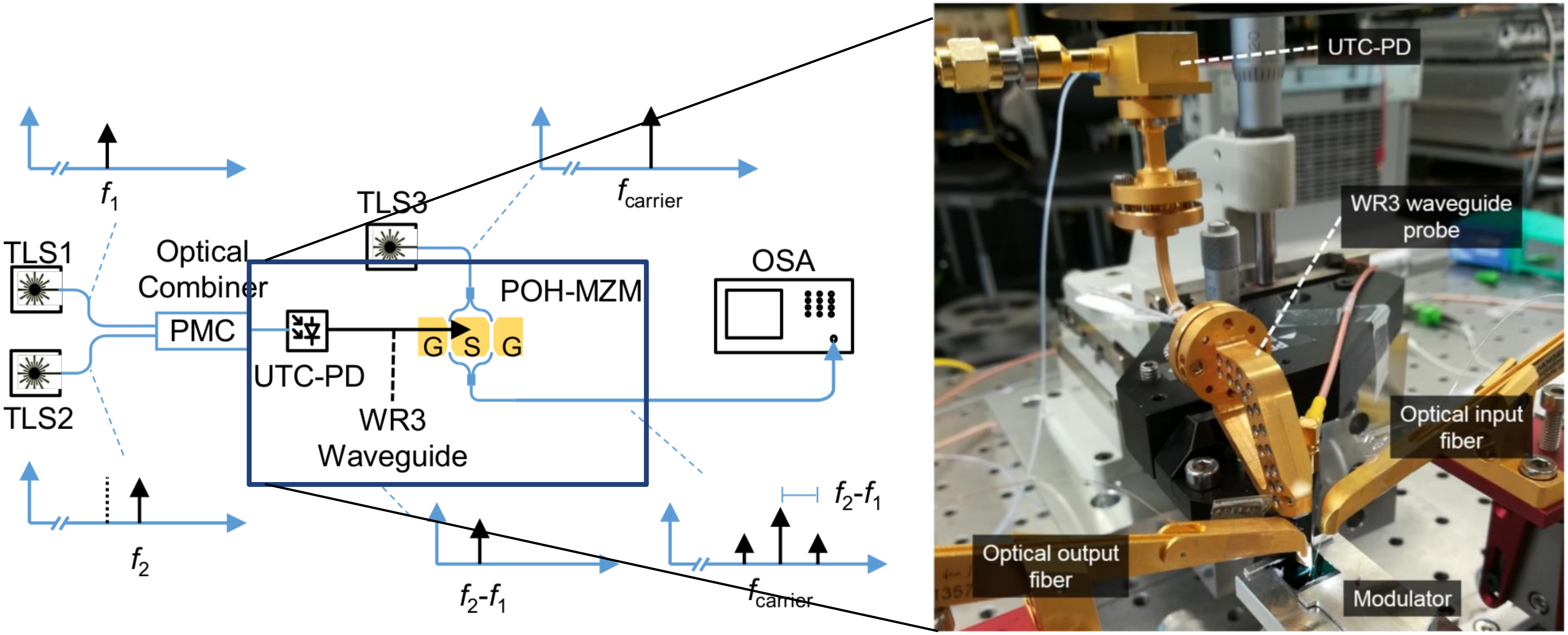
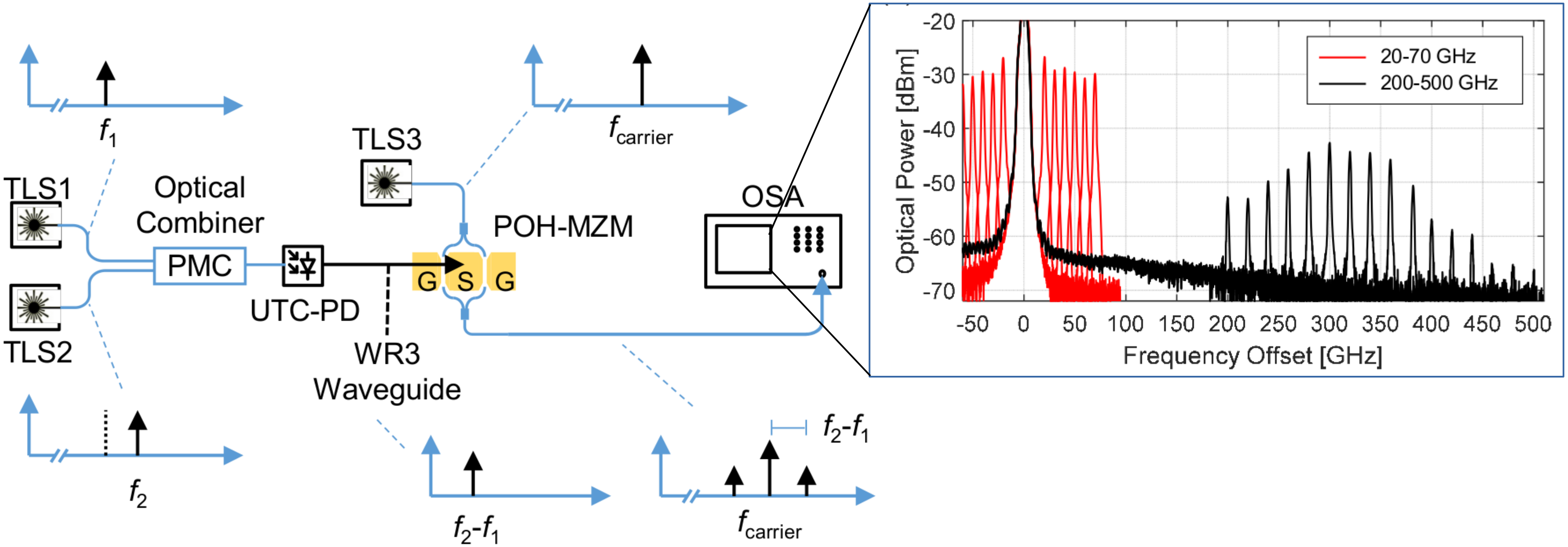


Pushing up the speed

- Clear modulation sidebands visible up to 500 GHz
- Only limited by bandwidth of UTC-PD



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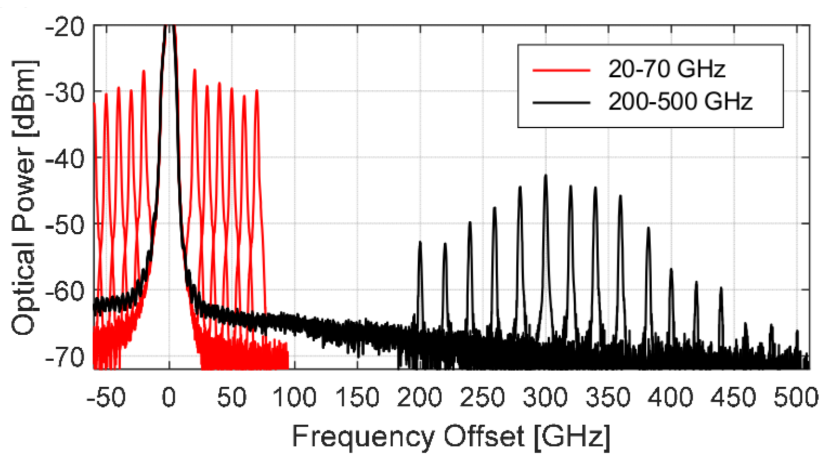
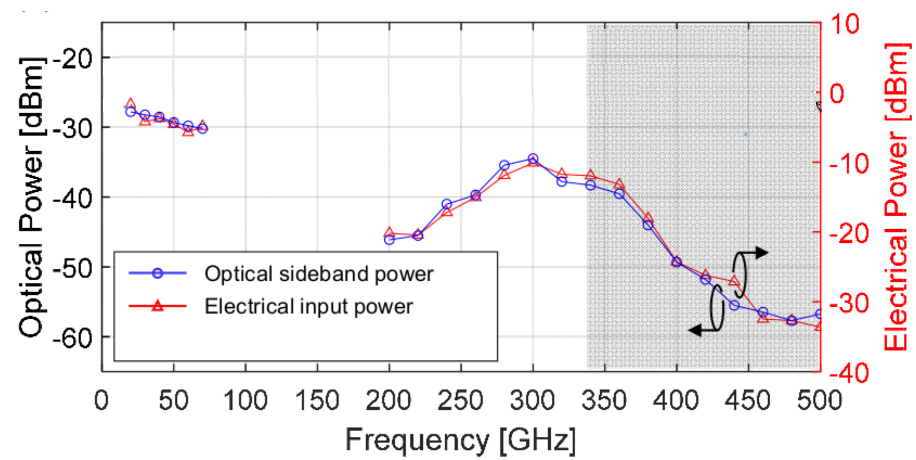
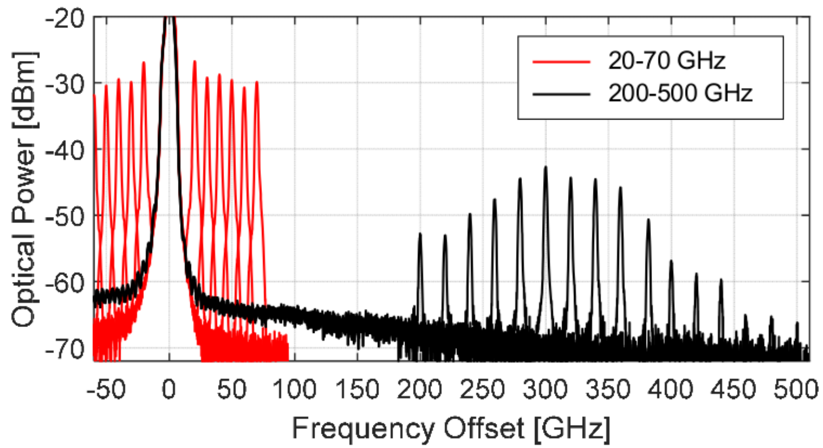


