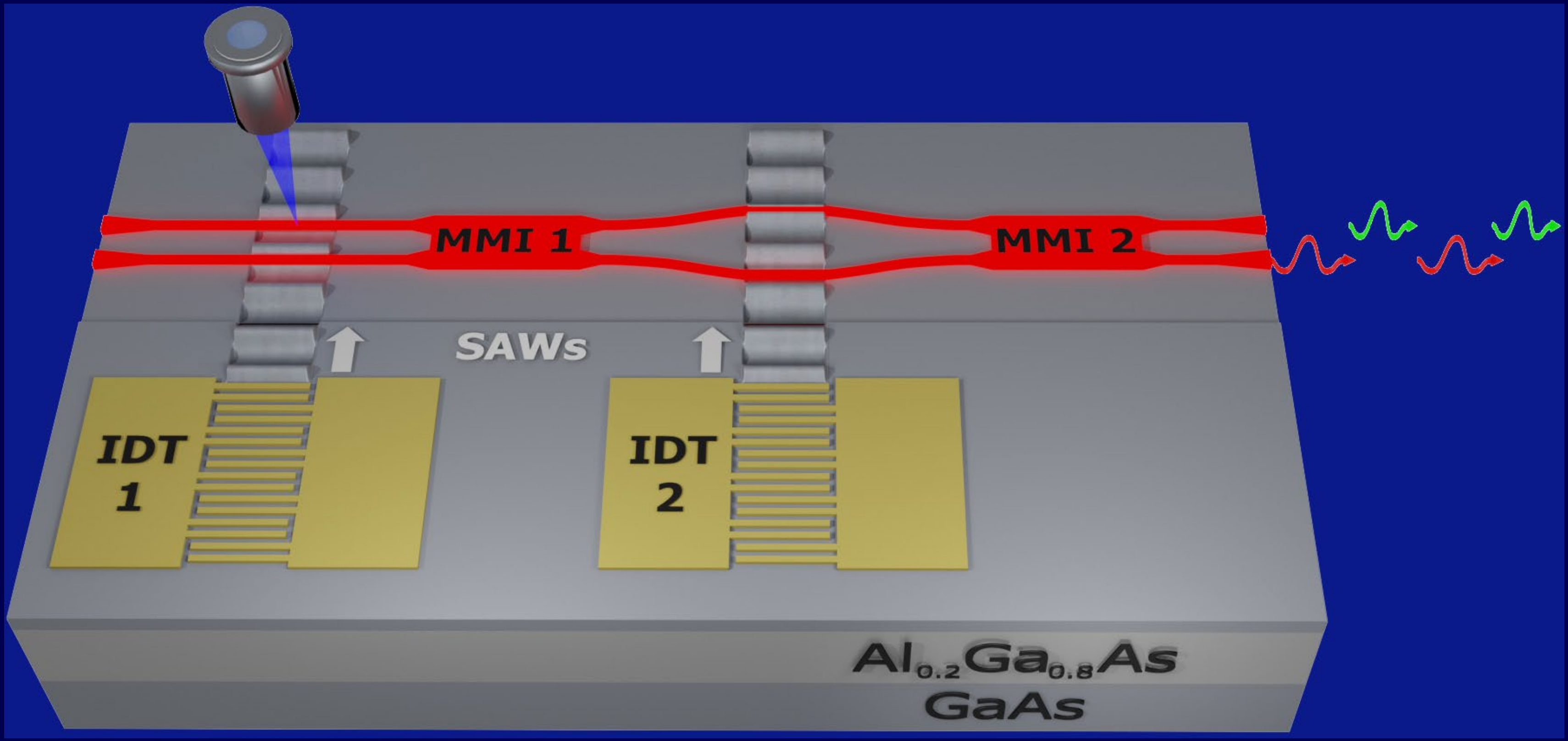
Integrated (quantum) photonic devices driven by surface acoustic waves



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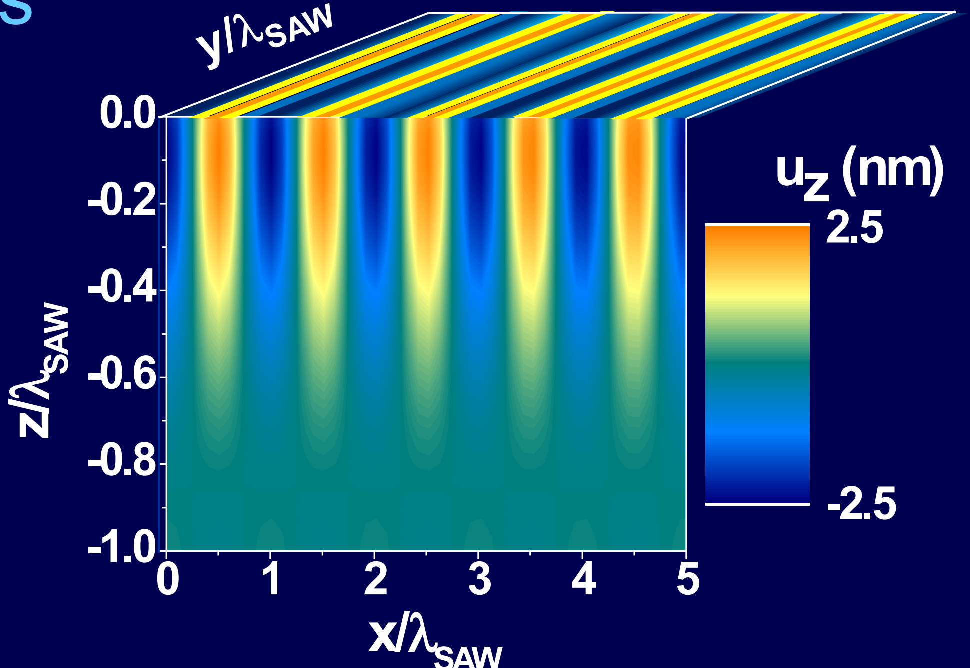
Outline

1. Overview
   – Surface Acoustic Waves
2. Out-of-plane geometries
   – Planar photonic microcavities
   – Polaritons
3. Integrated devices
   – SAW-driven modulators
   – SAW-driven tunable (de)multiplexing
   – SAW-driven single-photon Q-bits

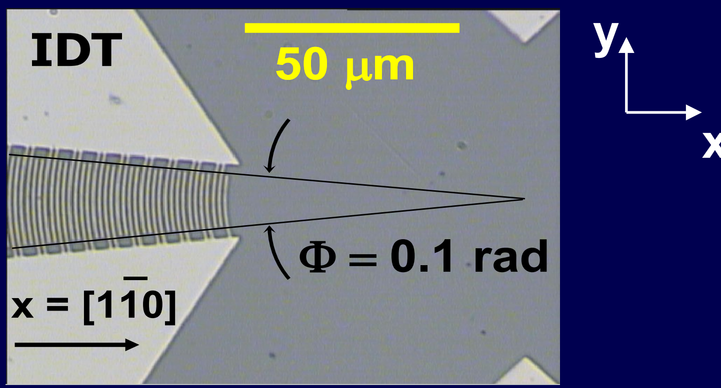
1. Overview

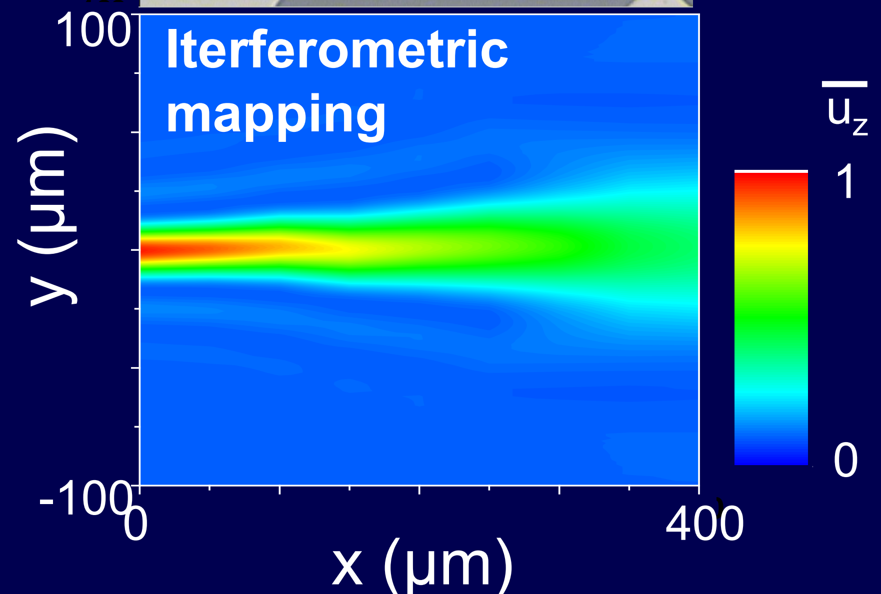
- Surface Acoustic Waves (SAWs)
  - Exponential decay towards the bulk
    - Surface acoustic phonons (rf signal, pulsed laser)
    - Speed: ~ km/s
  - Traditional applications
    - Electrical delay-lines
      - Mobile phones
    - Acousto-optics
      - Bragg cells

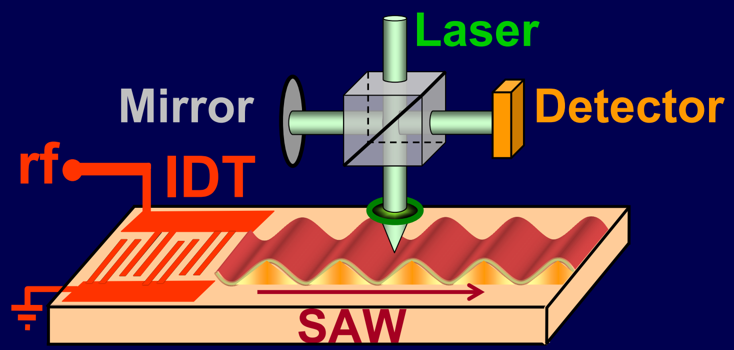


SAW Generation: Our Approach

- Easy to excite
  - Piezoelectric materials
    - Interdigital transducers (IDTs)
    - Electric generation
- Optical lithography fabrication
  - Typical wavelength: 5.6 μm
    - Smaller features: 700 nm
- Interferometry
  - Mapping the vertical displacements (u_z)

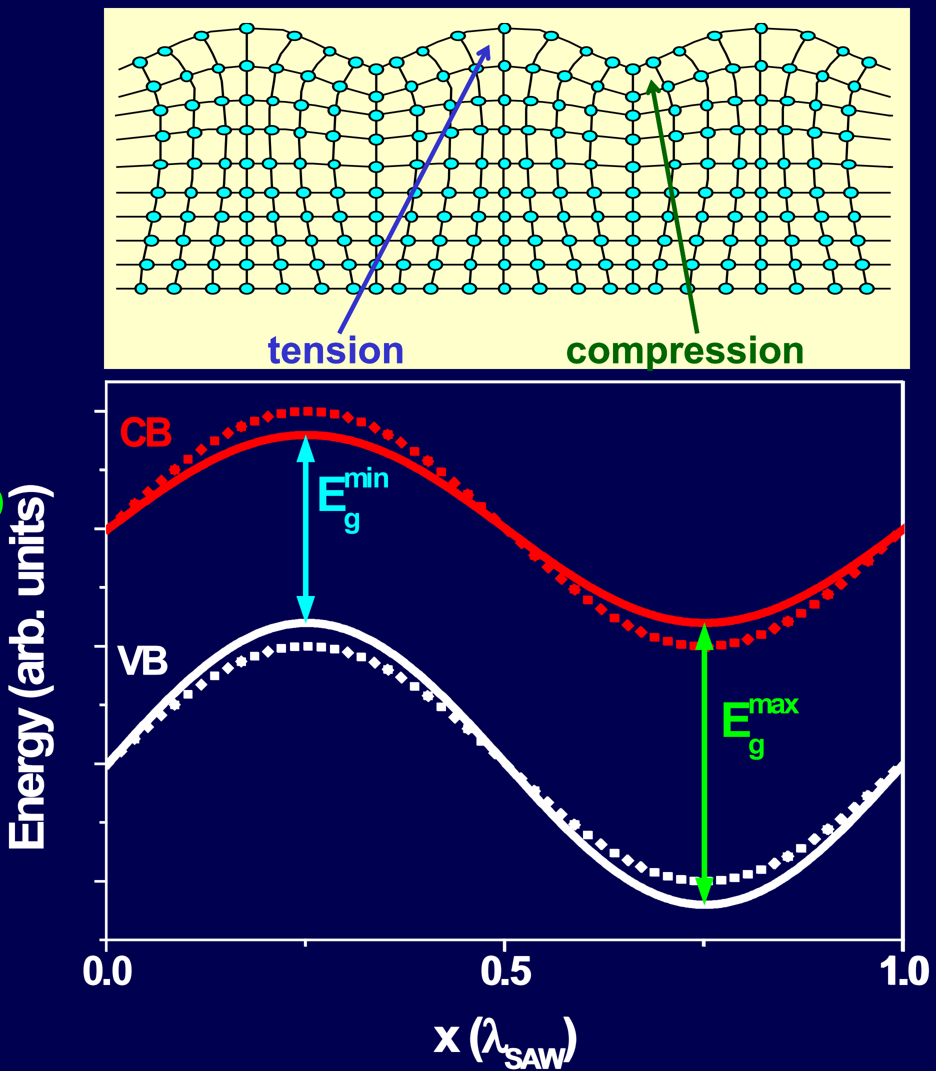






Modulation Effects

- Rayleigh Waves
  - Piezoelectric potential
    - Bend the bands
  - Deformation potential
    - Modulate the band gap value
  - Elasto-optical interaction
    - Refractive index modulatation



