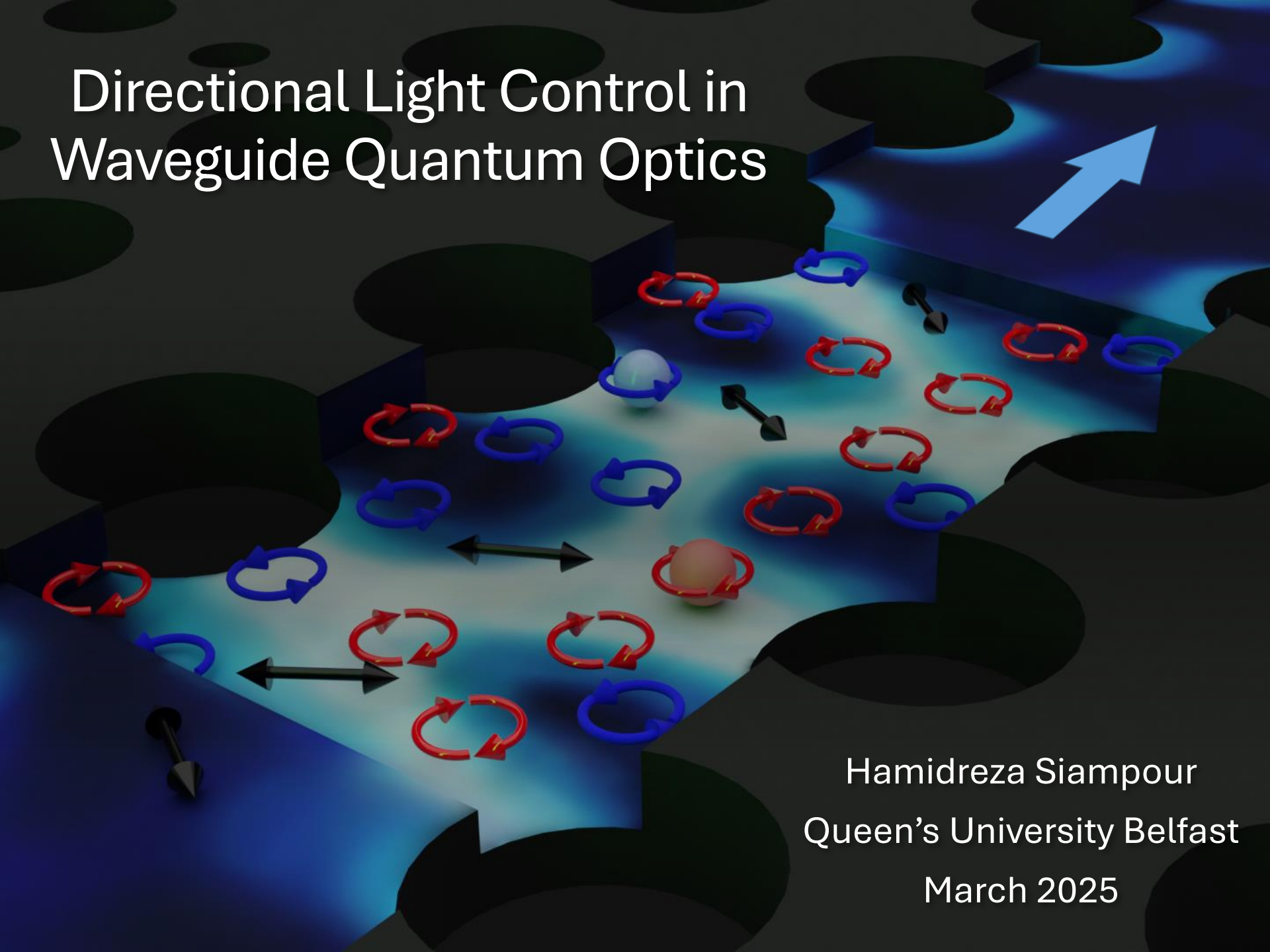
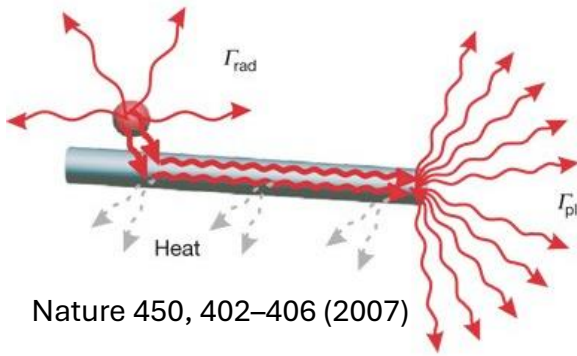