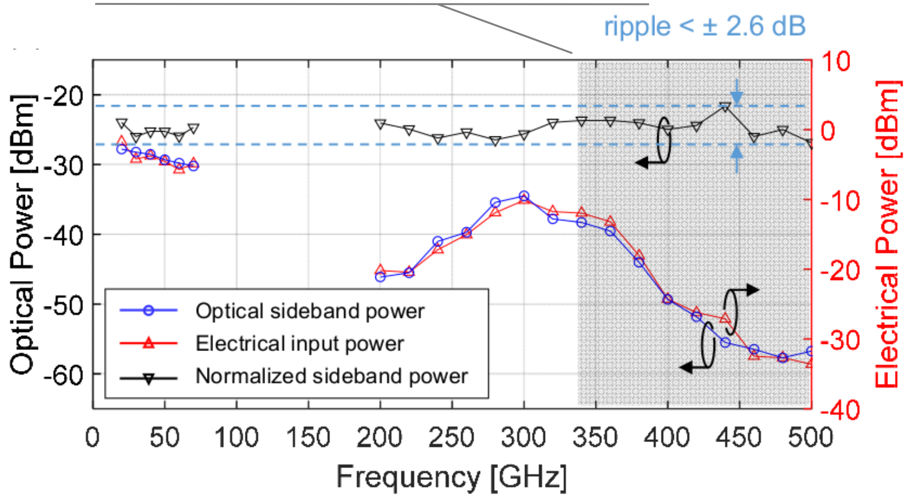


Pushing up the speed

- Normalizing the optical sideband power to the optical input power
- ***Flat response up to* 500 GHz**



Cutoff of higher order modes
in WR3 waveguide @ ~**347 GHz**



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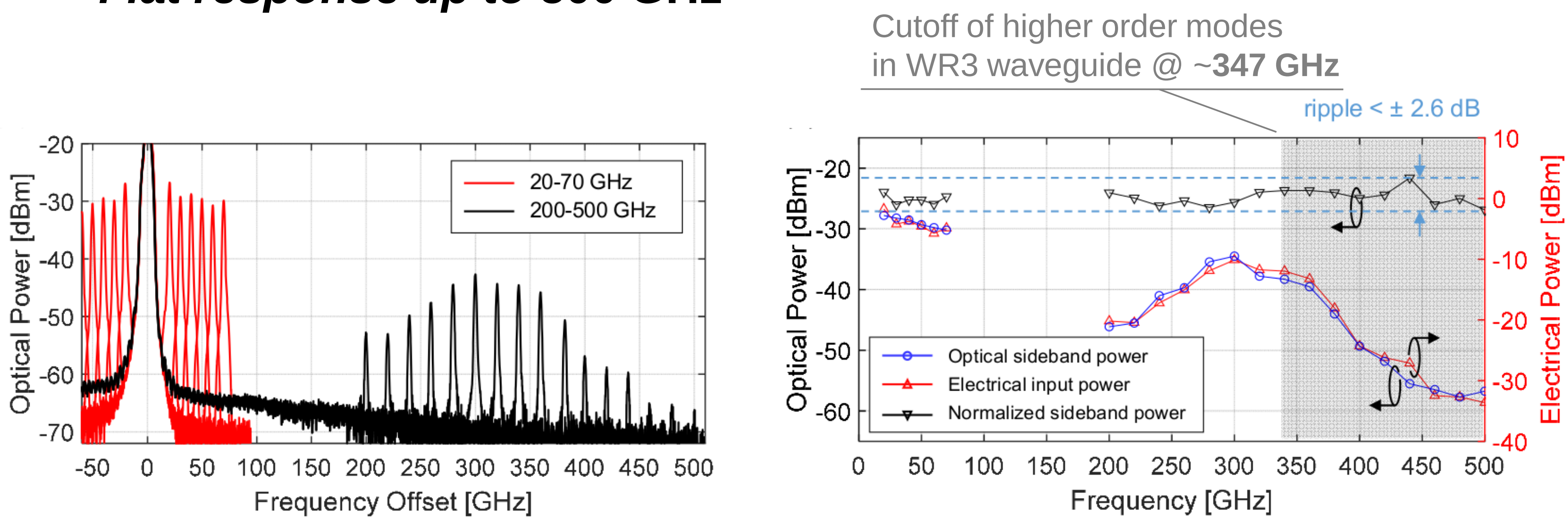

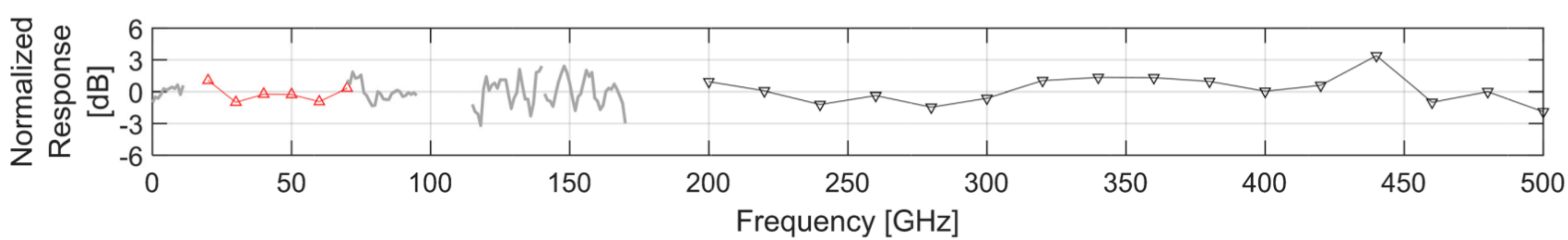

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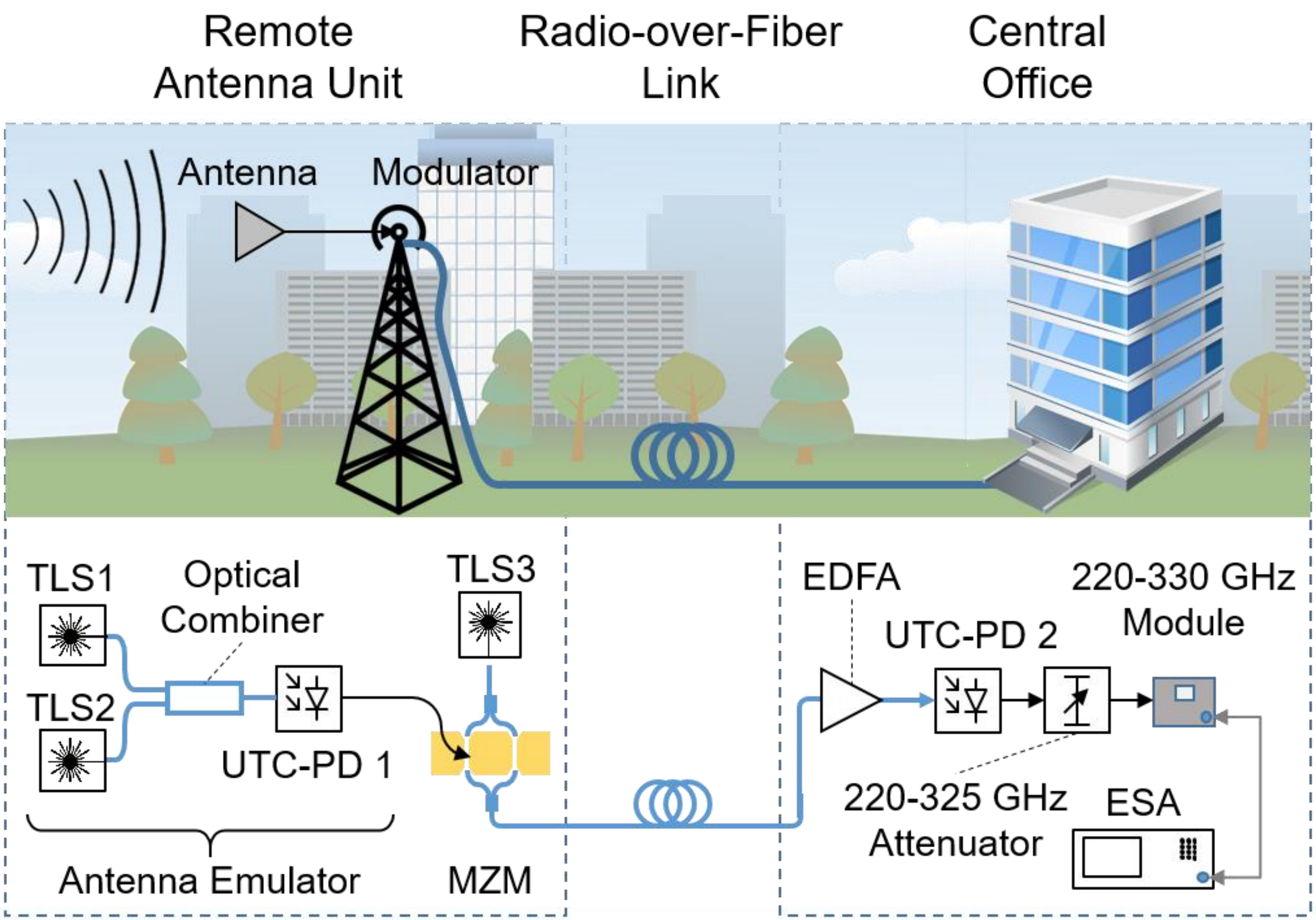
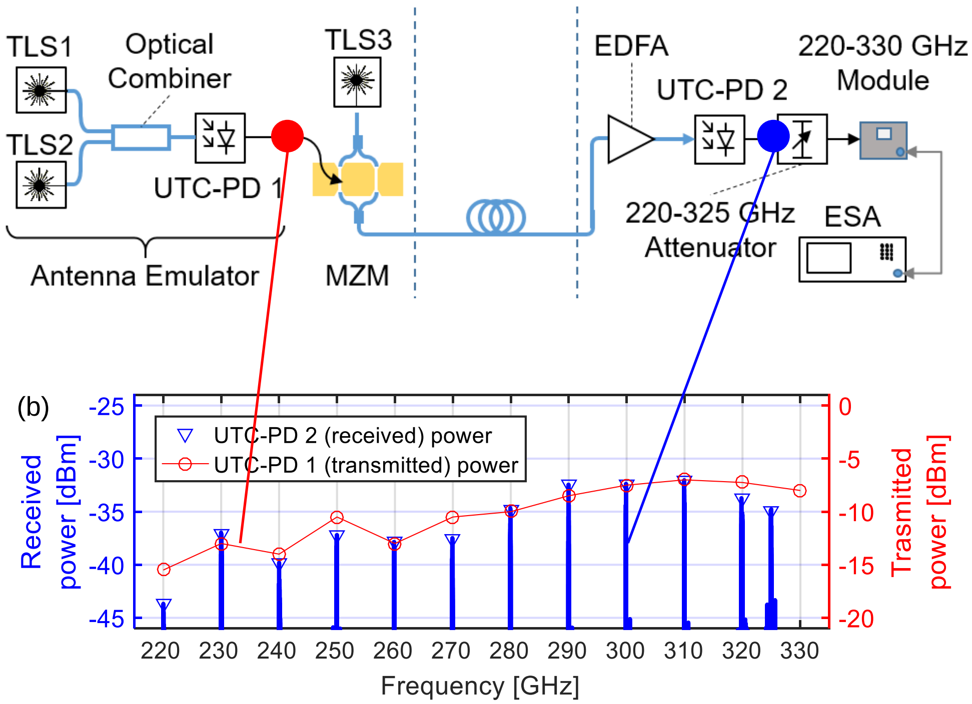
Contents