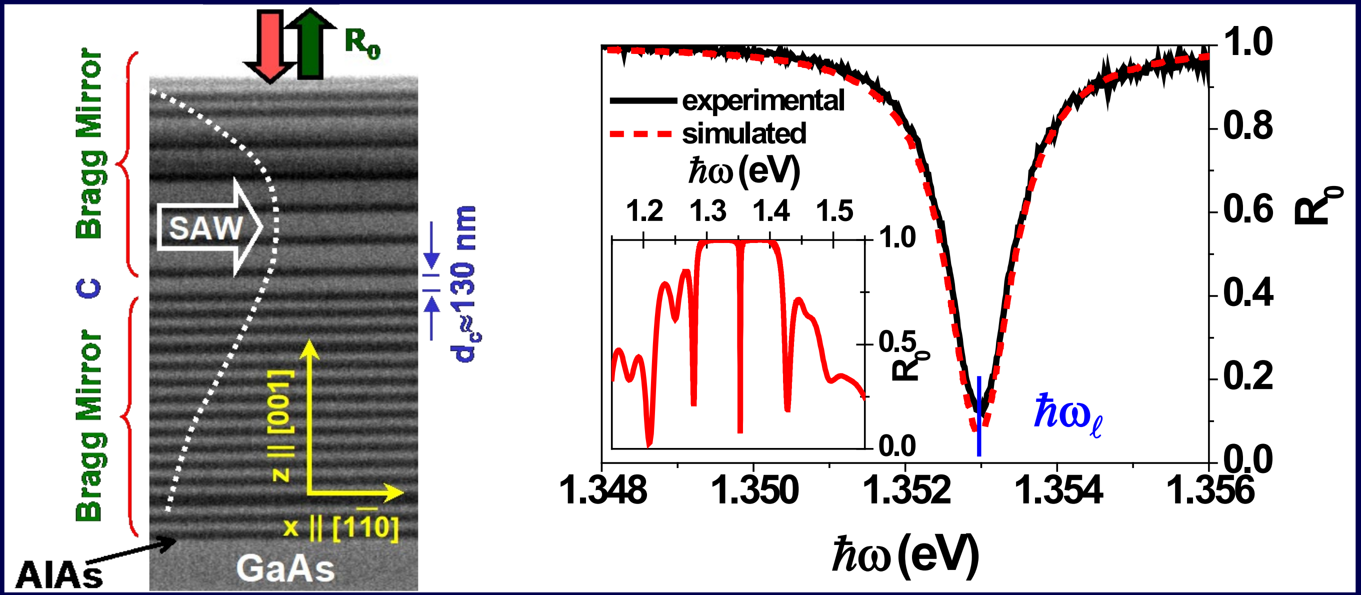
Combining Photonics & SAWs

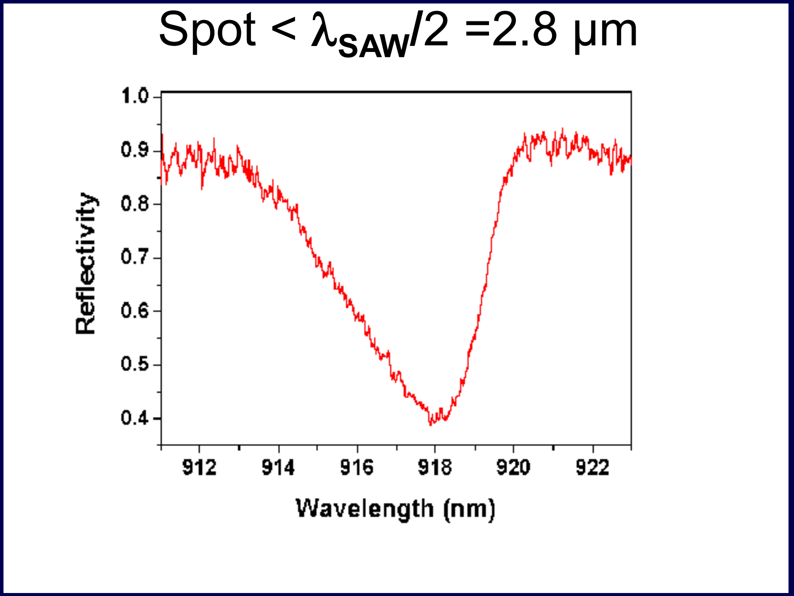
- Elasto-optical interaction
  - – Refractive index (n) modulation
- Strain (ε) components
  - – Structured systems
    - Photonic Crystals (PhC)
    - Semiconductor Microcavities
- Compatibility with many material systems (SOI, GaAs, InP, etc…)
  - – Monolithic
  - – Inexpensive

de Lima & Santos, *Rep. Prog. Phys*. **68**, 1639-1701 (2005).

2. Out of plane geometries

SAW Modulation in Microcavities



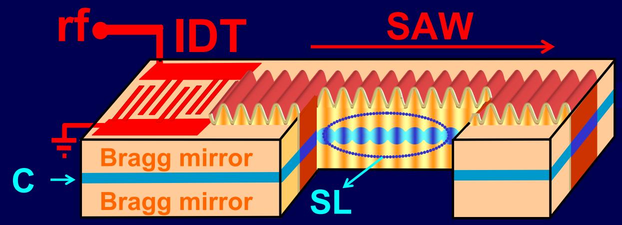


$$\hbar\omega_\ell = \pi c/(n_c d_c)$$

cavity frequency — strain — elasto-optic interaction

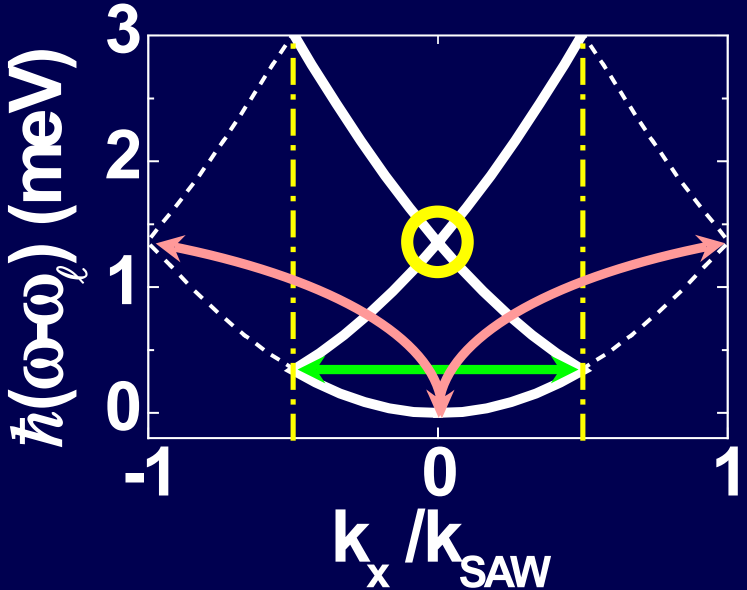
$$-\Delta\omega/\omega_\ell \approx \varepsilon_{zz} + \Delta n_{eo}/n \;>\; \Gamma$$

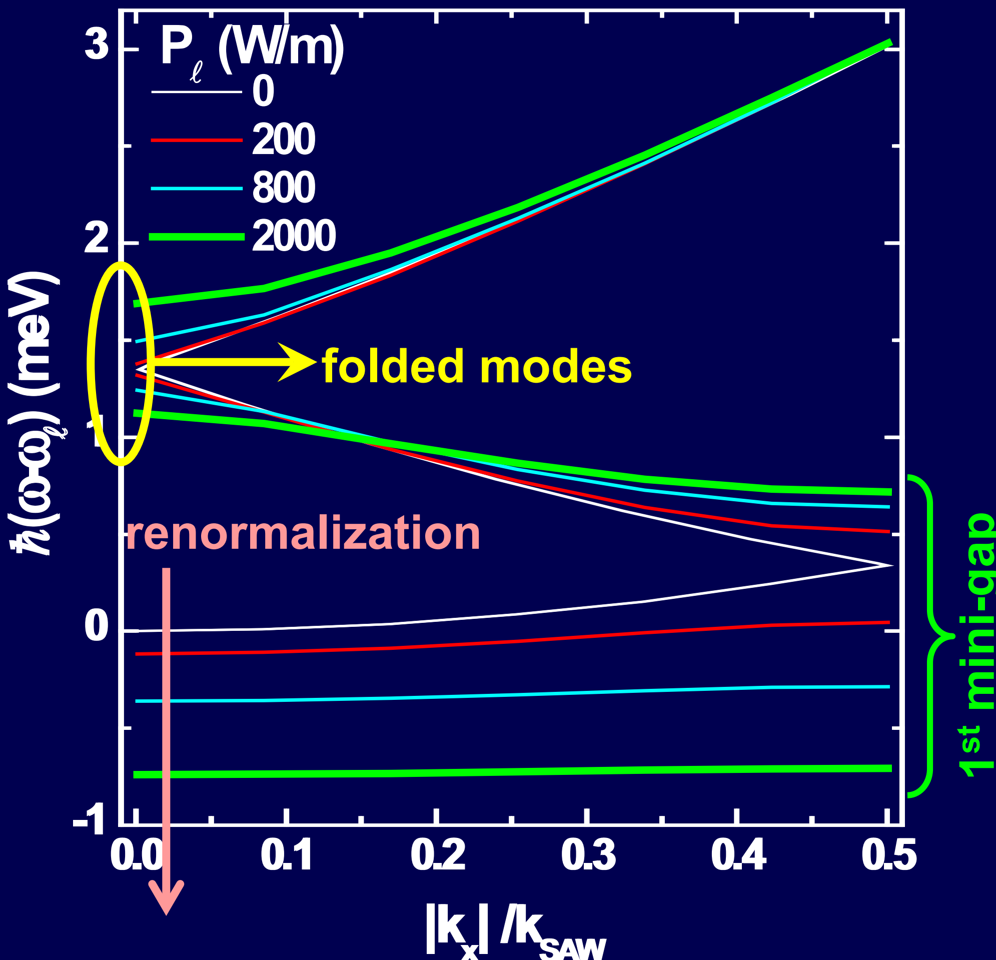
Optical Superlattice



$$\hbar\omega = \hbar\omega_\ell \{1+[k_x/(n_c k_\ell)]^2\}^{1/2}$$

- Reciprocal space

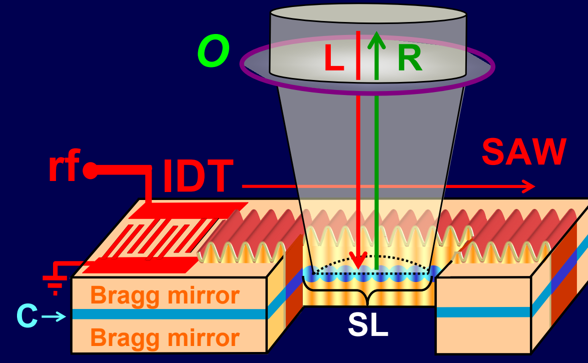


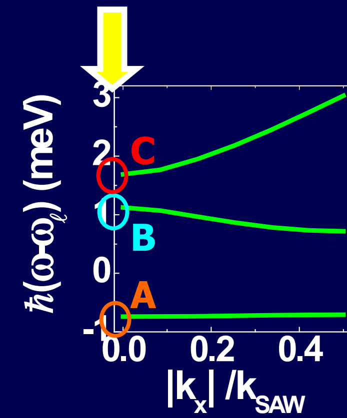


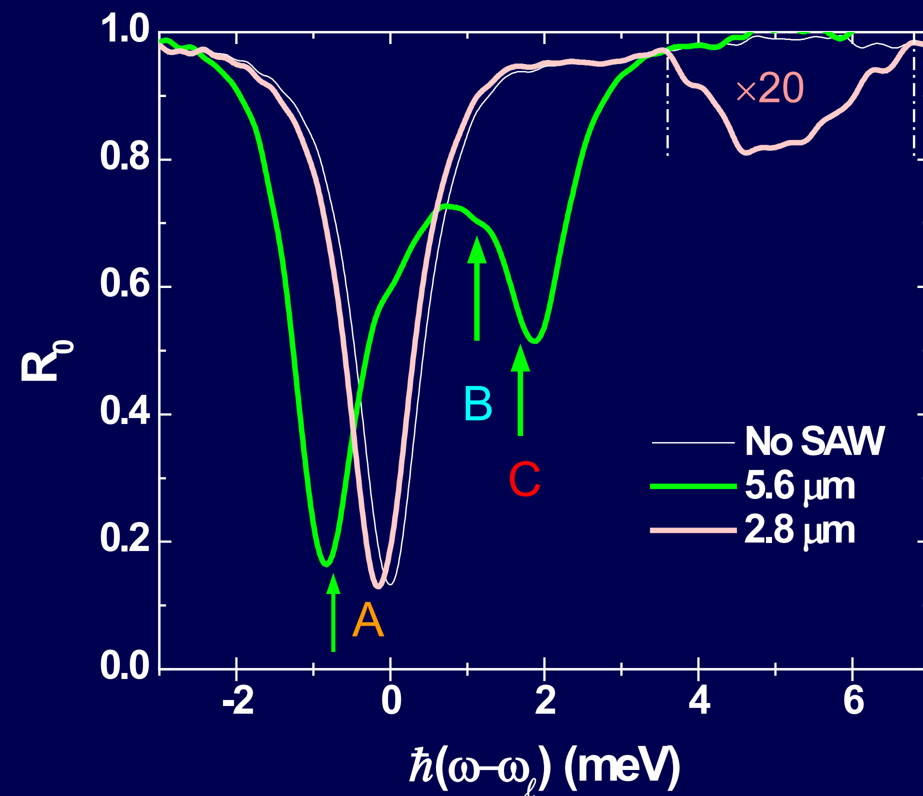
de Lima *et al.*, *Phys Rev. Lett* **94**, 126805 (2005).

Optical Superlattice

- Center of MBZ
  - Normal incidence
    - $K_x = 0$
  - k_{SAW} defines MBZ size

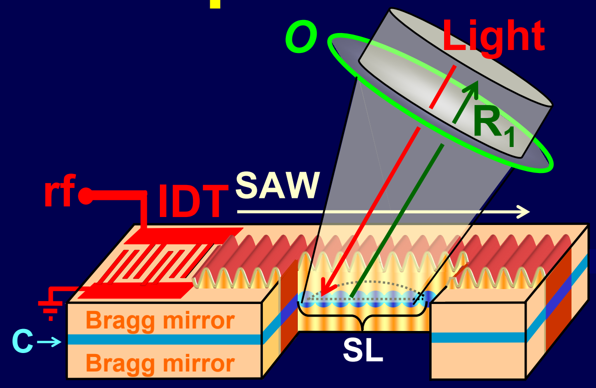


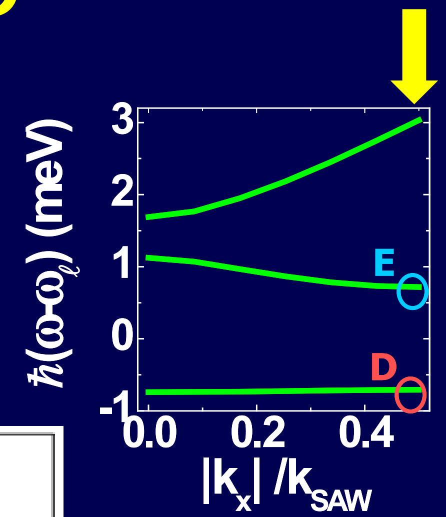


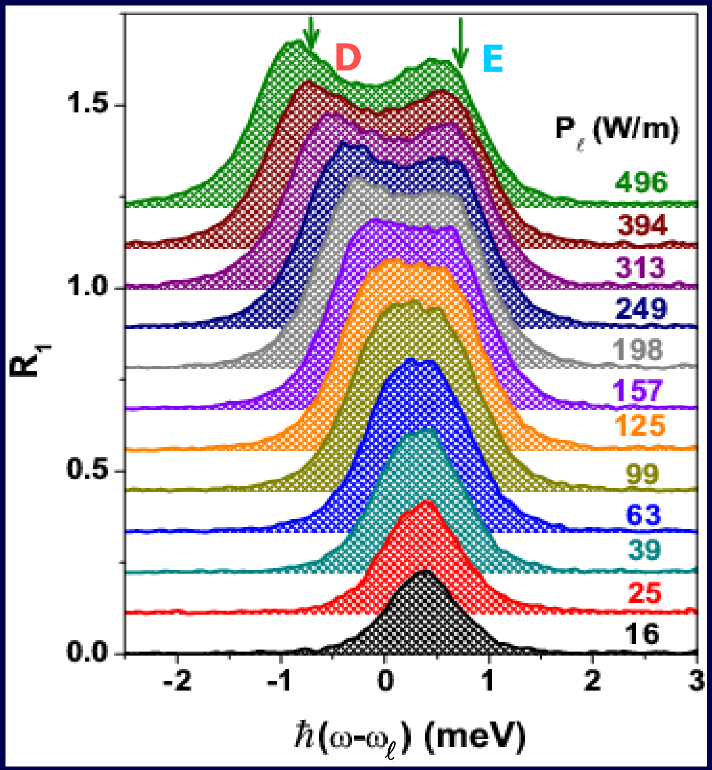


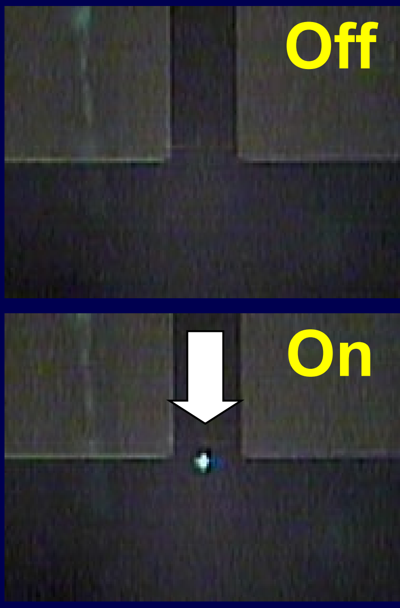
Optical Superlattice

- Edge of MBZ
  - Bragg angle
    $\theta_B = tan^{-1}(k_\ell/k_{SAW})$
  - Strong interaction
    - Phonon-dressed photons
  - High diffraction efficiency*
    - ~50%