Directional Light Control in Waveguide Quantum Optics



Hamidreza Siampour
Queen's University Belfast
March 2025

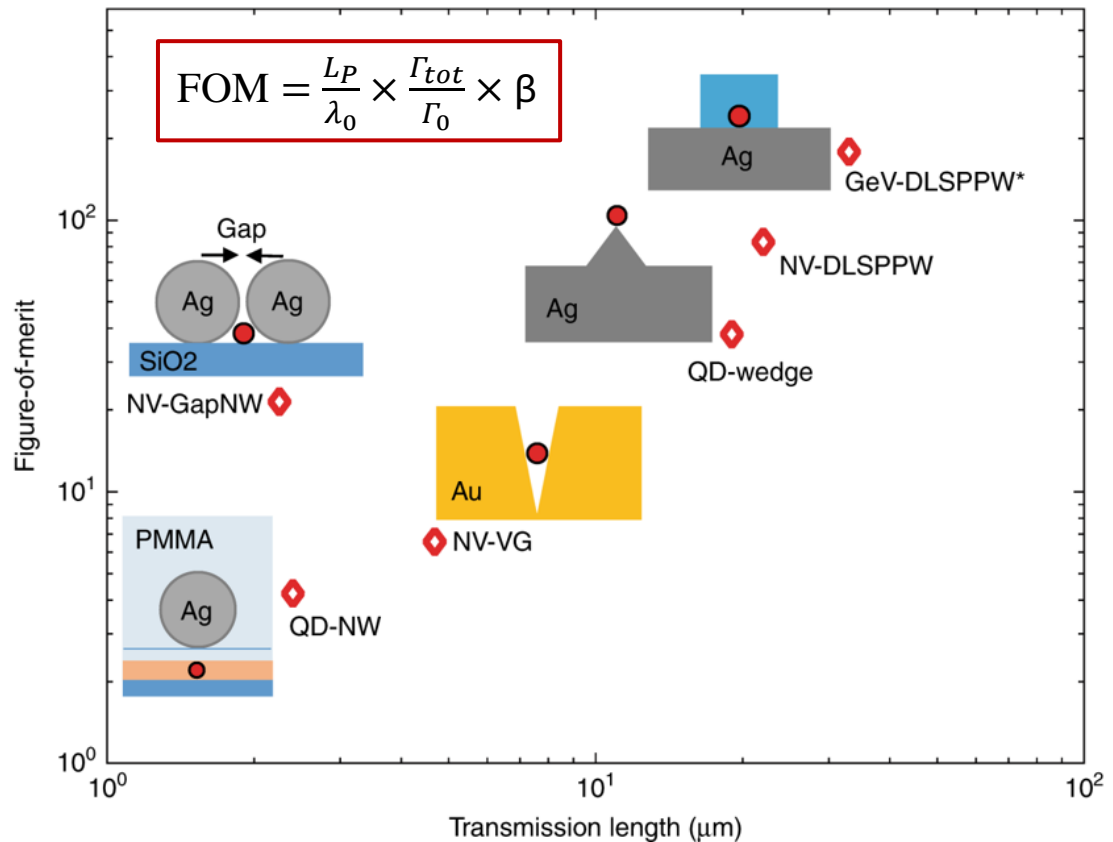
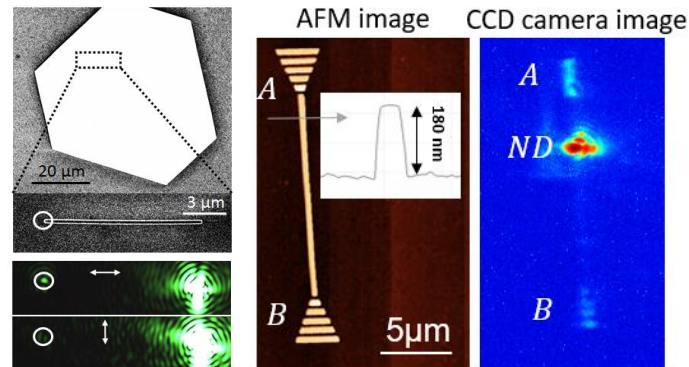
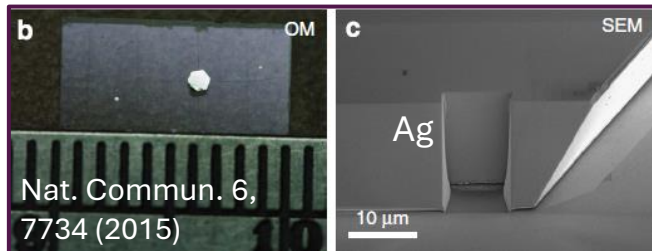
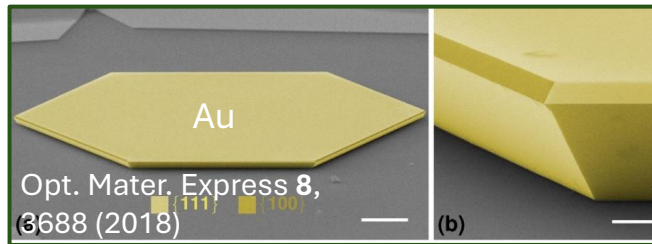
Emitter-waveguide coupling systems