325 GHz microwave photonic link



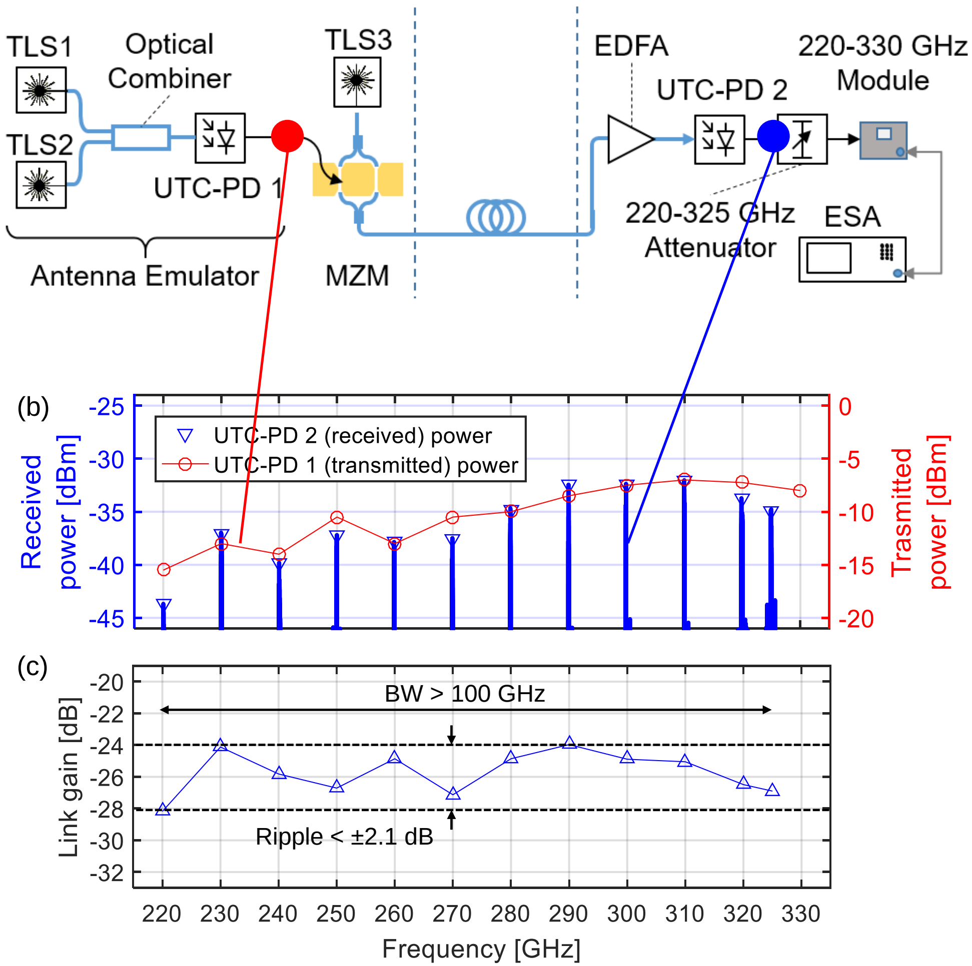
Link gain



- Remove frequency-dependent losses of mm-wave extension module
- Calculate ratio between output and input mm-wave power

M. Burla et al., "500 GHz plasmonic Mach-Zehnder modulators for sub-THz microwave photonics," APL Photonics, 4, 056106 (2019). (Featured Article)

325 GHz microwave photonic link



- Remove frequency-dependent losses of mm-wave extension module
- Calculate ratio between output and input mm-wave power

- **Link gain** is relatively flat over 220-325 GHz (> 100 GHz bandwidth)
- Only limited by the spectrum analyzer extension module

M. Burla et al., “500 GHz plasmonic Mach-Zehnder modulators for sub-THz microwave photonics,” APL Photonics, 4, 056106 (2019). (Featured Article)

Noise and SFDR evaluation

- Noise power density: $$P_\mathrm{N} = (1+g)P_\mathrm{th} + \frac{1}{4}P_\mathrm{shot} + \frac{1}{4}P_\mathrm{rin} + \frac{1}{4}P_\mathrm{EDFA}$$

- Evaluation for our link:

Noise term	Power (logarithmic scale)	Power (linear scale)
Thermal noise (modulator, $P_{th,MZM}$)	-197.7523 dBm/Hz	1.6779e-12 W
Shot noise (P_{shot})	-163.3311 dBm/Hz	4.622e-09 W
Relative intensity noise (P_{rin})	-152.7666 dBm/Hz	5.2635e-08 W
EDFA noise (P_{EDFA})	-153.28 dBm/Hz	4.6767e-08 W
Thermal noise (photodetector, $P_{th,PD}$)	-173.9752 dBm/Hz	4.0039e-10 W
Total noise power (P_N)	**-149.8119 dBm/Hz**	**1.0443e-07 W**

- Noise figure:

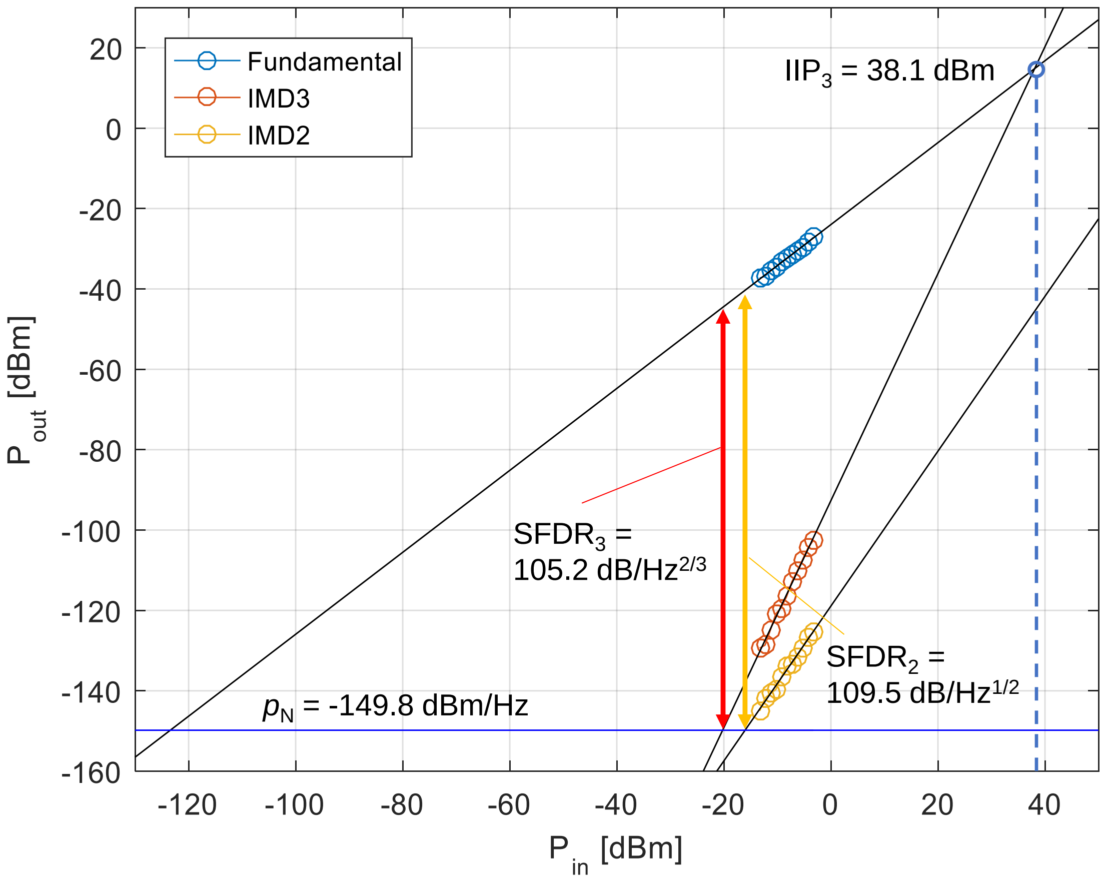
$$\mathrm{NF} = 10\ \log_{10}\left(\frac{P_\mathrm{N}}{gkTB}\right)$$ = 45.8 dB @ 300 GHz