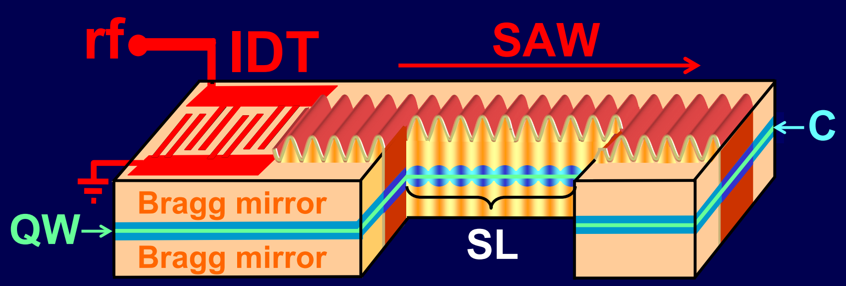


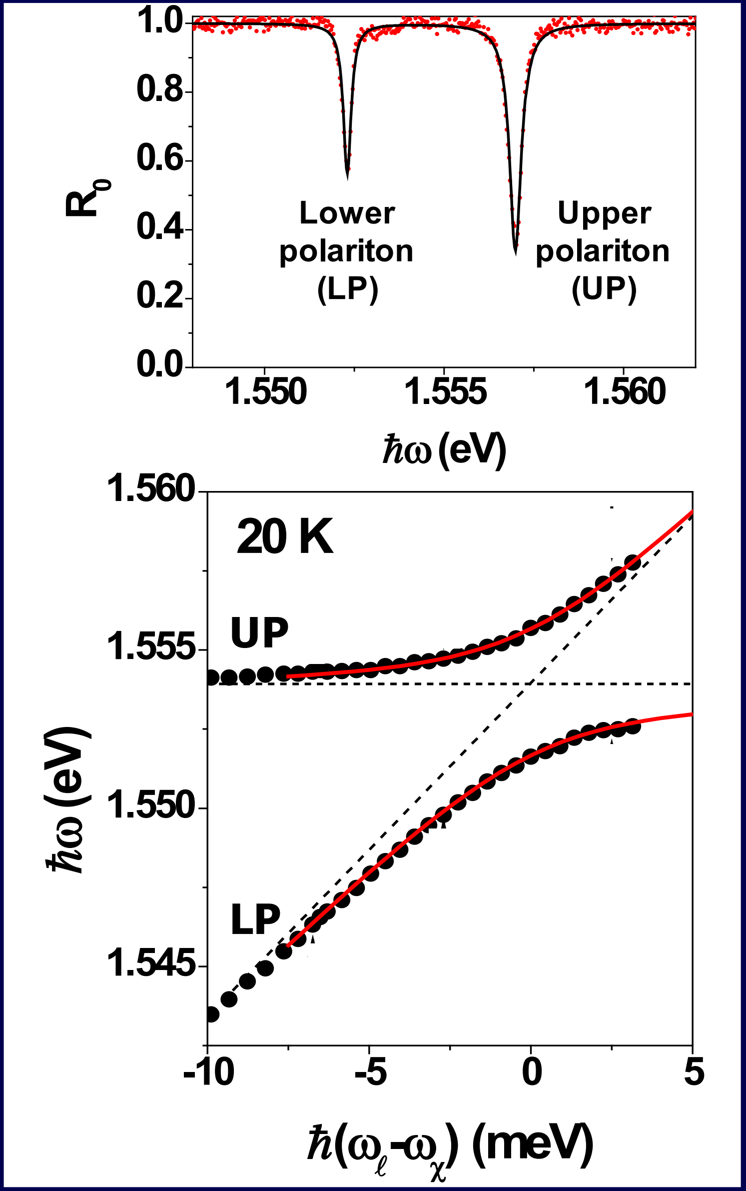


*de Lima *et al.*, *Appl Phys. Lett.* **83**, 2997 (2003).

SAW & Polaritons

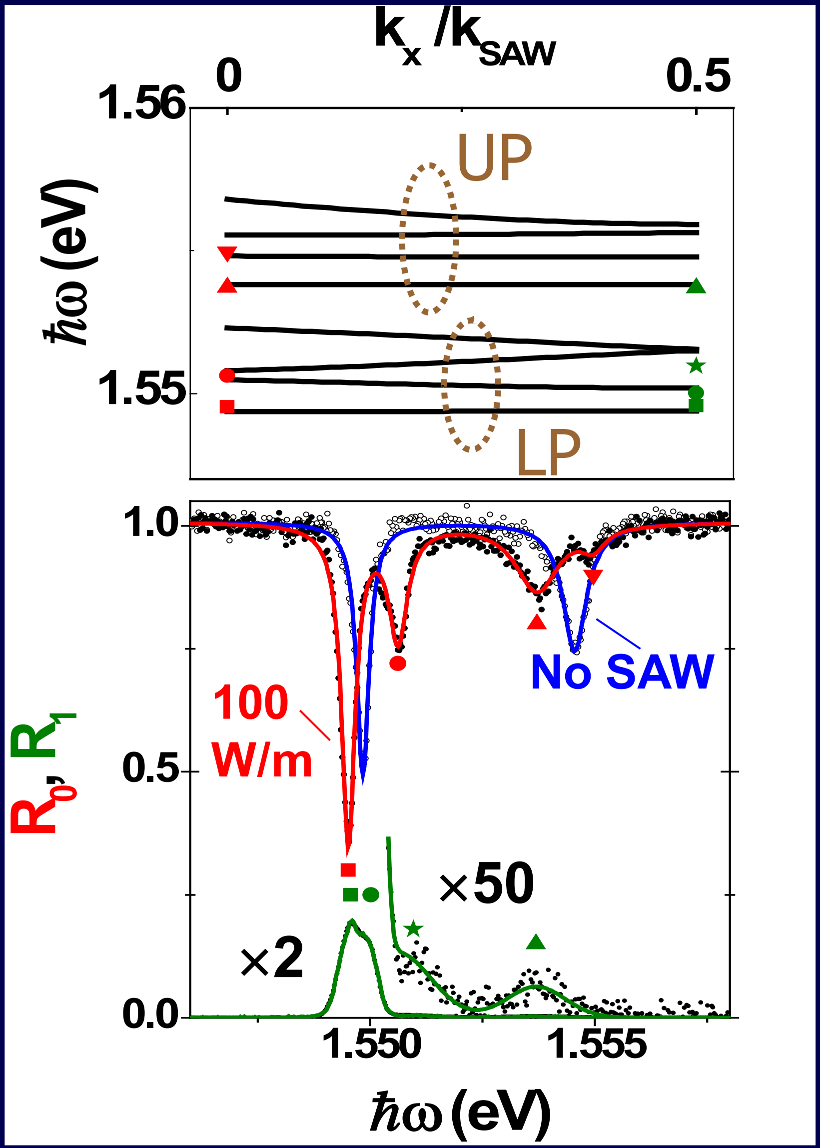
- 10-nm-GaAs quantum well (QW)
  $\hbar\omega_\chi = 1.5535$ eV
- Wedged cavity
  $\hbar\omega_\ell(x) = \pi c/[n_c d_c(x)]$
- Detuning (δ)
  $\delta(x) = \hbar[\omega_\ell - \omega_\chi(x)]$

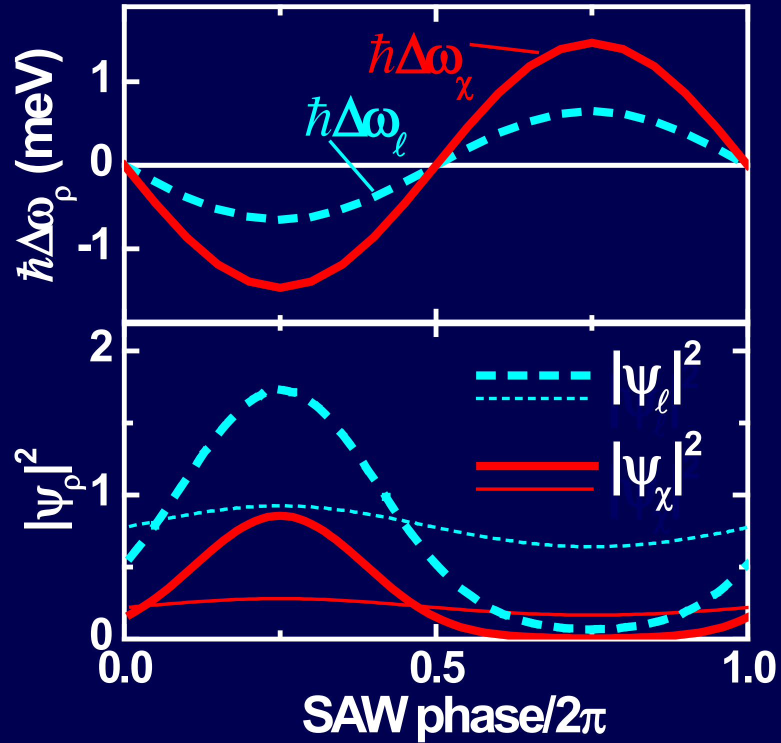




Proposed by Ivanov & littlewood, *Phys. Rev. Lett.* **87**, 136403 (2001).

Polariton superlattice





- $\hbar\Delta\omega_\chi = 2\times\hbar\Delta\omega_\ell$
- Phonon-dressed polaritons
- Transition from a superlattice to an array of weakly-coupled polariton wires
- Lead to many works on SAW modulation of polariton condensates

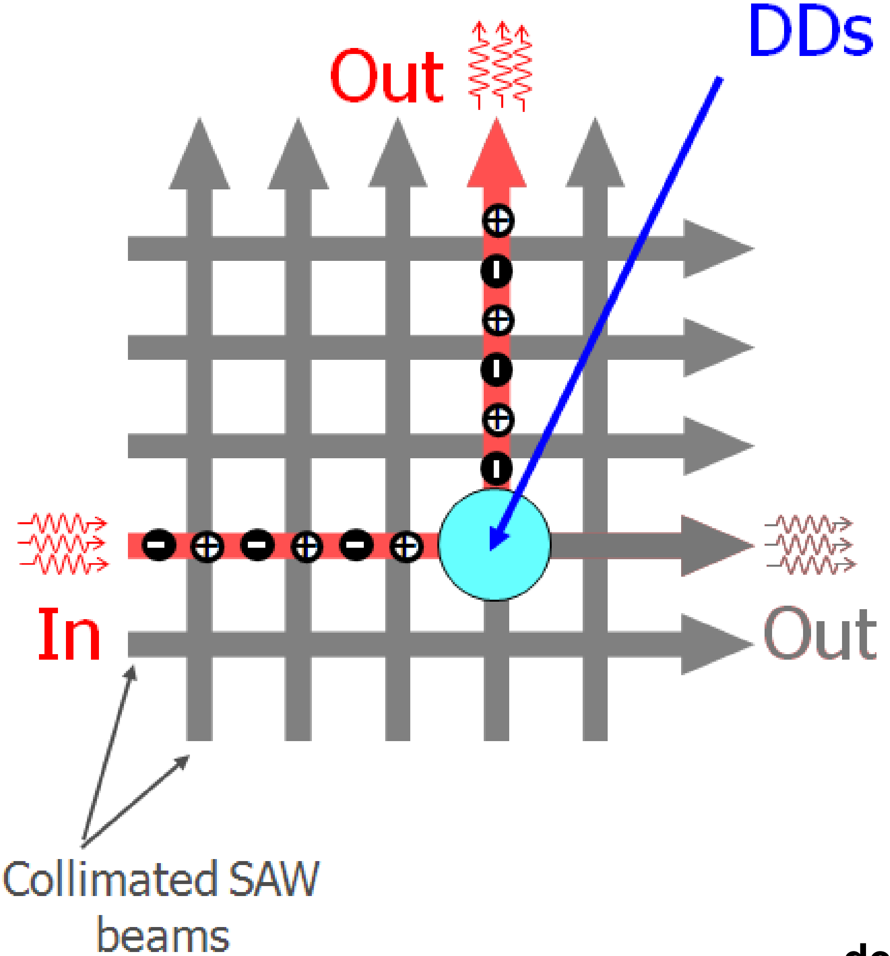
de Lima *et al*., *Phys. Rev. Lett*. **97**, 045501 (2006).

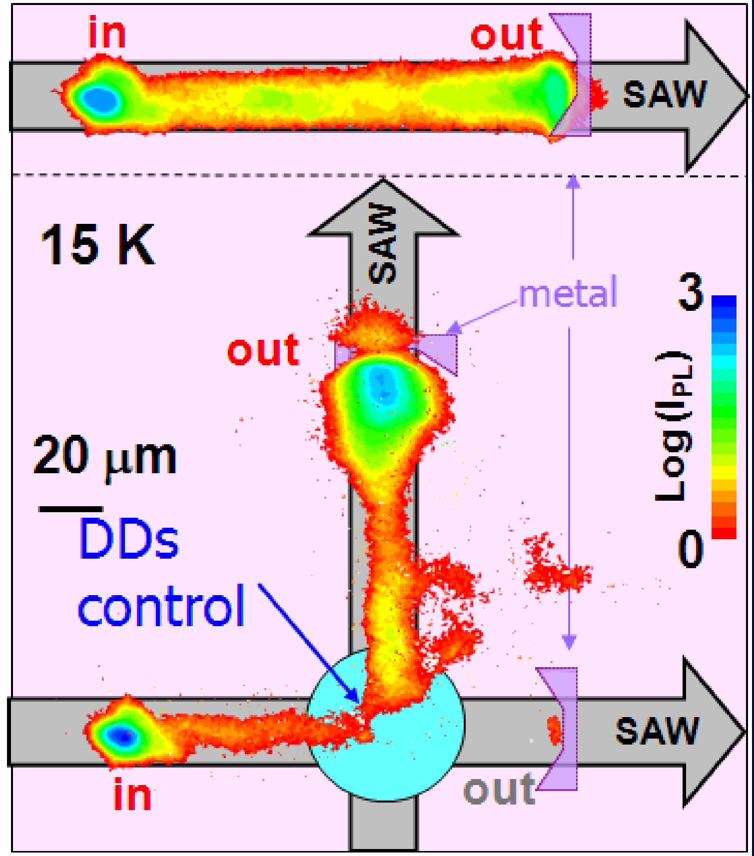
3. In-plane devices

In-Plane Concepts & Devices

SAW-Driven Ambipolar Transport in QWs

Alsina *et al.* Solid State Commun. **129**, 453 (2003).