Noise and SFDR evaluation

- Spurious-free dynamic range:

$SFDR_3$ = 105.2 dB/Hz$^{2/3}$

$SFDR_2$ = 109.5 dB/Hz$^{1/2}$



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Symbol-by-Symbol Beamsteering

- Ultra-fast Beam Steering

R. Bonjour et al., "Ultra-fast Millimeter Wave Beam Steering." JSTQE, Feb. 2016.

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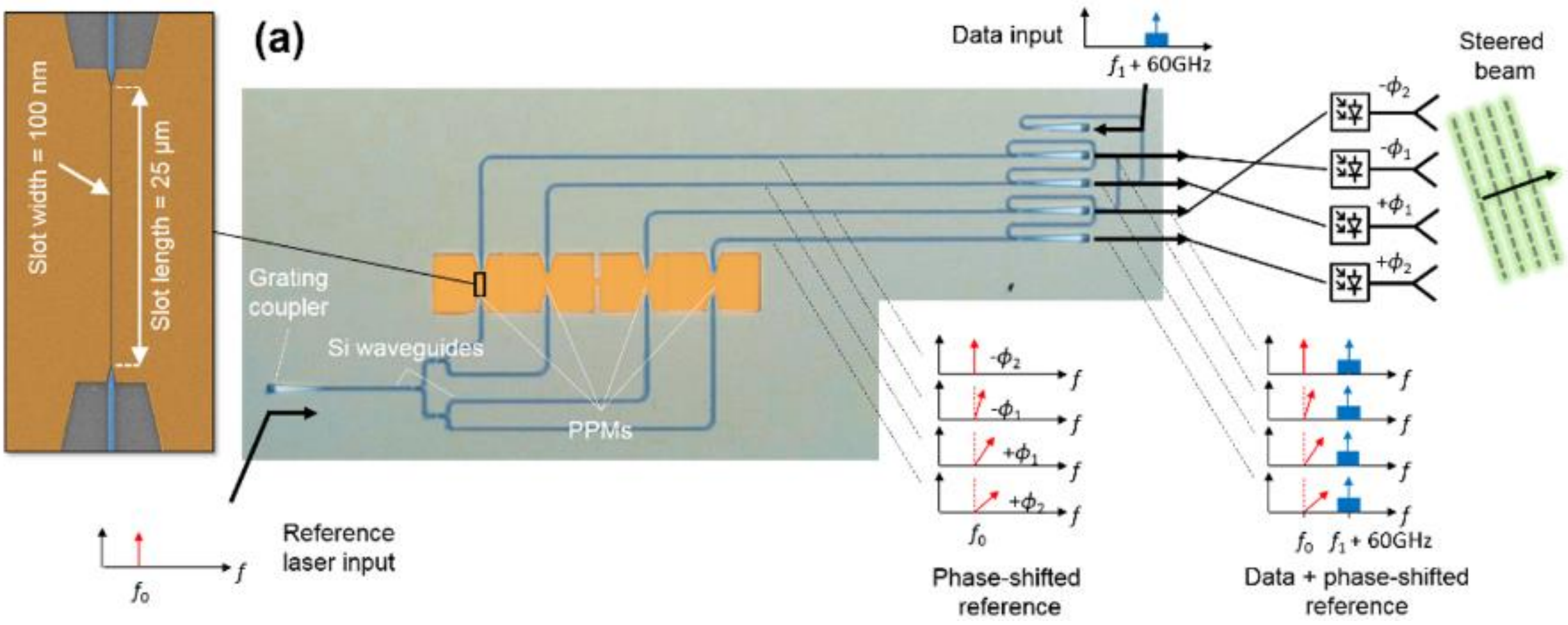
Plasmonic Beamformers for Antenna Arrays

- 4-Elements Integrated Ultra-fast Beam Steering Beamformer



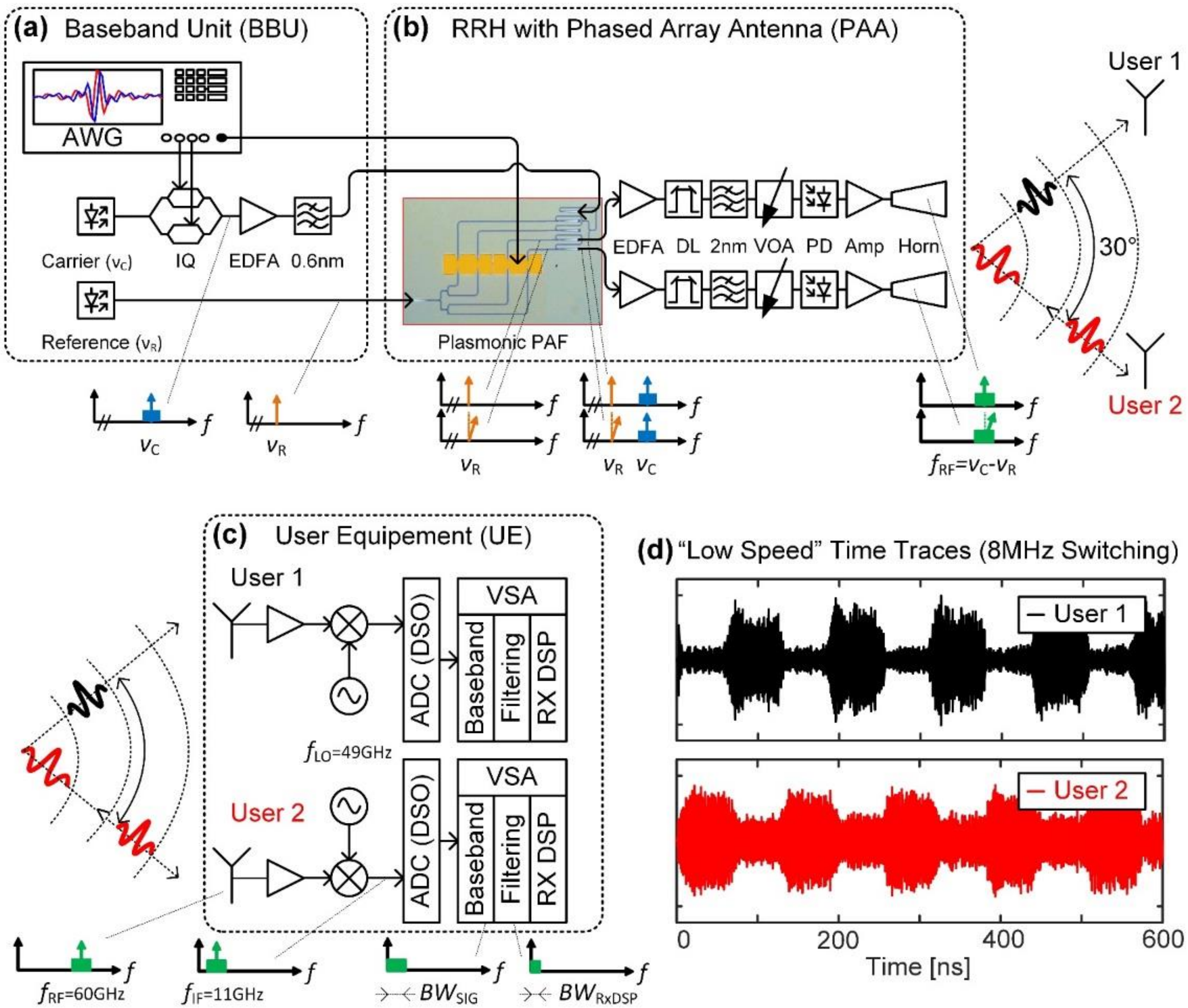
Expected up to 100s GHz steering speeds (symbol-by-symbol)

R. Bonjour et al., "Plasmonic Phased Array Feeder Enabling Ultra-Fast Beam Steering at Millimeter Waves," Opt. Express 24, 25608-25618 (2016).

System Demonstration

TX

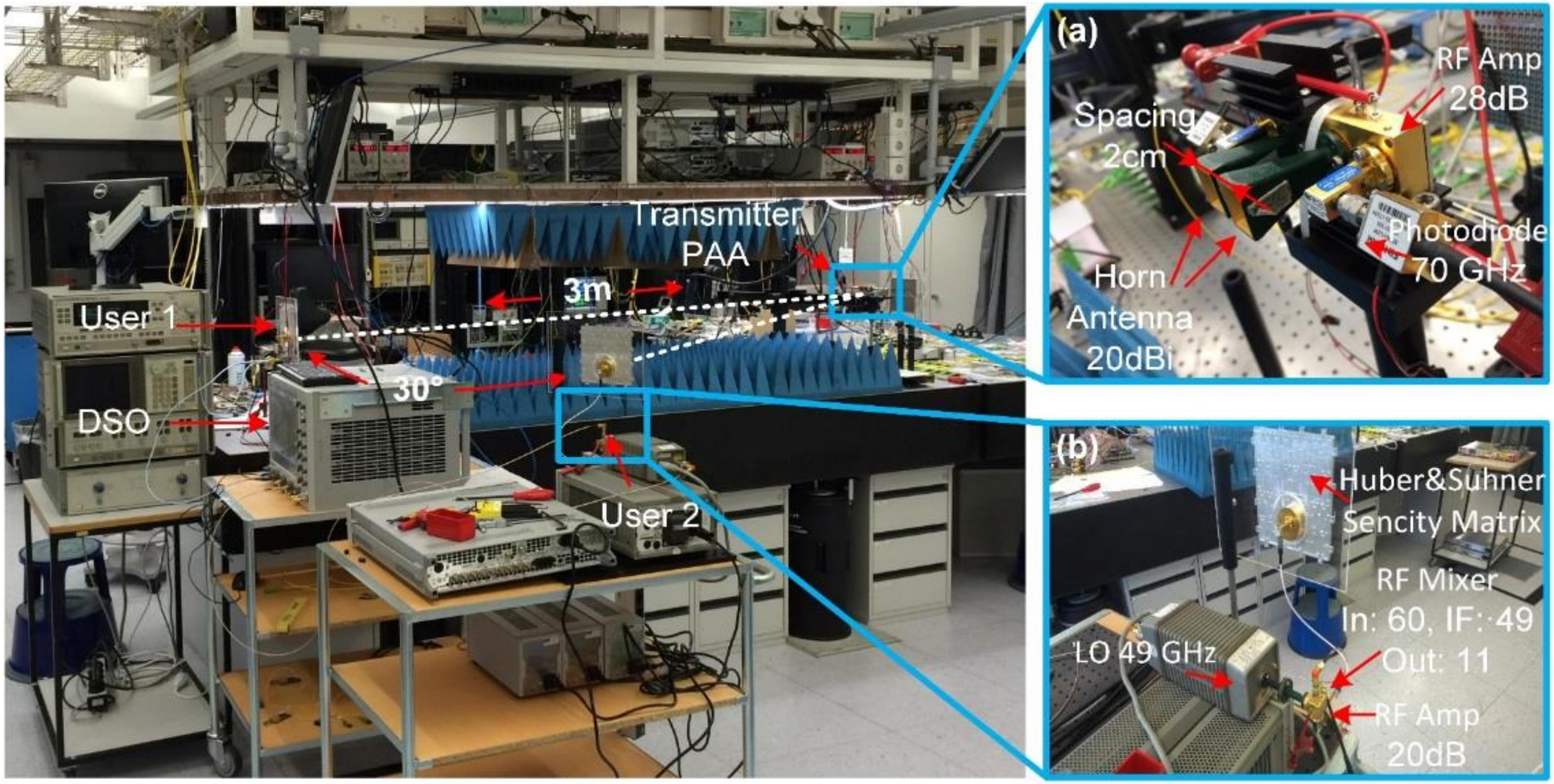
RX



R. Bonjour et al., "Plasmonic Phased Array Feeder Enabling Ultra-Fast Beam Steering at Millimeter Waves," Opt. Express 24, 25608-25618 (2016).

System Demonstration

- Experimental setup



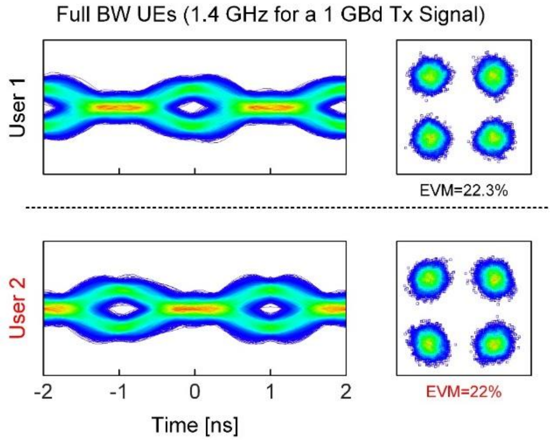
R. Bonjour et al., "Plasmonic Phased Array Feeder Enabling Ultra-Fast Beam Steering at Millimeter Waves," Opt. Express 24, 25608-25618 (2016).

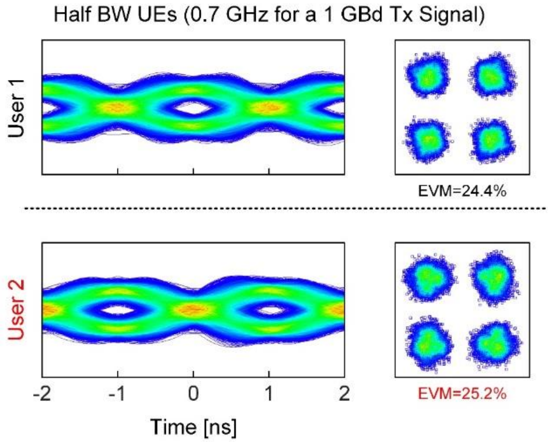
System Demonstration

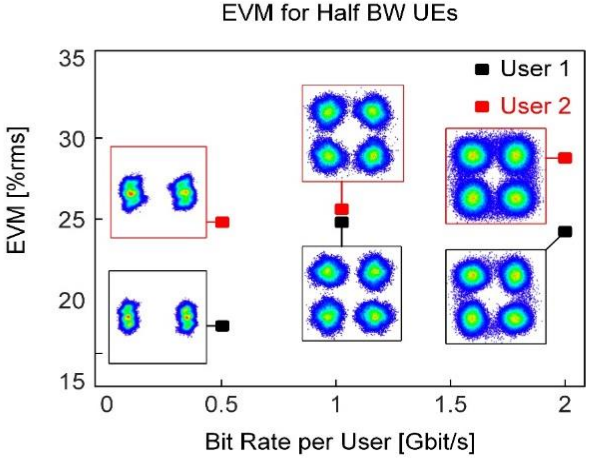
- Use of narrowband receivers possible

Full RX bandwidth 1.4 GHz

Half RX bandwidth 0.7 GHz







R. Bonjour et al., "Plasmonic Phased Array Feeder Enabling Ultra-Fast Beam Steering at Millimeter Waves," Opt. Express 24, 25608-25618 (2016).

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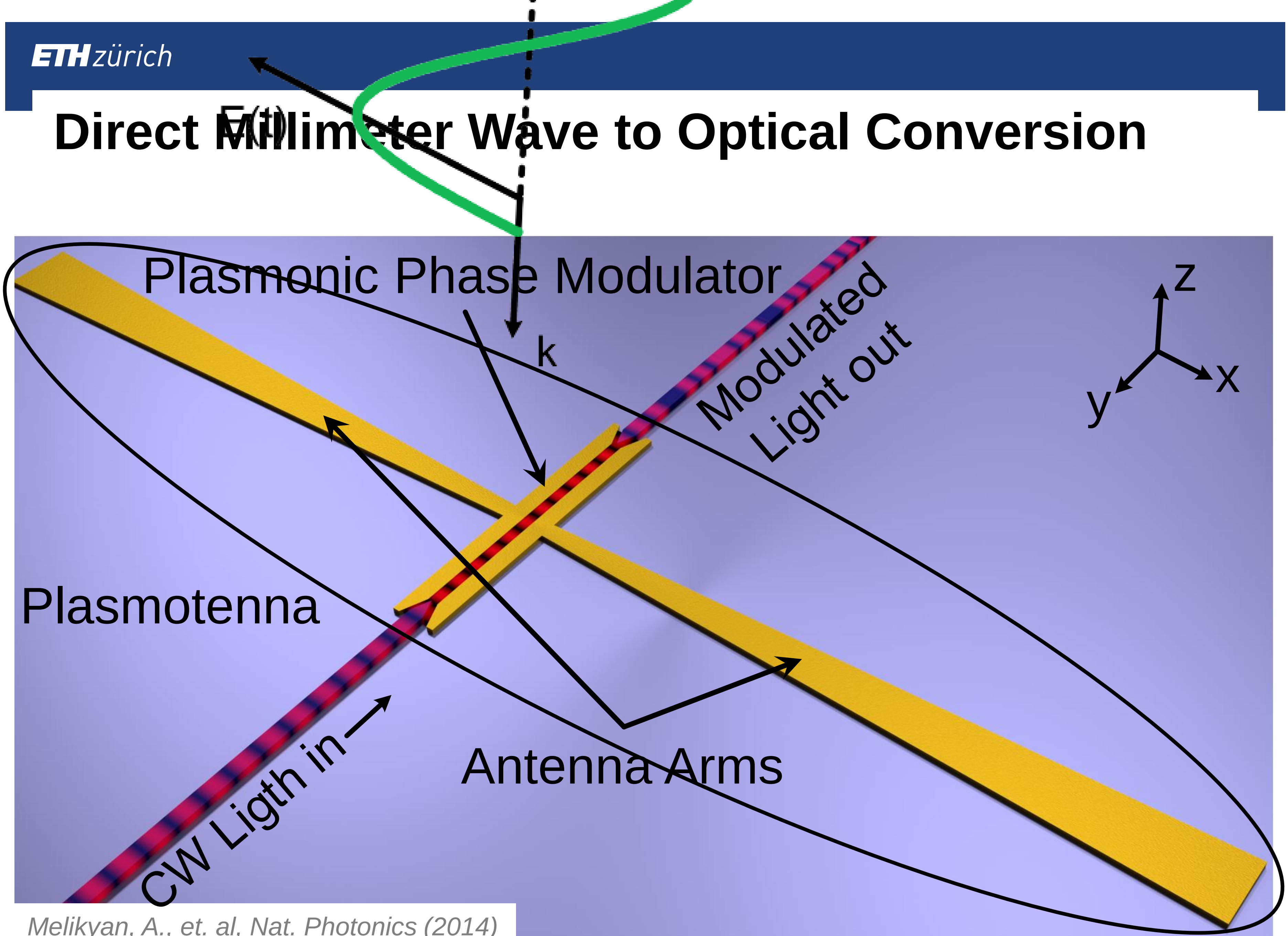
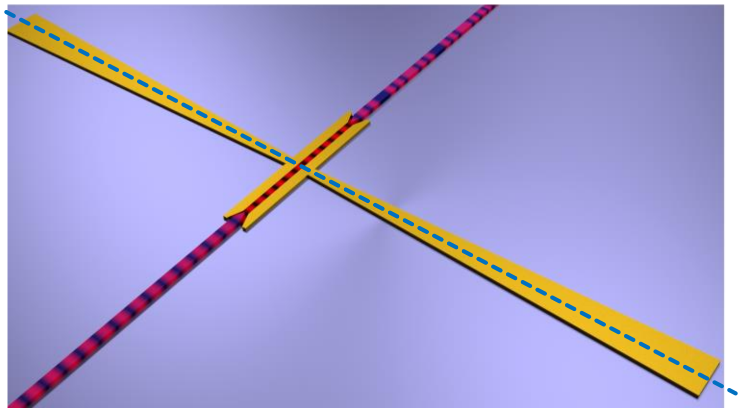
Direct Millimeter Wave to Optical Conversion