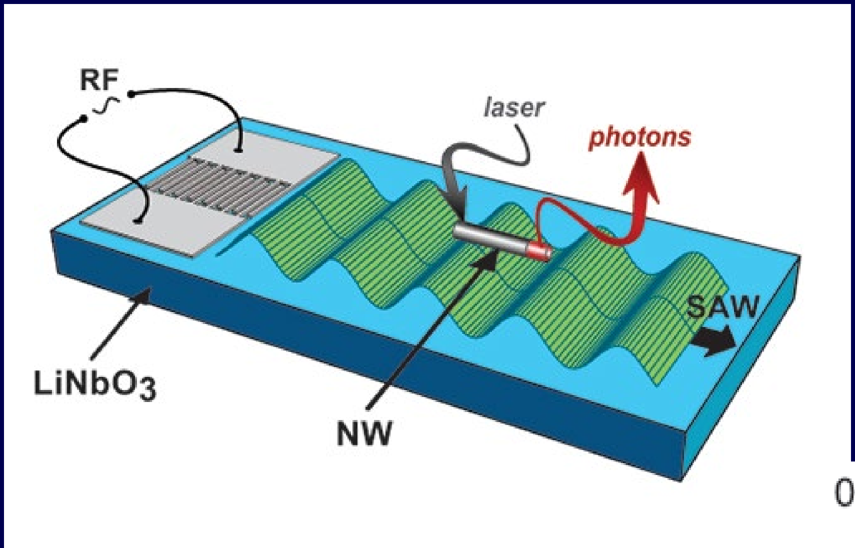


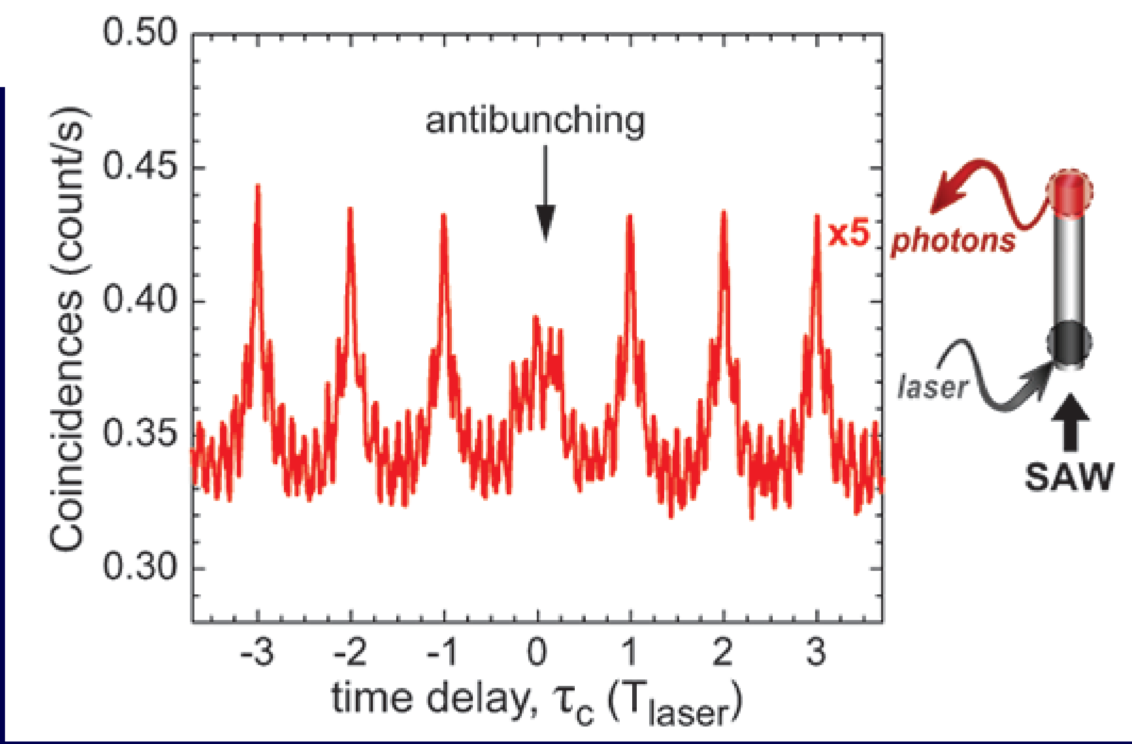


Also operates at RT!

de Lima *et al.* Appl. Phys. Lett 84, 2569 (2004).

SAW-driven single photon sources

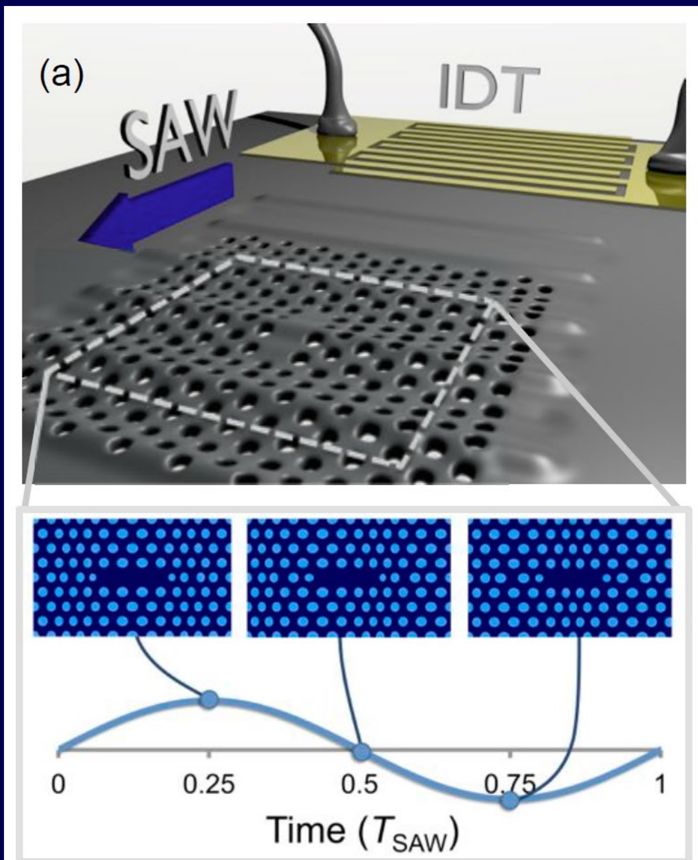




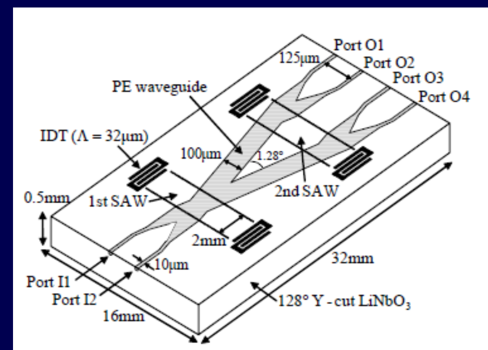
A. Hernández-Mínguez *et al.*, *Nanoletters* **12**, 252 (2012).

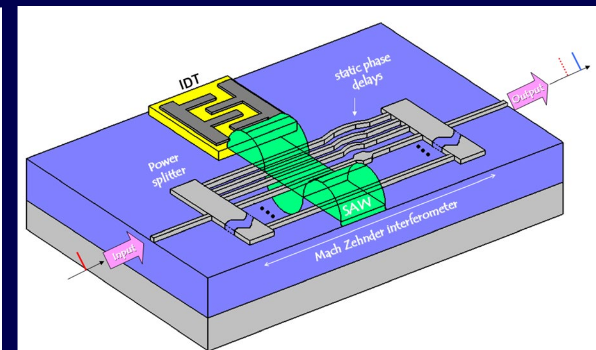
Novel approaches for SAW-driven acousto-optic devices

Photonic crystal cavity[1]

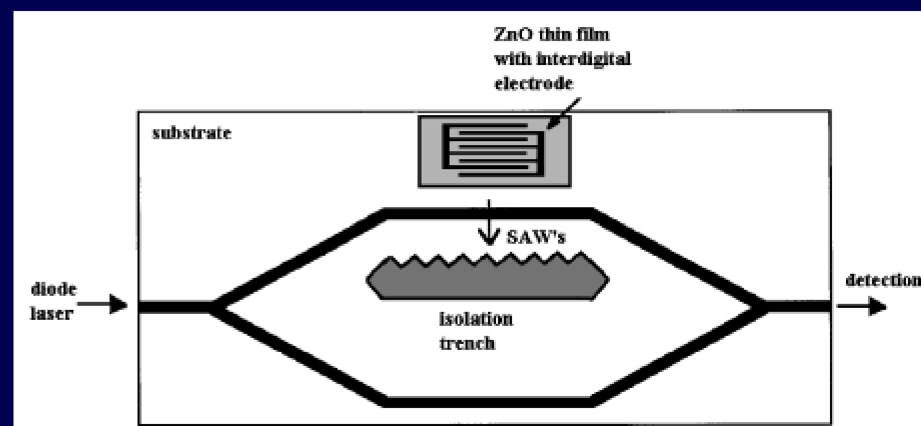


Frequency shifters[2]





Silicon Mach-Zehnder modulator[3]

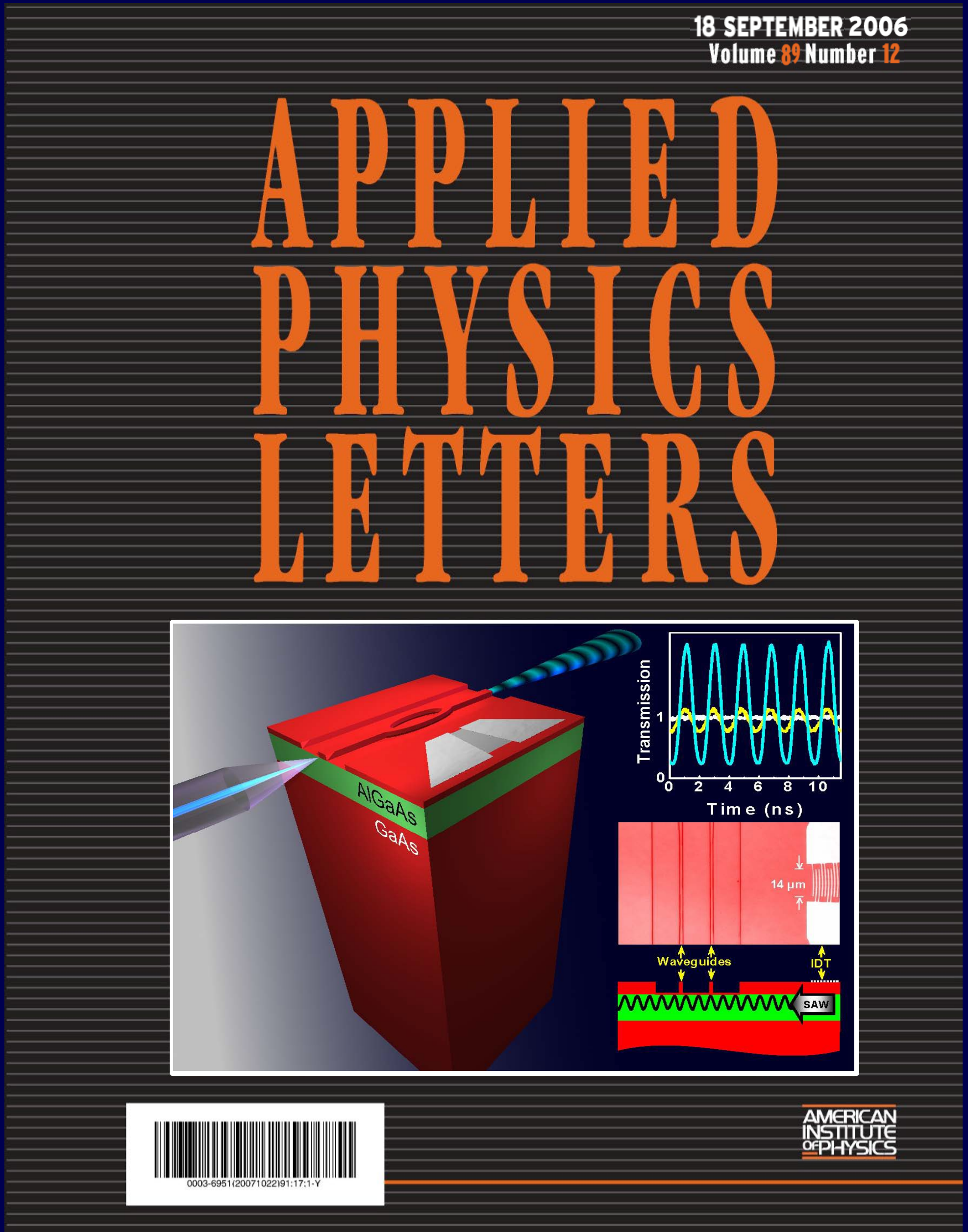


[1]Fuhrmann et al., Nat. Phot. 5, 605 (2011)

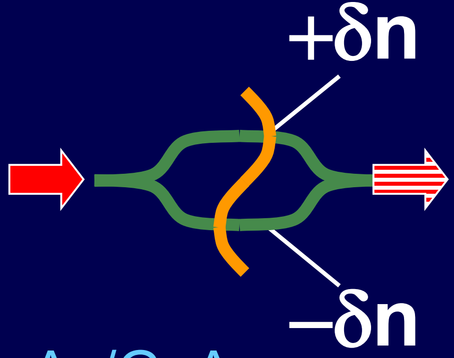
[2]Kakio et al., *JJAP* **46**, 4608 (2007); Barreto and Hvam, *Proc. SPIE* ***7719****, 771920 (2010).*

[3]Gorecki et al., Opt. Lett. **22**, 1784 (1997).