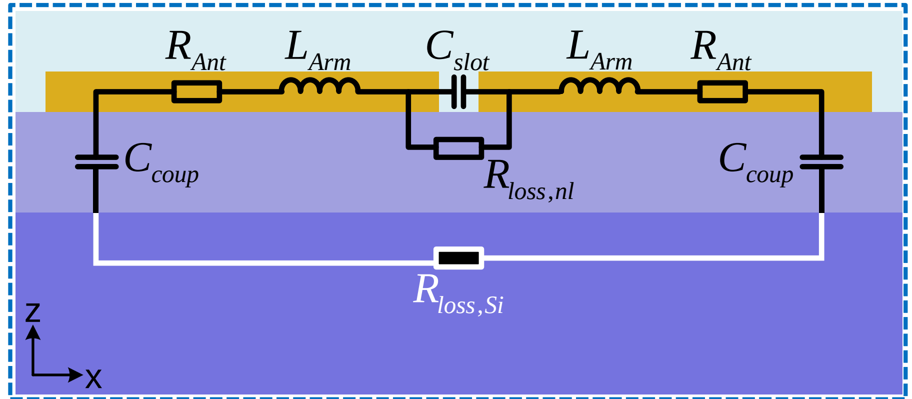
Melikyan, A., et. al, Nat. Photonics (2014)
Salamin, Y., et. al, Nano Letters (2015)

Plasmotenna – Field Enhancement by Resonance

Plasmotenna device



Equivalent circuit model

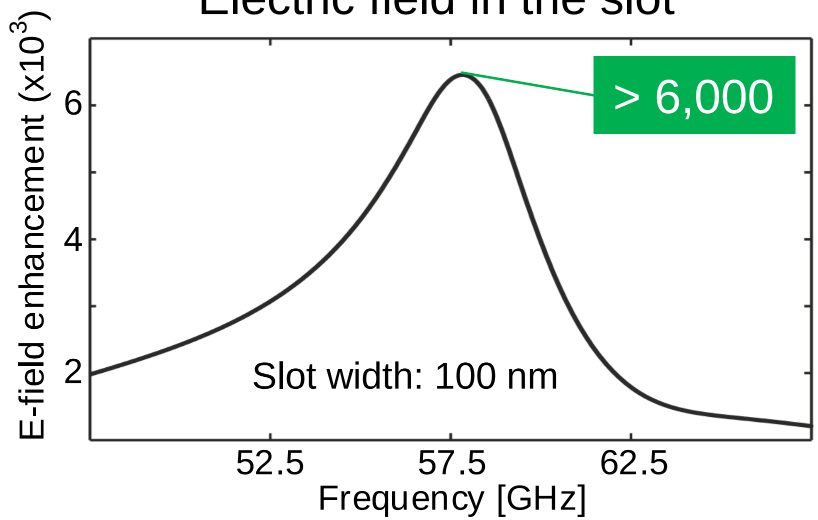


Resonance condition

$$Z = R - j\underbrace{\left(\frac{1}{\omega C_{slot}} - \omega L_{Arm}\right)}_{0}$$

$$L_{Arm} = C_{slot}^{*}$$

Electric field in the slot

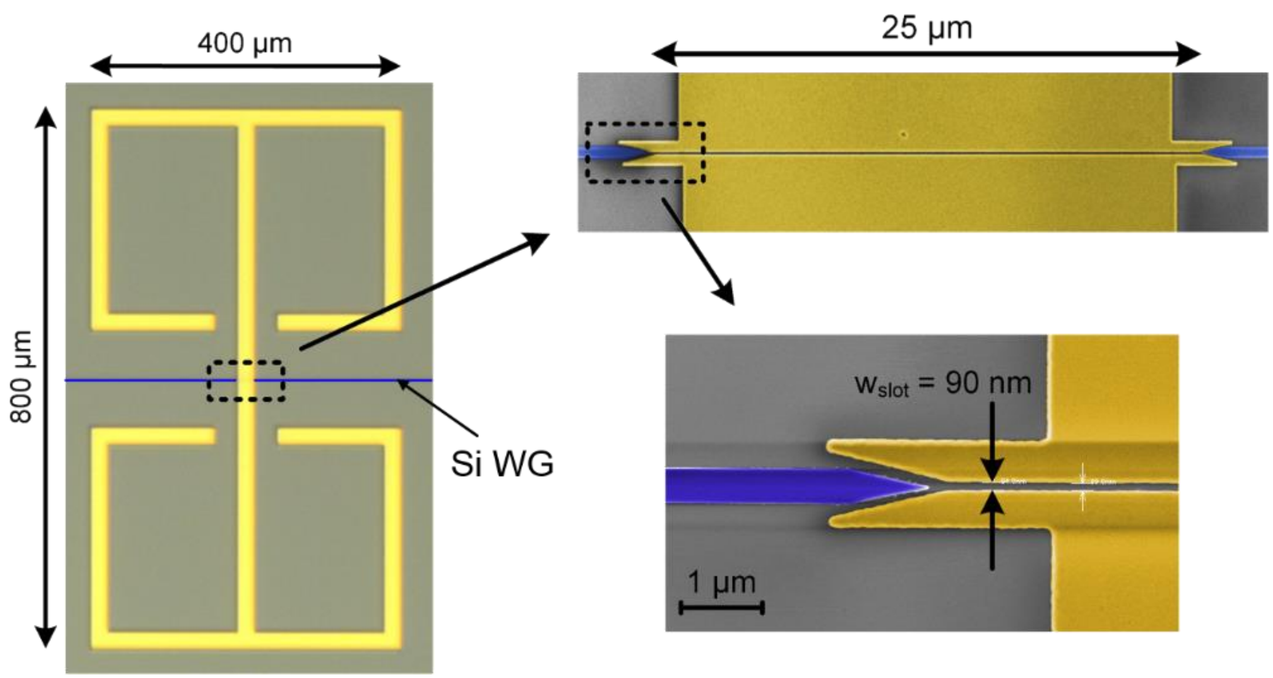


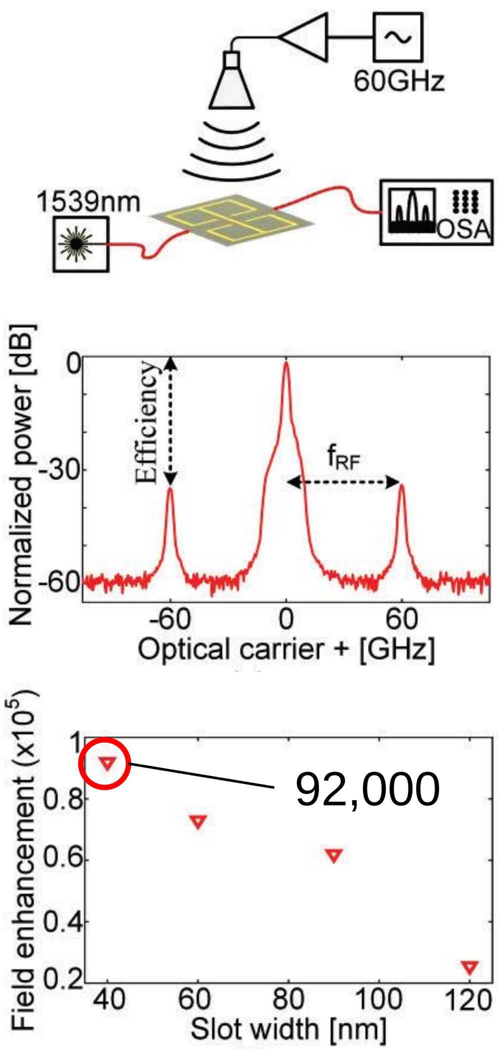
Salamin, Y., et. al, Nano Letters (2015)