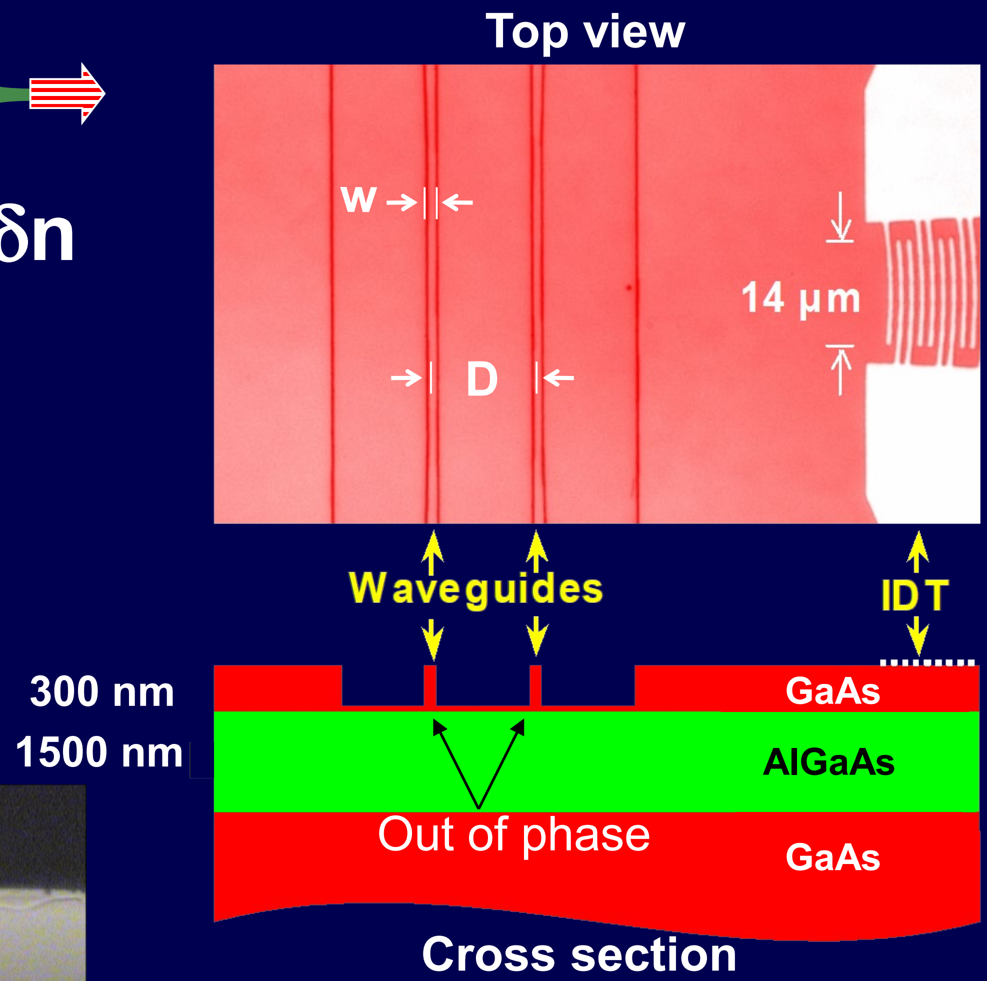
Ultra Compact In-Plane Modulators



Taking advantage of the phase coherence

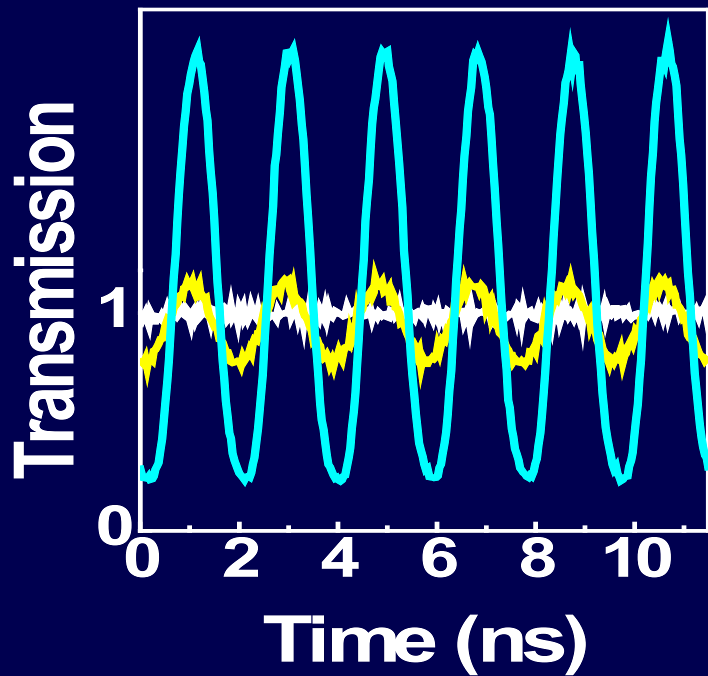


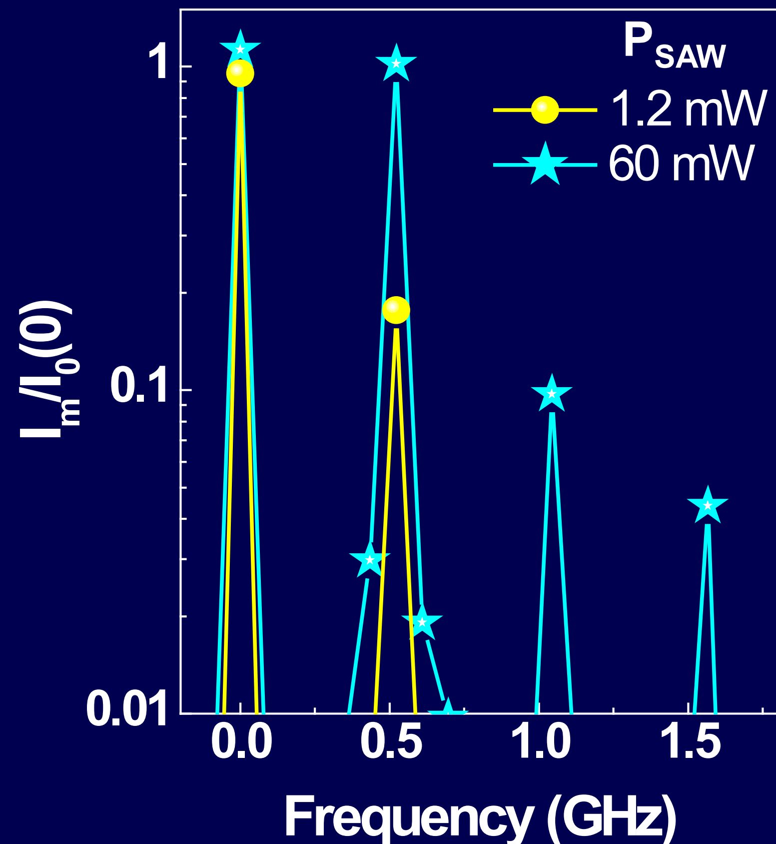
- Fabrication
  - MBE sample
  - $GaAs/Al_{0.2}Ga_{0.8}As/GaAs$
- Processing
  - Photolithography
  - Plasma etching of WGs
  - Metallization of IDTs
- $D = 2.5\lambda_{SAW}$
- $w = \lambda_{SAW}/4$



de Lima *et al.*, *Appl. Phys. Lett.* **89**, 121104 (2006).

Ultra-Compact Modulator

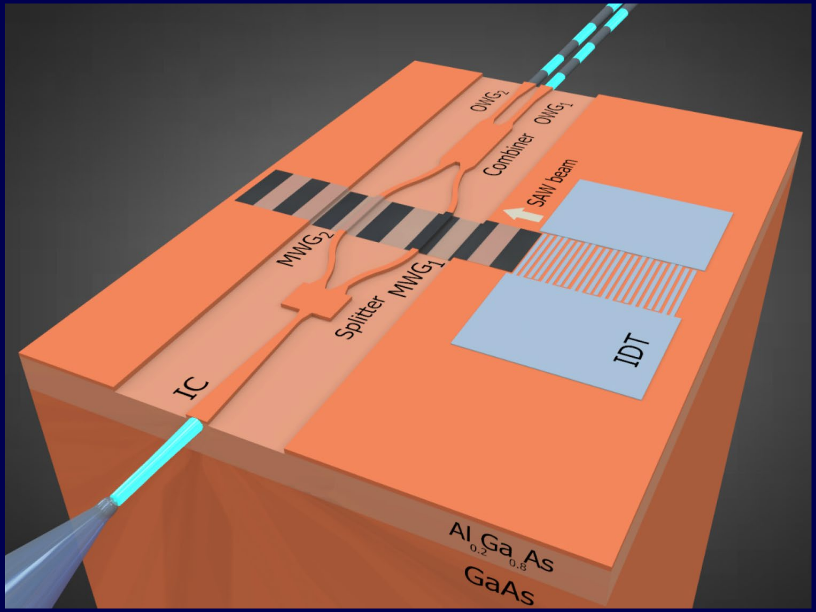


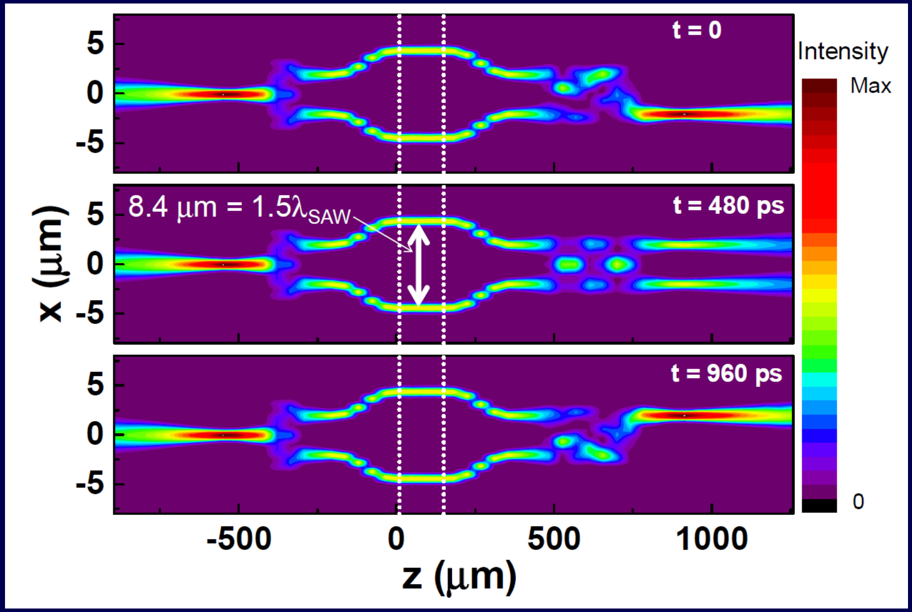


- 15 µm active region
- GHz operation
- Close to 100% modulation
- Presence of higher harmonics

Two-port modulators

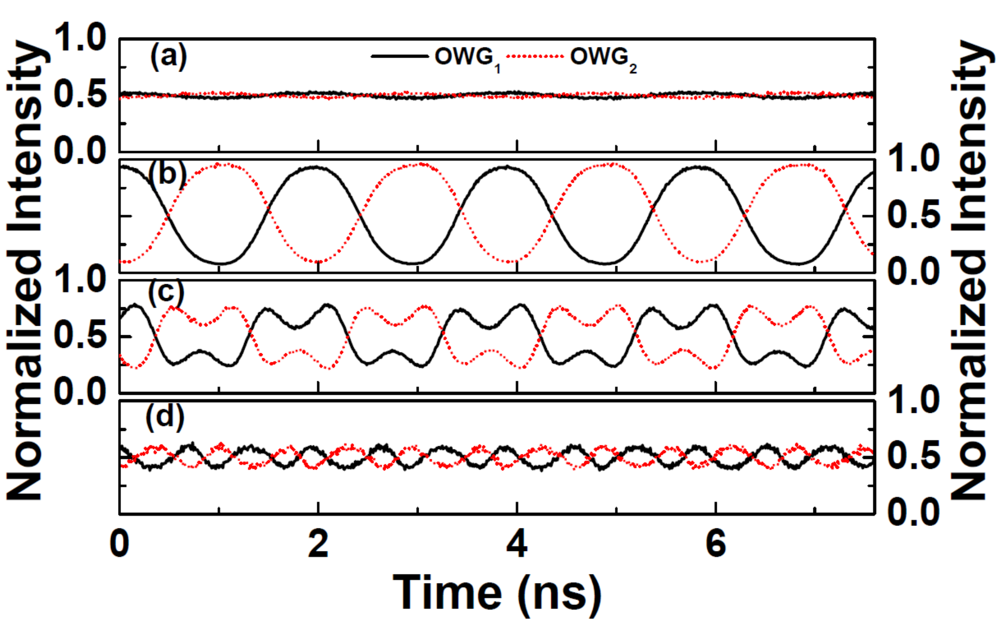
- Simulation using beam propagation method
  - Cosine-bends for setting WG positions
- Light lossless configuration





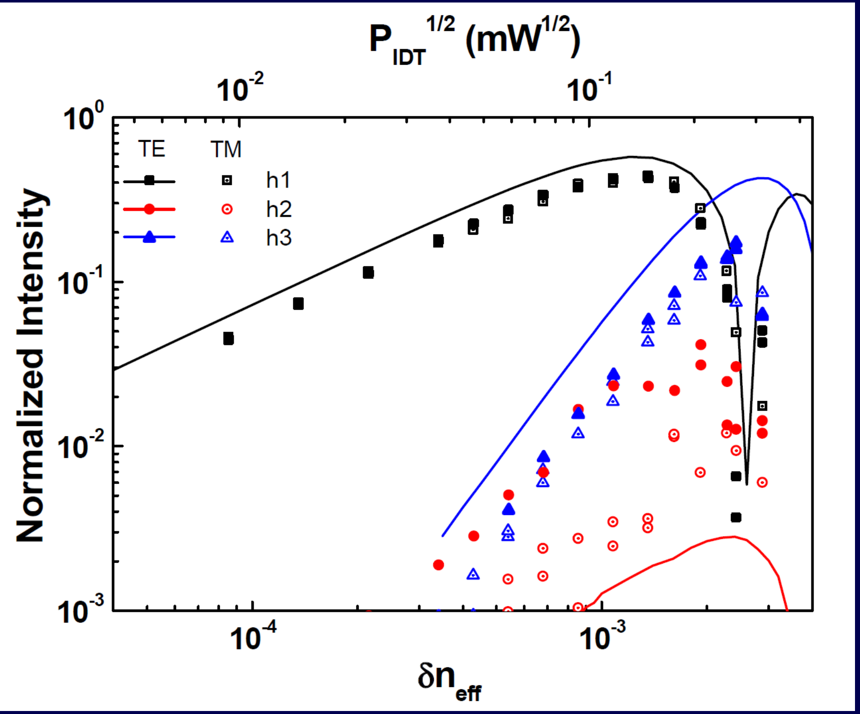
Crespo-Poveda *et al.*, *Optics Exp*. 21, 21669 (2013).