Further enhancement of the electric field in the slot using ***resonant*** structure

Efficient Wireless-to-Optical Conversion

- "Four-clover-leaf"-shaped resonant antenna at 60 GHz
- 92,000× field enhancement in the slot

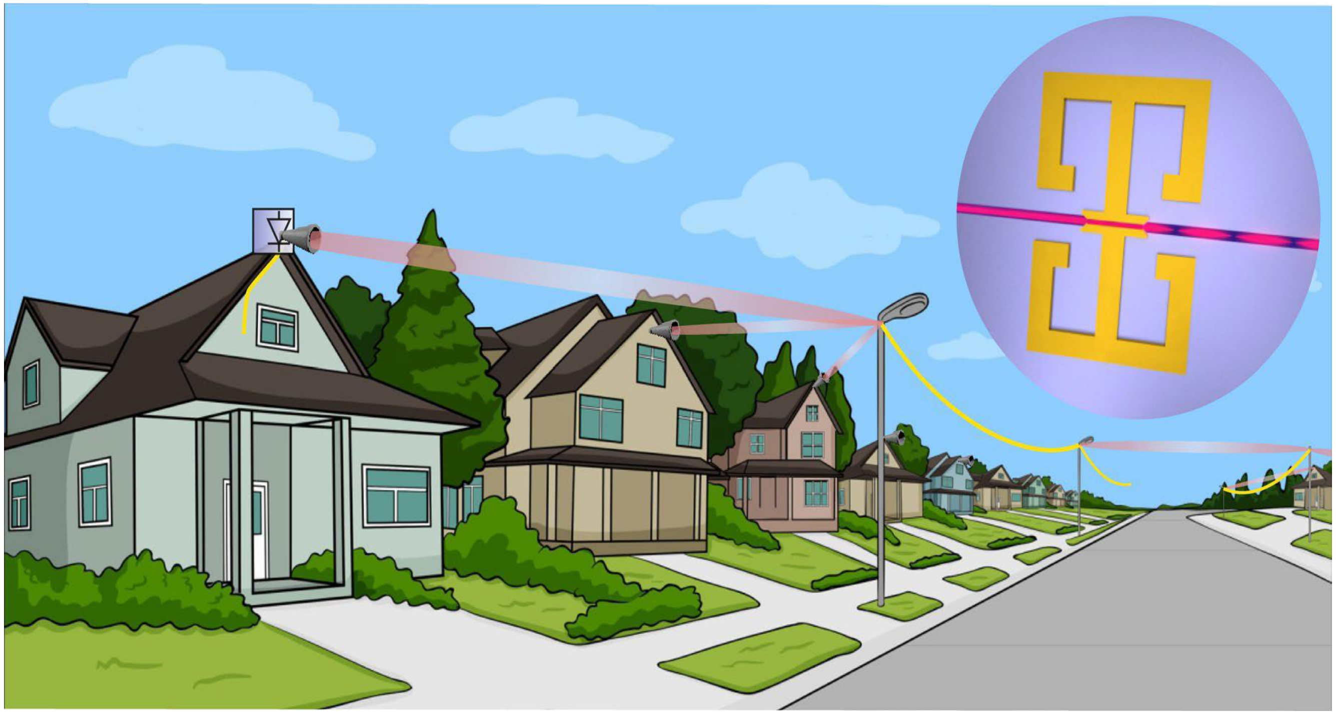




Y. Salamin et al, CLEO (2016)

Microwave Plasmonic Mixer

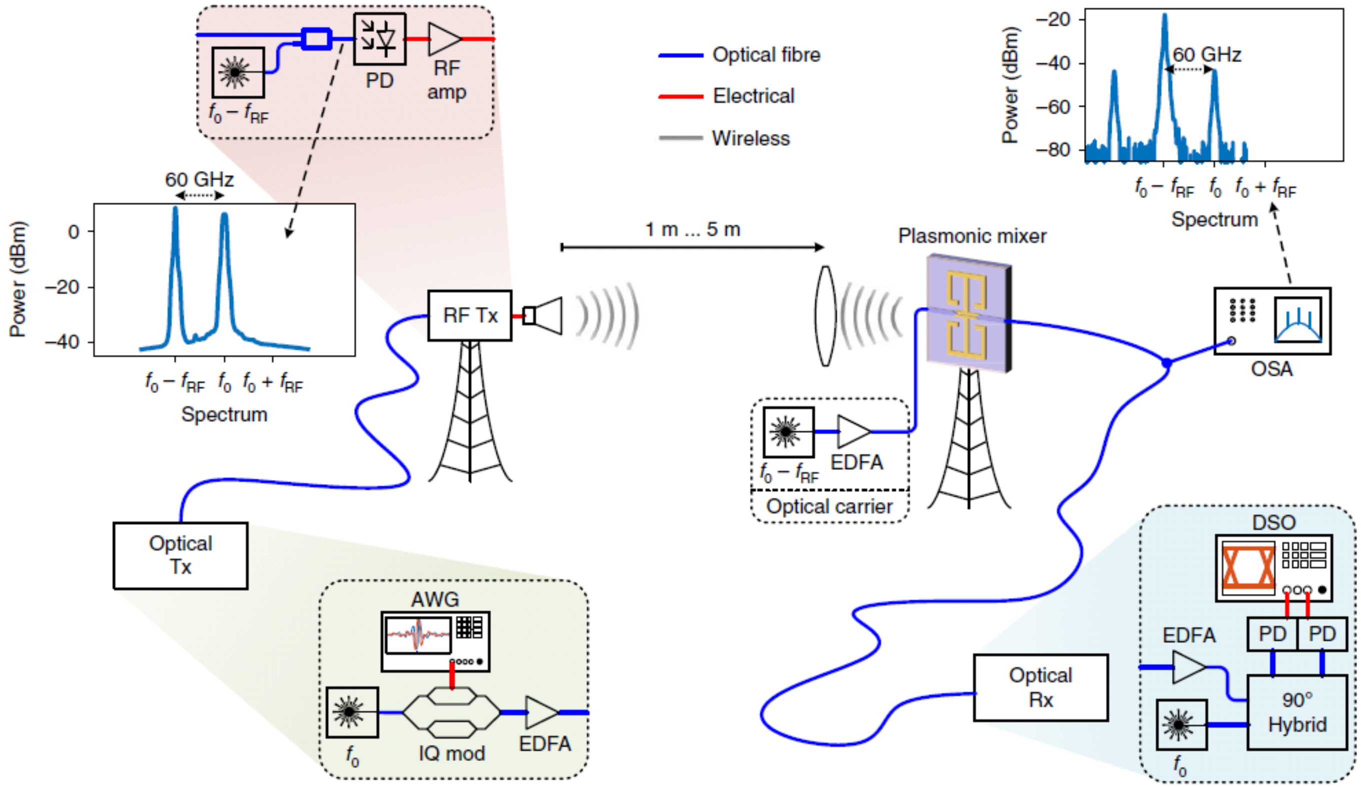
- Virtual fibers (point-to-point fiber-wireless links)
- Directly map a wireless signal to an optical fiber - without the need for any electrical power connection.



Y. Salamin et al., "Microwave plasmonic mixer in a transparent fibre-wireless link", Nature Photonics (2018), DOI: 10.1038/s41566-018-0281-6

Mirowave Plasmonic Mixer

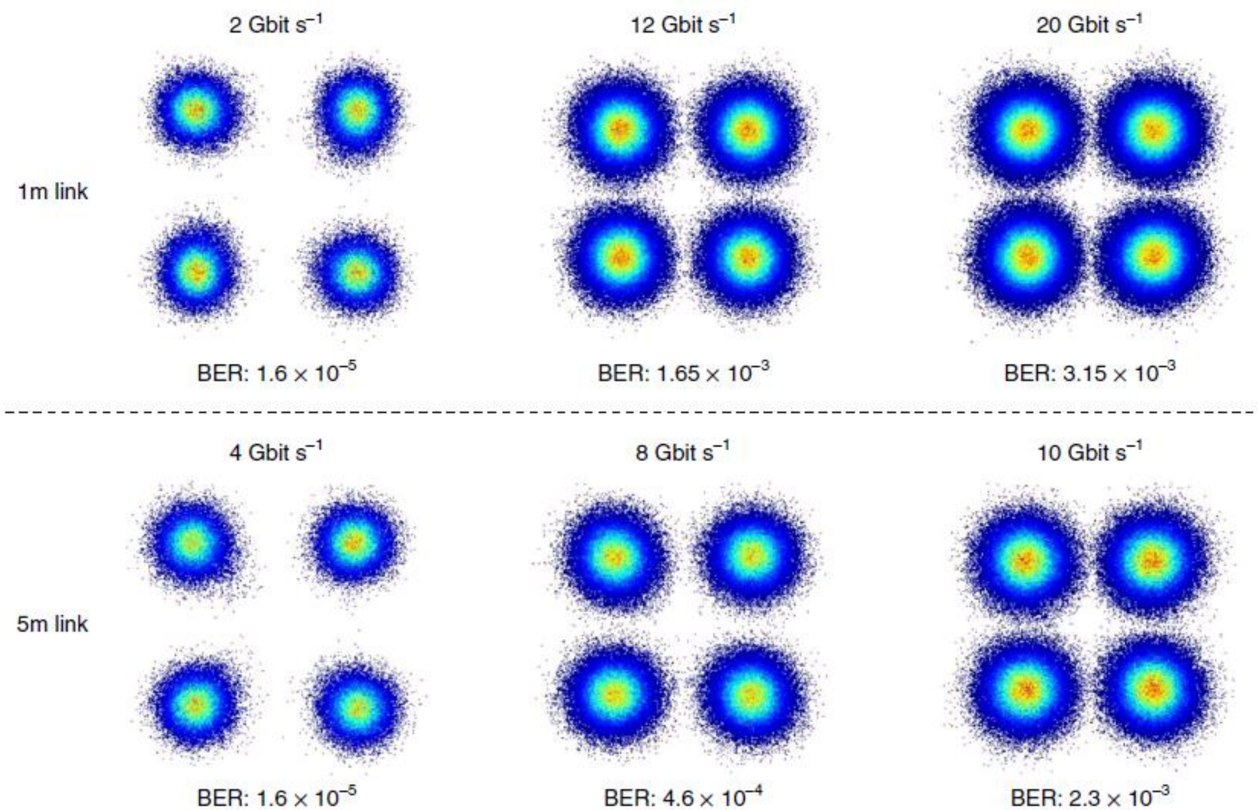
- Experimental setup



Y. Salamin et al., "Microwave plasmonic mixer in a transparent fibre-wireless link", Nature Photonics (2018), DOI: 10.1038/s41566-018-0281-6