Two-port modulators

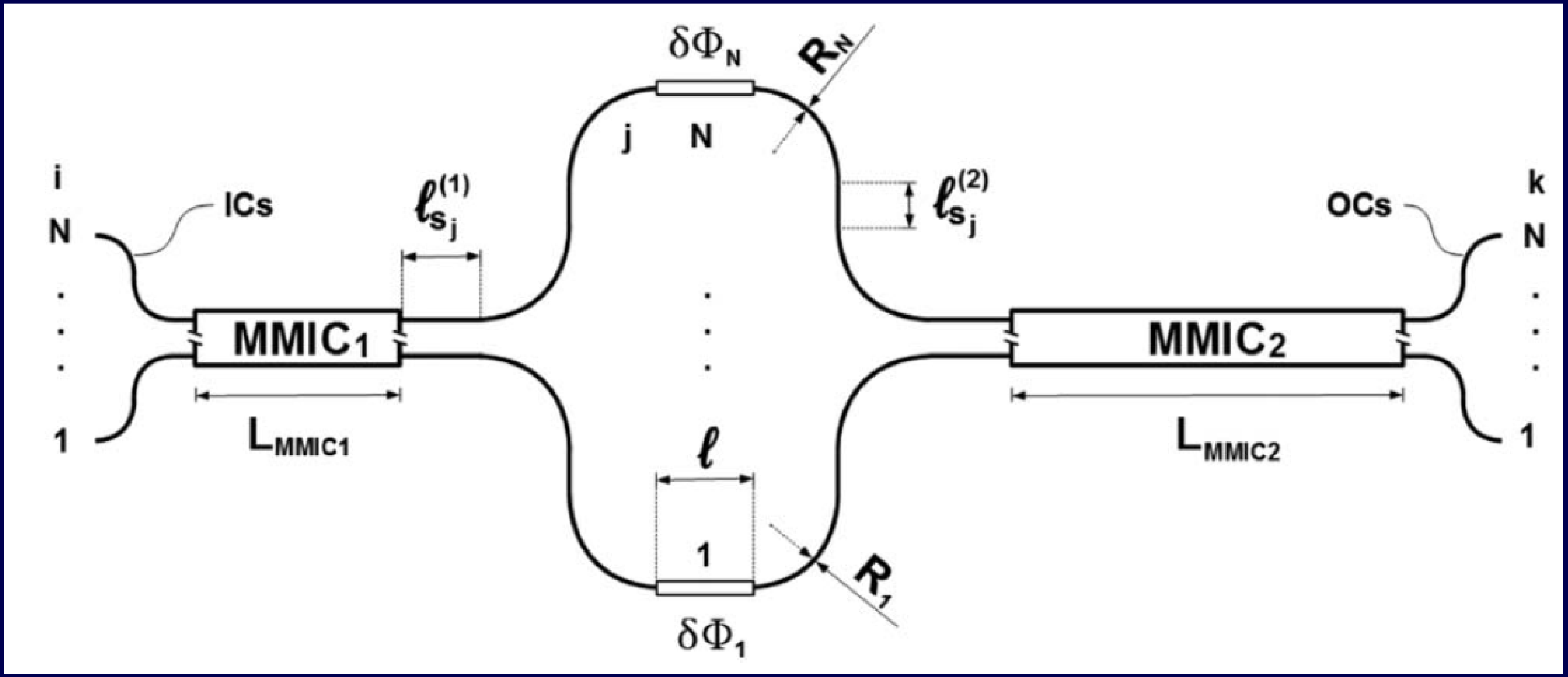


- Amplitude modulation ~1
- π-phase difference between the output WGs
- Higher harmonic operation
  - Controlled by SAW power

- Good agreement with simulations
- Measurements of higher harmonics dumped by detector time resolution (~300 ps)



N×N modulators

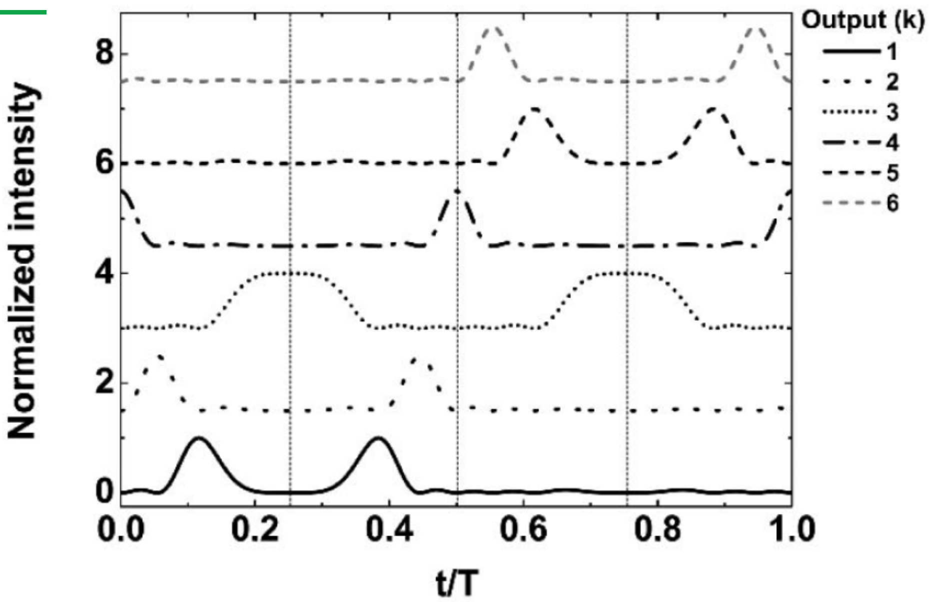


Crespo-Poveda *et al., J. of the Optical Society of America B* **33**, 81 (2016).

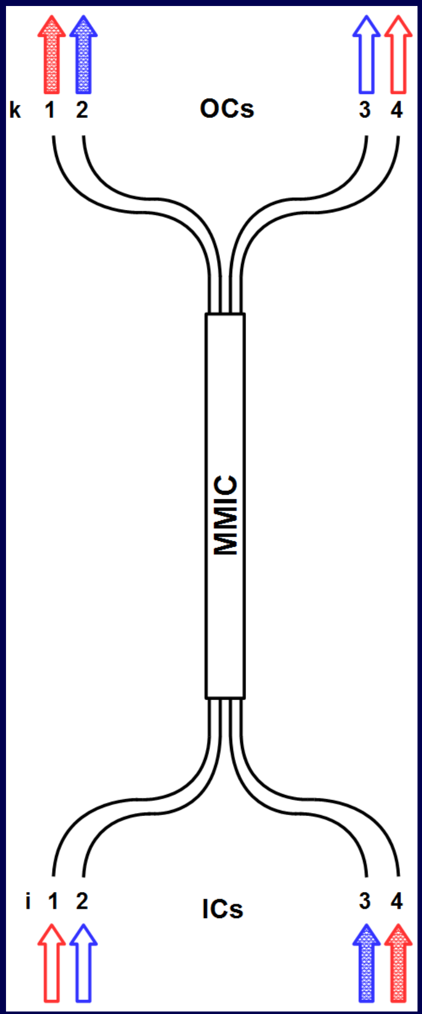
N×N modulators

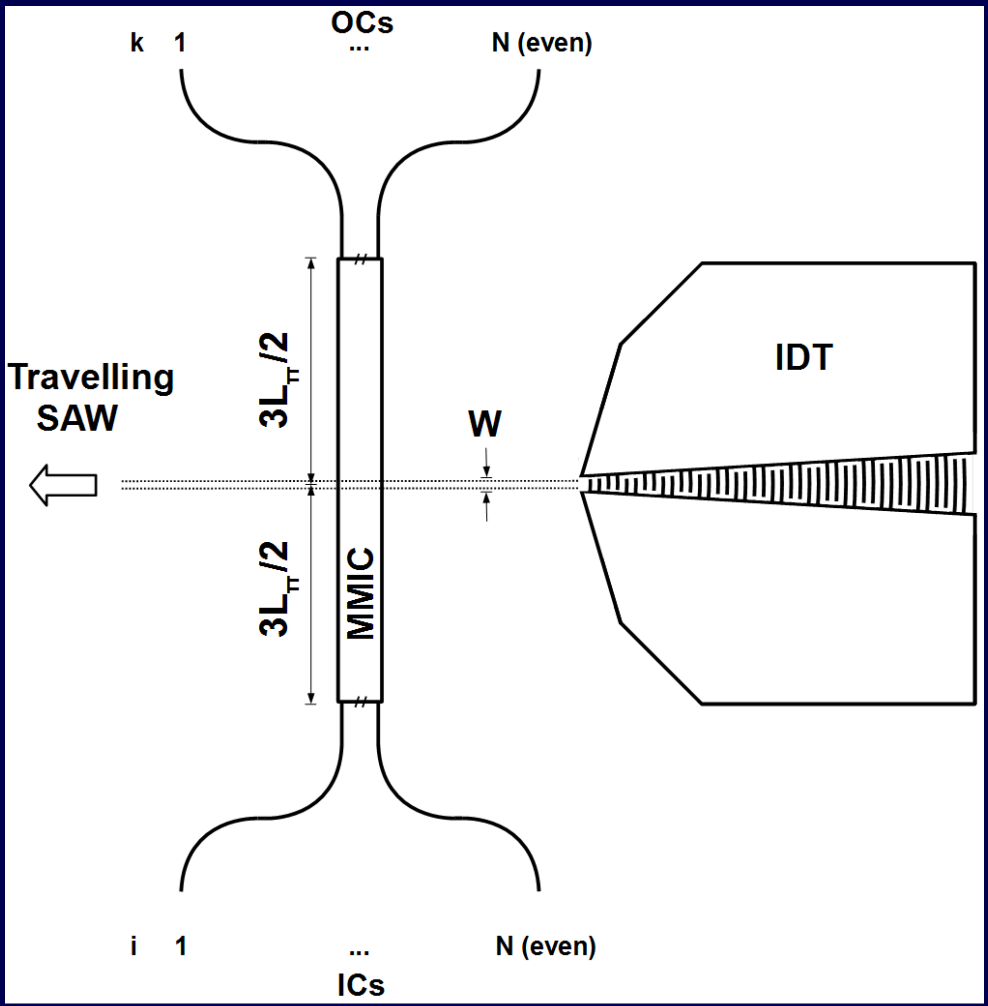
Table 3. Calculated Array Arm Factors $\langle\kappa_j\rangle$ for a 5 × 5 Device

Solutions	Arm Weight Factor (κ_j)				
	κ_1	κ_2	κ_3	κ_4	κ_5
S_1'	0	−1/2	1/2	−1	1
S_2'	1/2	0	1	−1/2	−1
S_3'	−1/2	−1	0	1	1/2
S_4'	1	1/2	−1	0	−1/2
S_5'	−1	1	−1/2	1/2	0
S_1''	0	−1	1	1/2	−1/2
S_2''	1	0	−1/2	−1	1/2
S_3''	−1	1/2	0	−1/2	1
S_4''	−1/2	1	1/2	0	−1
S_5''	1/2	−1/2	−1	1	0