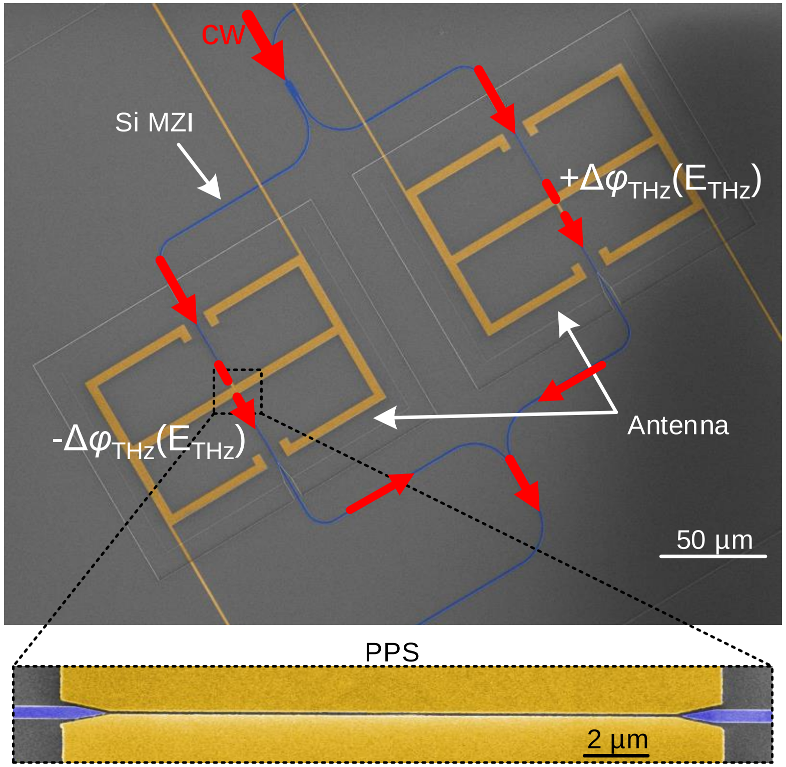
Mirowave Plasmonic Mixer

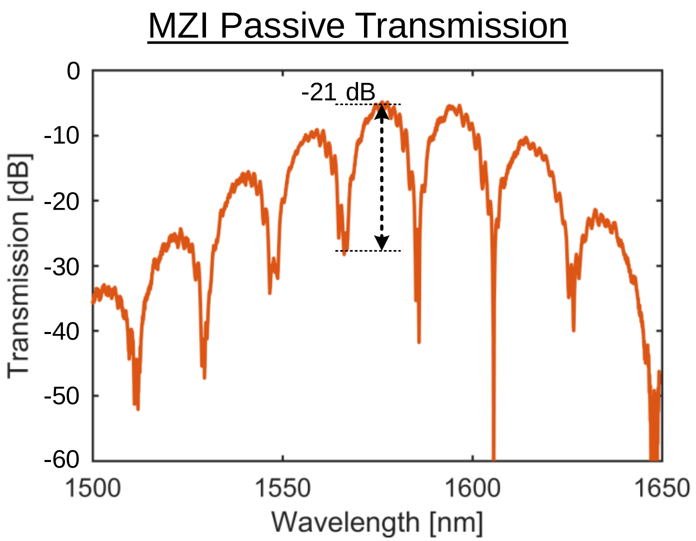
- 20 Gbps up to 1 m; 10 Gbps up to 5 m



Y. Salamin et al., "Microwave plasmonic mixer in a transparent fibre-wireless link", Nature Photonics (2018), DOI: 10.1038/s41566-018-0281-6

300 GHz Plasmonic Mixer





Y. Salamin et al., "300 GHz Plasmonic Mixer", IEEE International Topical Meeting on Microwave Photonics (MWP 2019), Ottawa, Canada, Oct. 2019. (Best Student Paper Award)

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Conclusions

- **The THz region** above 300 GHz can solve the speed bottlenecks of today’s wireless communications
- The creation of analog radio-over-fiber links at THz frequencies is **not trivial**
- We showed a modulator with **a flat response up to 500 GHz, high power handling and high linearity, simultaneously**
- We implemented an **analog optical link with >100 GHz bandwidth** and a **plasmonic mixer for direct THz-optical conversion**
- Strong potential to enable **microwave photonics** applications to reach the THz range

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  - H. Massler

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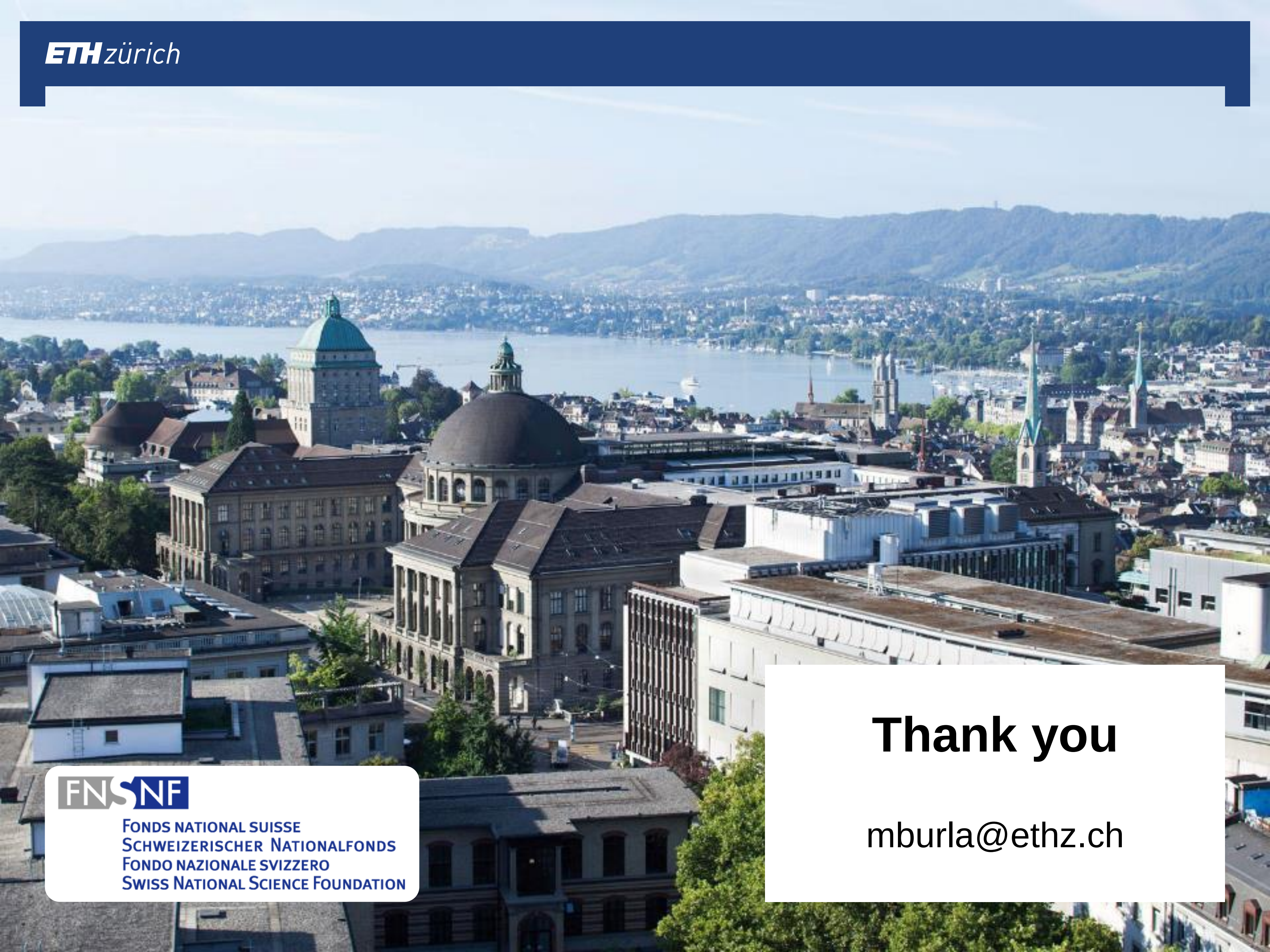

Thank you

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