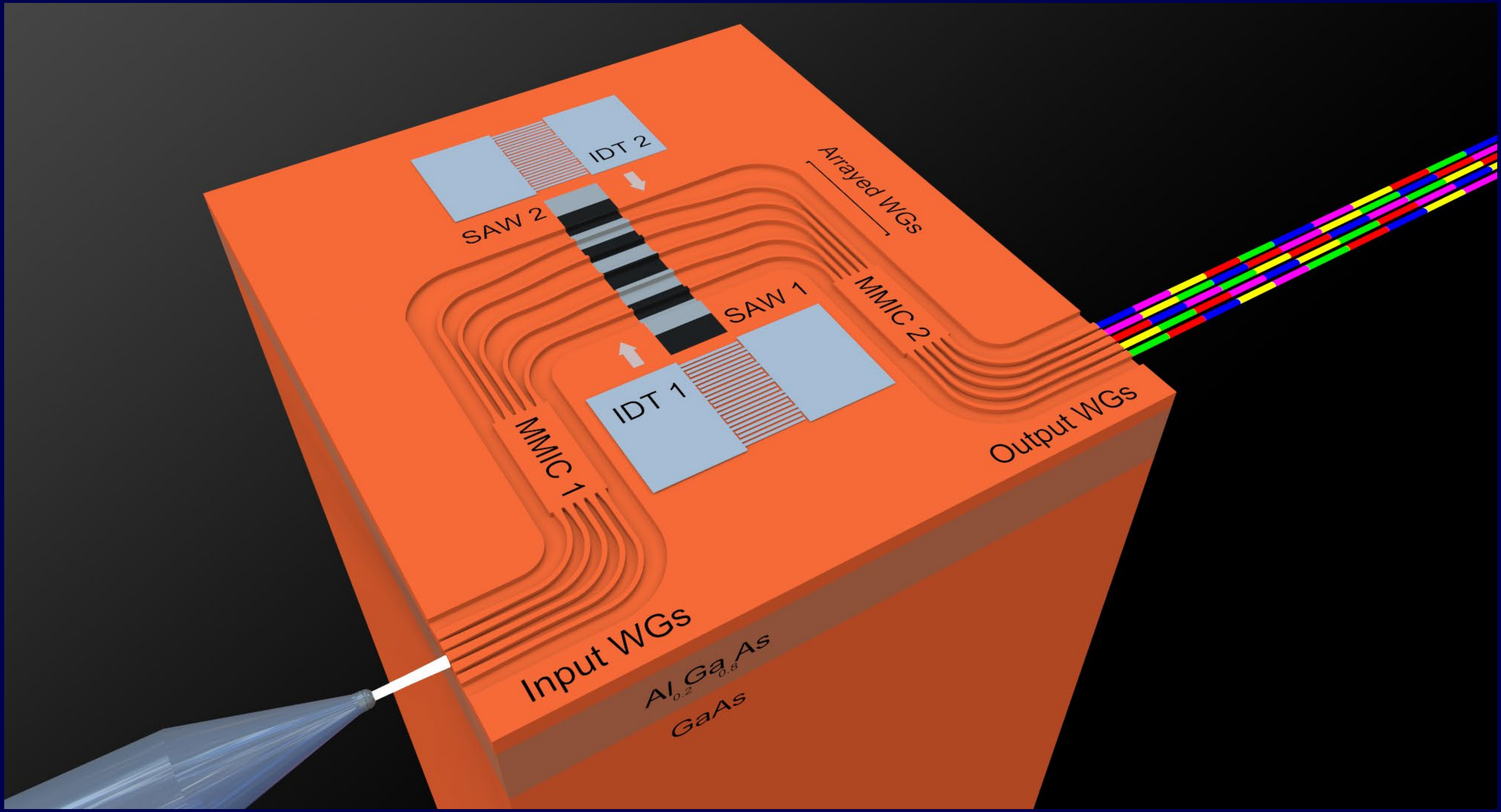
Ultra-compact MMI modulators





A. Crespo-Poveda *et al.,J. Phys. D: Appl. Phys.* **52** 253001 (2019).

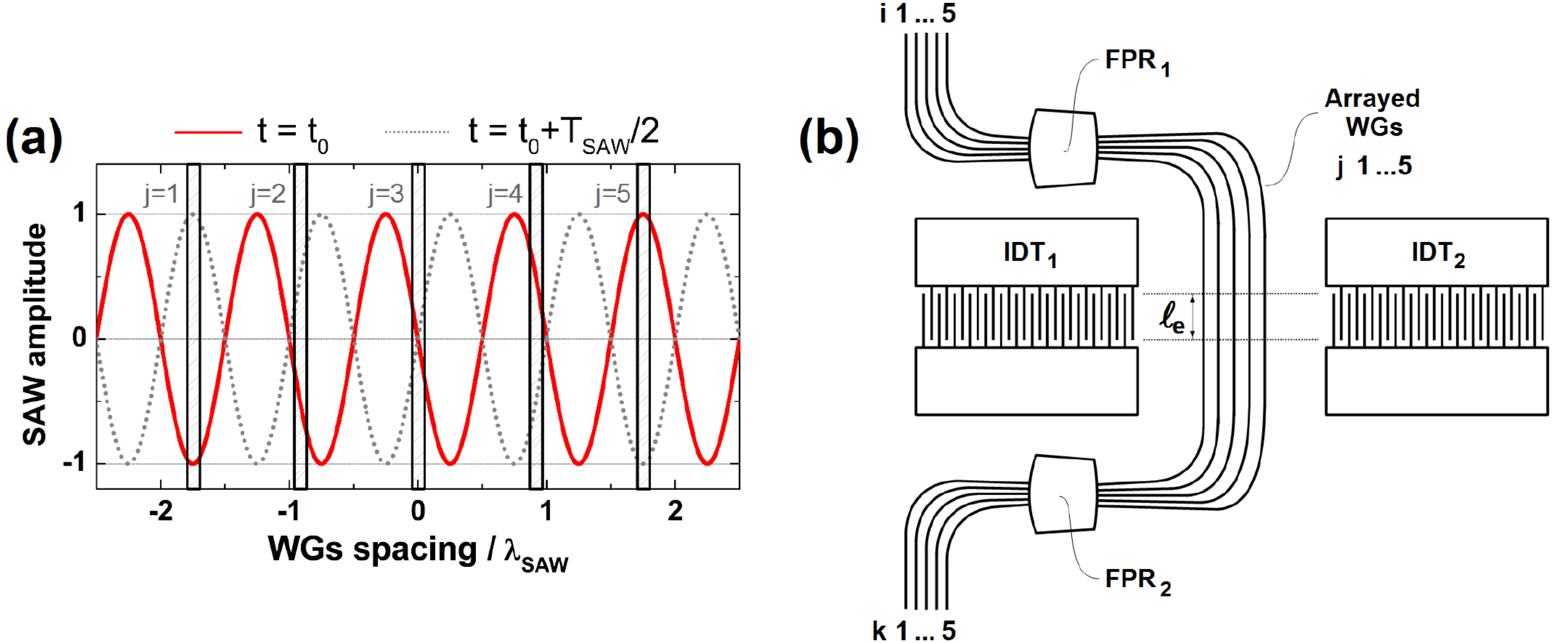
SAW-driven tunable AWGs



Patent application WO 2012/152977 A1

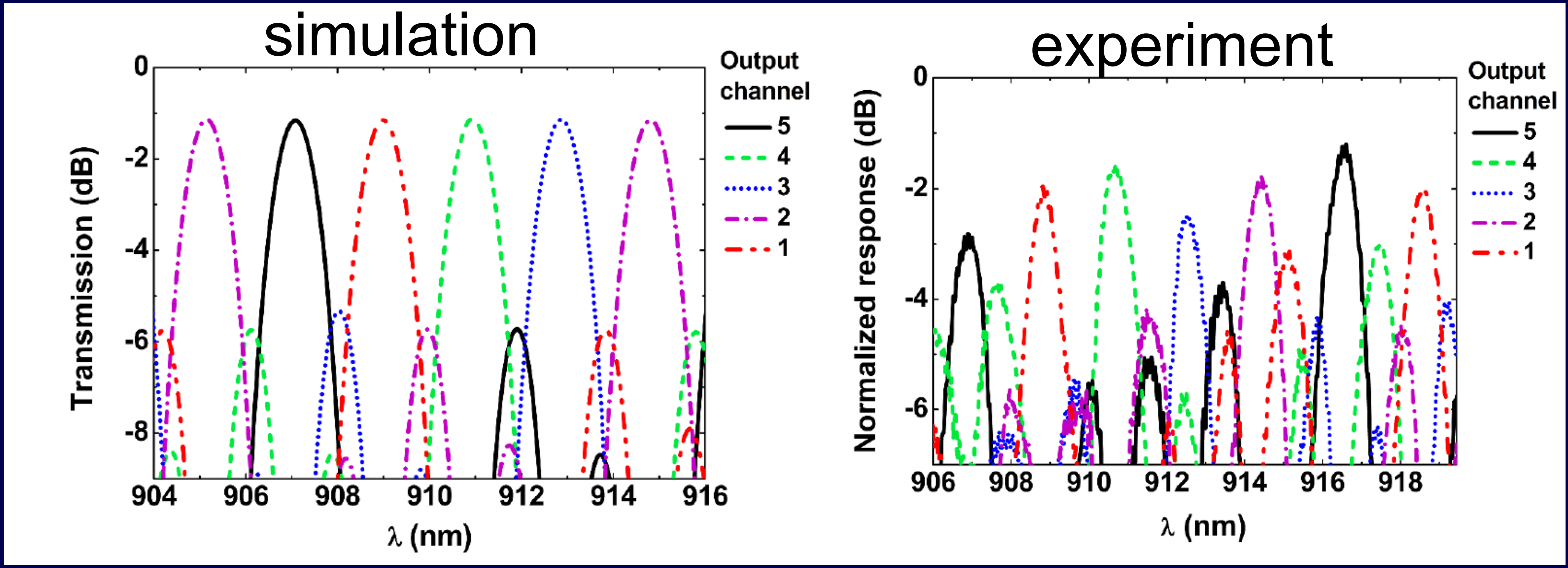
Optics Express **23**, 21213 (2015).

Placing the WGs: a key point in the design concept

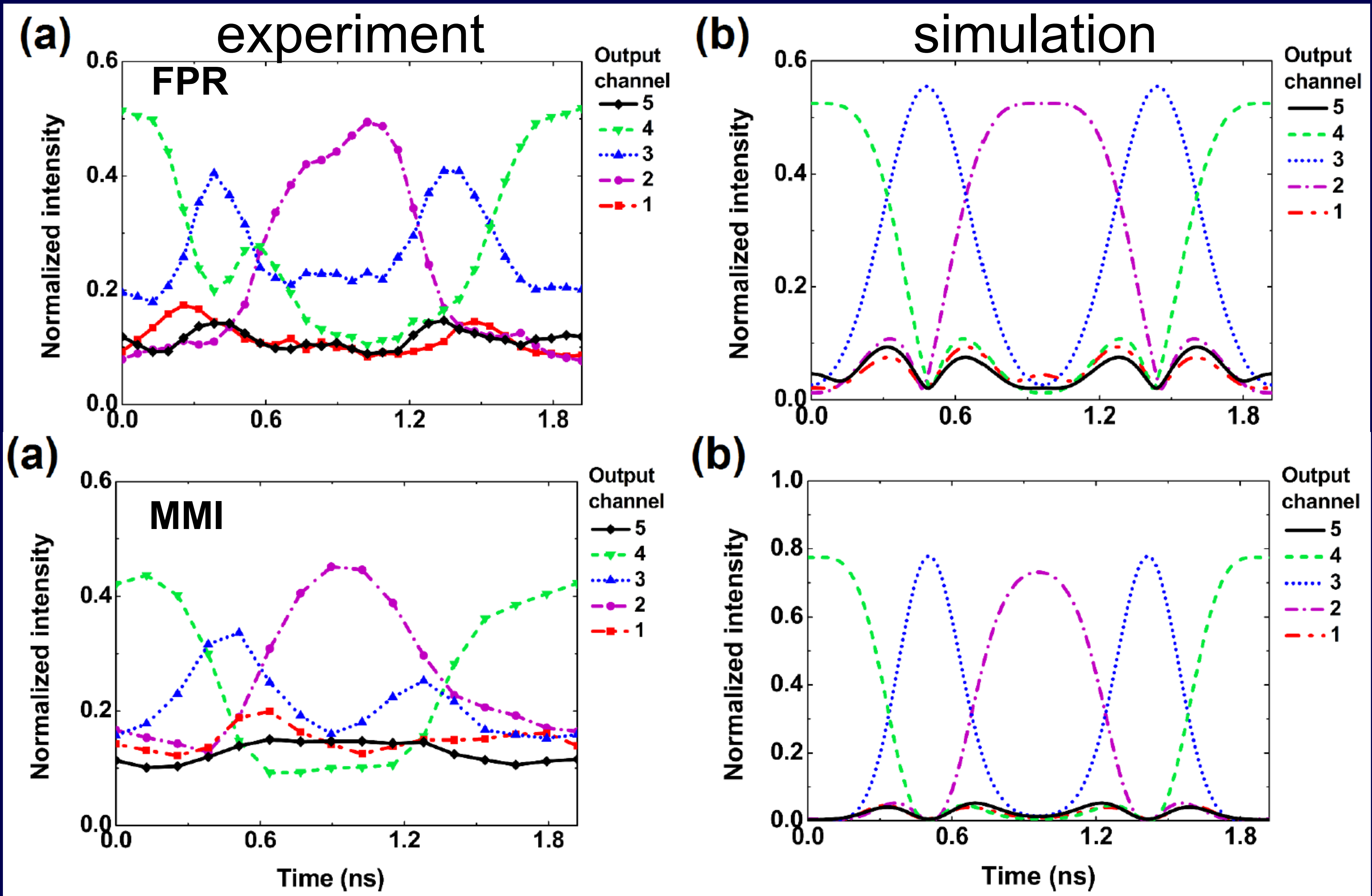


Results

- Preset response

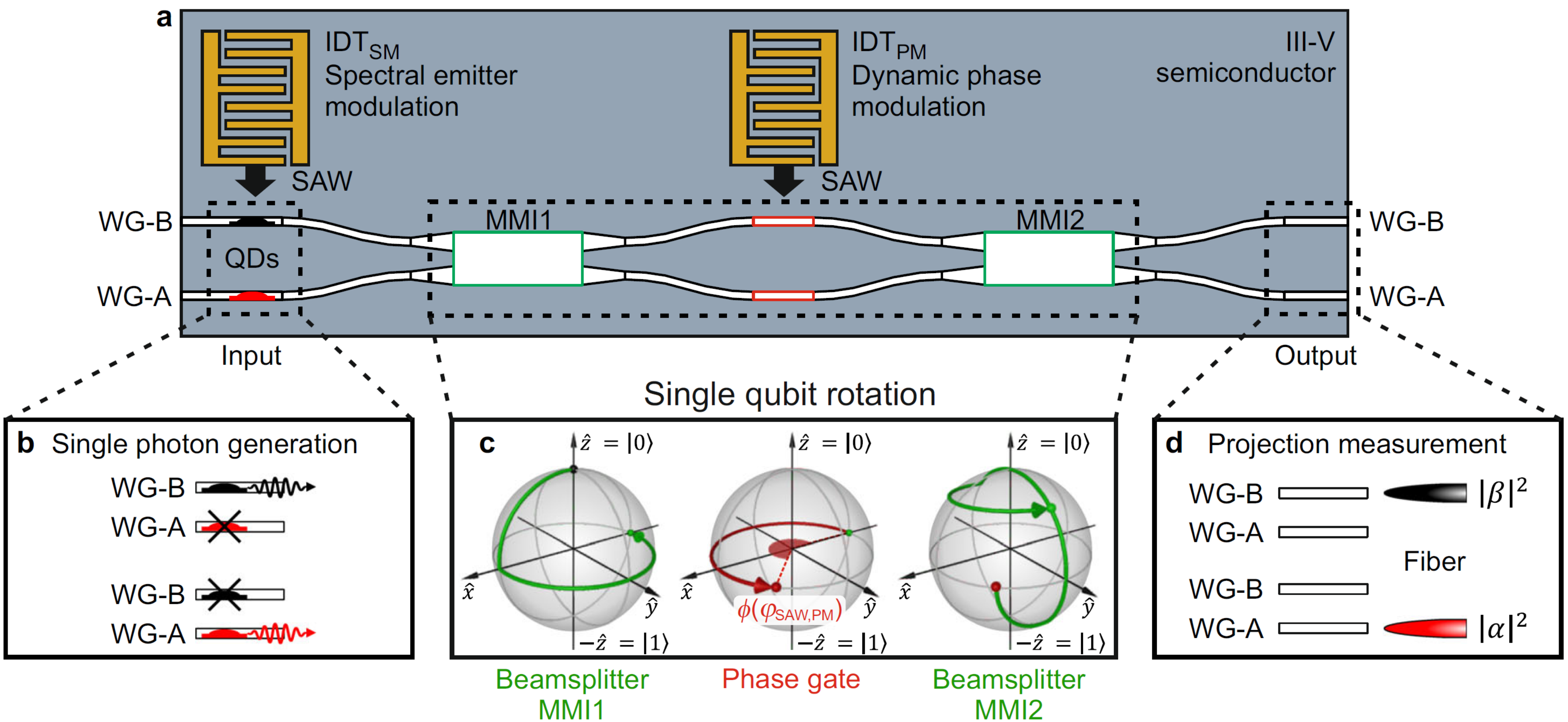


Results



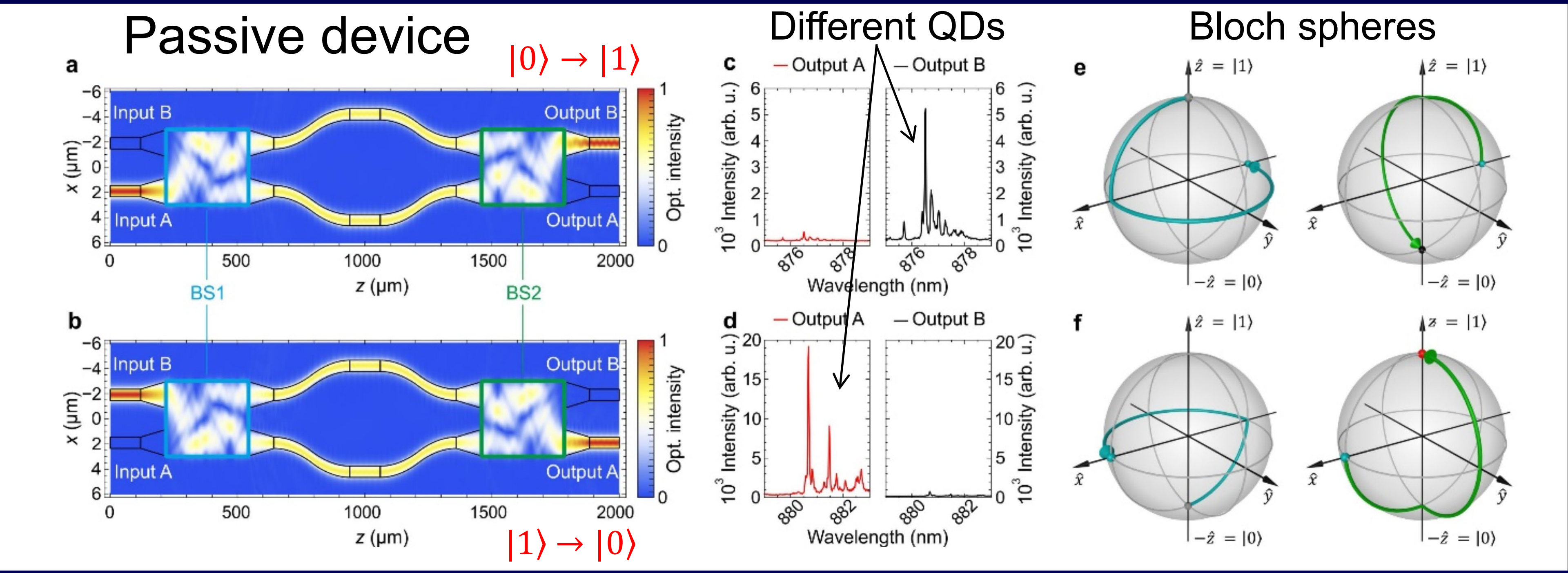
(a)
experiment
FPR
Output channel
5
4
3
2
1
Normalized intensity
0.0
0.2
0.4
0.6
0.6
1.2
1.8
(b)
simulation
Output channel
5
4
3
2
1
Normalized intensity
(a)
MMI
Output channel
Time (ns)
(b)
Output channel
1.0
0.8
Time (ns)

Rotating photonic Q-bits with SAWs



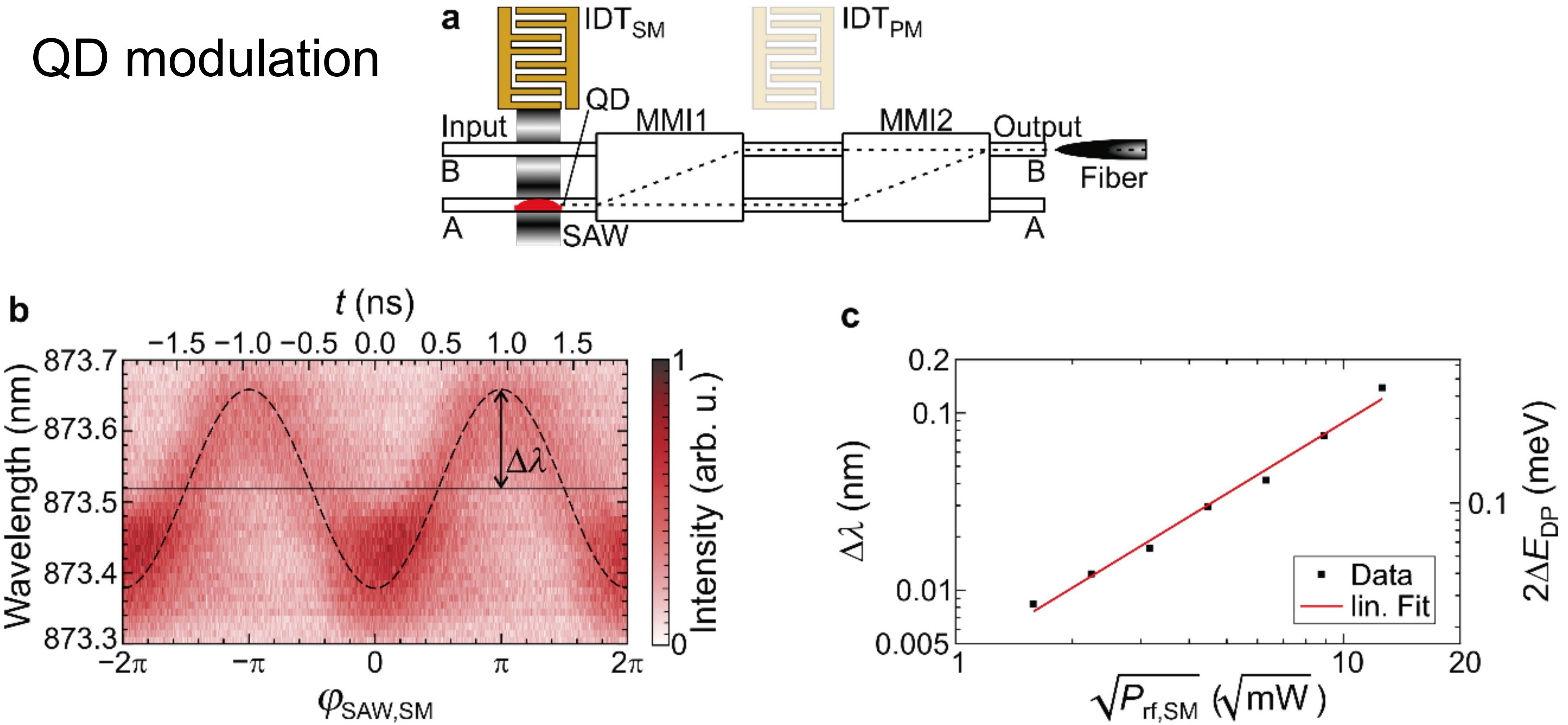
Bühler *et al.*, Nature Communications **13**, 6998 (2022).

Rotating photonic Q-bits with SAWs

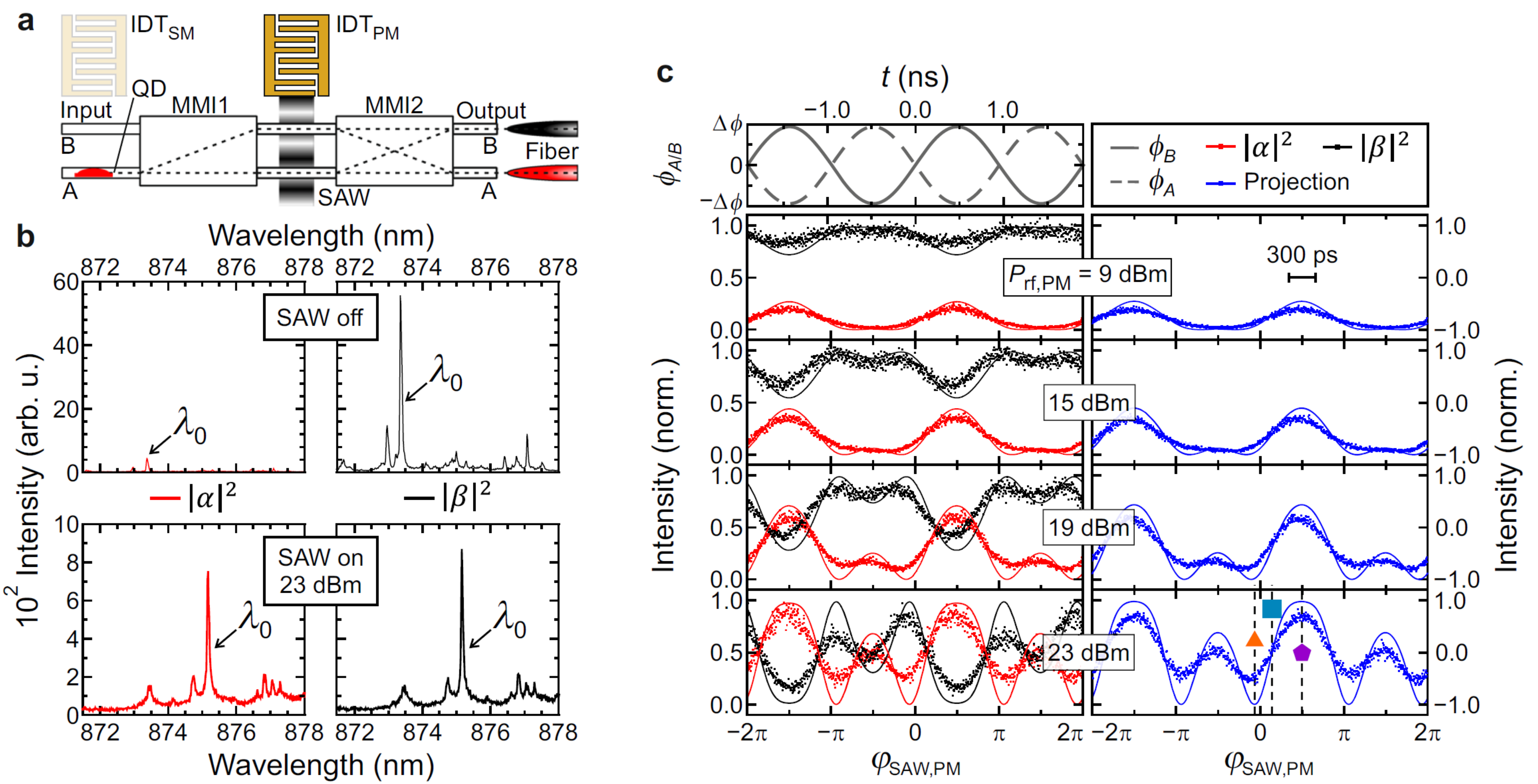


Rotating photonic Q-bits with SAWs

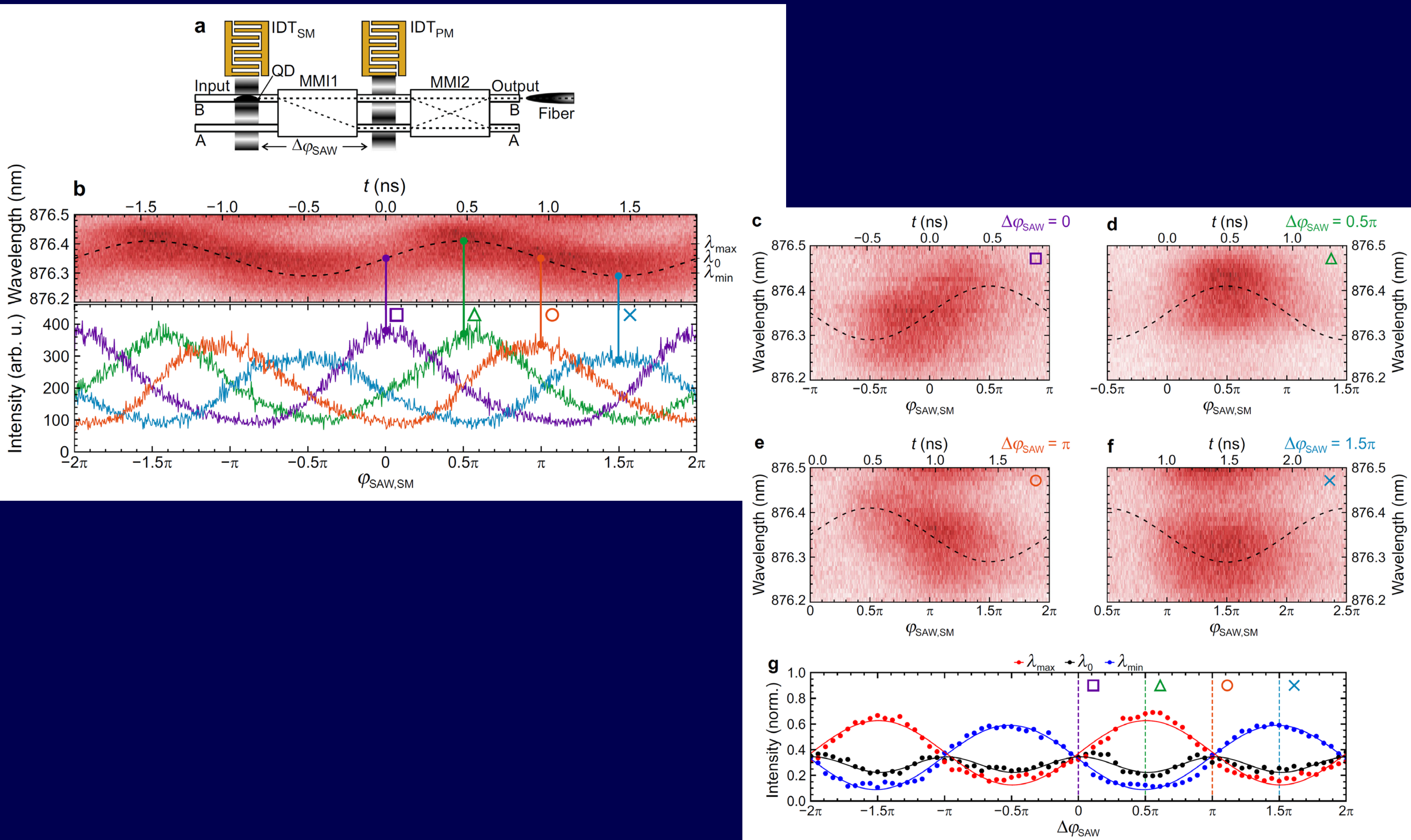
QD modulation



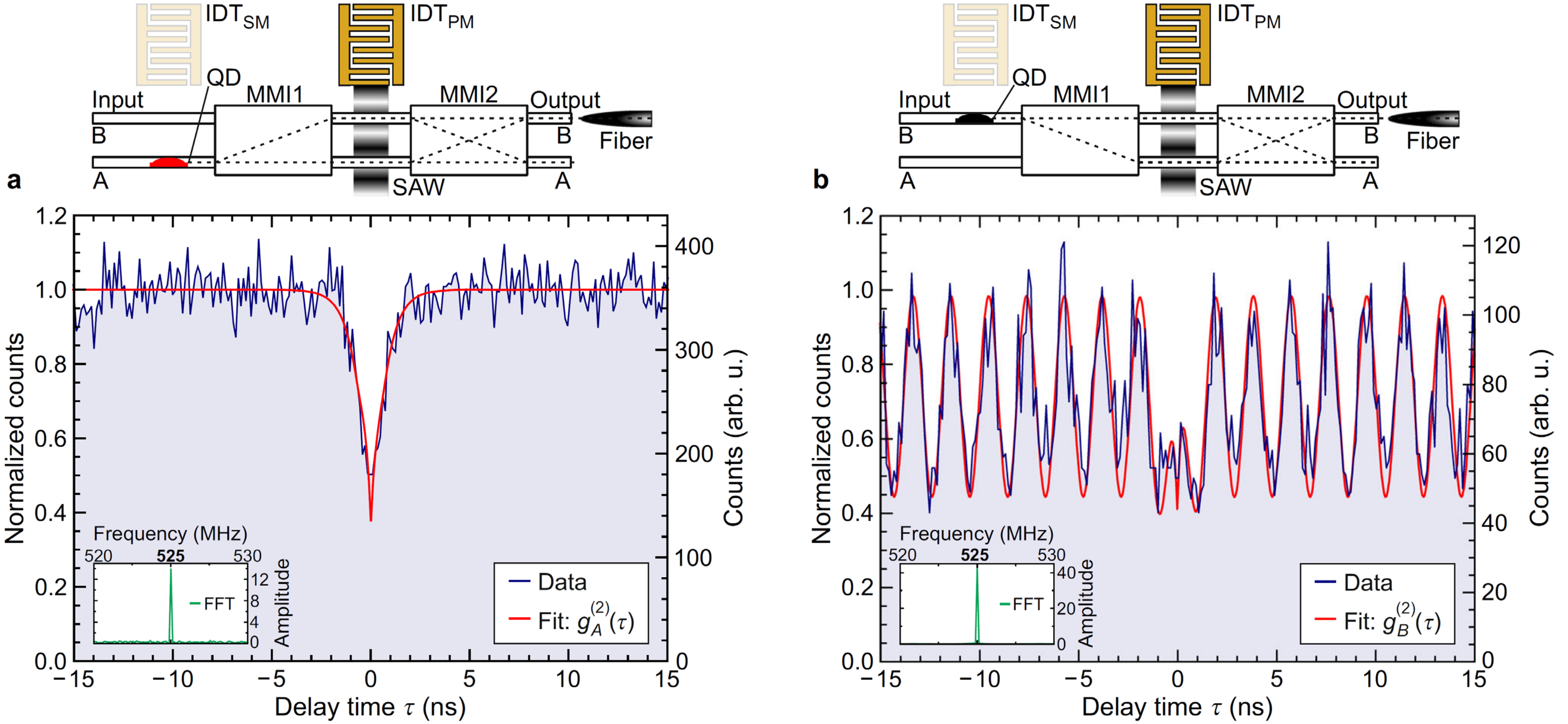
Rotating photonic Q-bits with SAWs



Rotating photonic Q-bits with SAWs



Rotating photonic Q-bits with SAWs



Conclusions

- The modulation using SAWs
  - Leads to novel and interesting physical phenomena
    - Phonon-dressed photons and polaritons
  - Are powerful tools to fabricate devices
    - Switches, modulators, pulse shapers, harmonic generators, tunable multiplexers, etc…
  - Up to the quantum limit

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Hebert Krenner

Jonathan Finley,
Kai Müller,

Michael Möller, Antonio Crespo-Poveda
Dominik Bühler, André Bilobran,
Alberto García-Cristóbal, Andrés Cantarero

Paul-Drude-Institut für Festkörperelektronik

DTU Fotonik
Institut for Fotonik

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