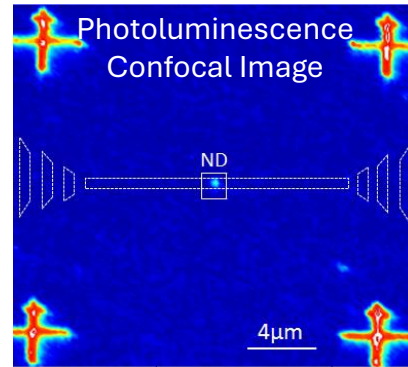
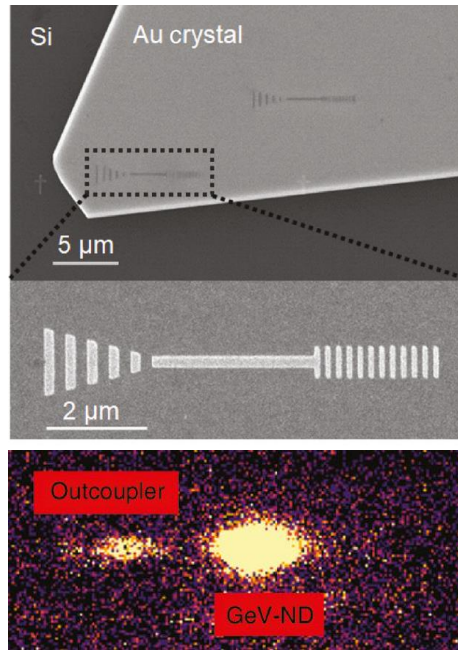
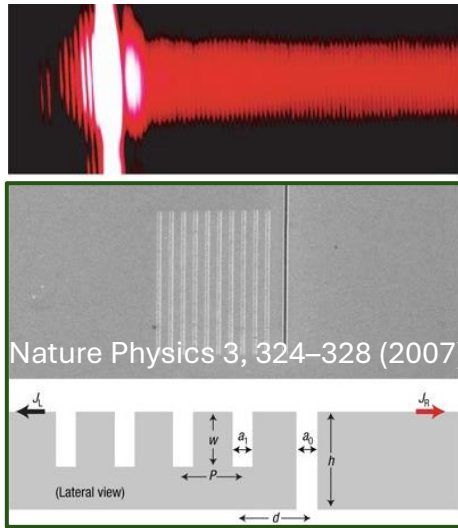
Nature 450, 402–406 (2007)

Figure-of-merit: The ability to efficiently deliver single photons in an emitter-waveguide system.

- Confined slow-light mode (high Purcell factor, $\frac{\Gamma_{tot}}{\Gamma_0}$)
- Moderate losses (large propagation length L_P)
- High emitter-waveguide coupling efficiency ($\beta = \frac{\Gamma_{wg}}{\Gamma_{tot}}$)



Directional coupling



- × β -factor is limited (<70%)
- × Limited scalability

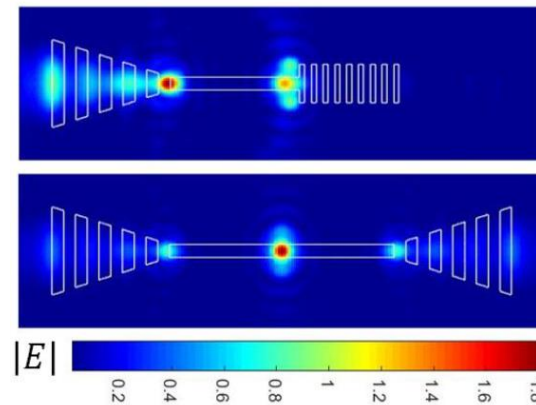
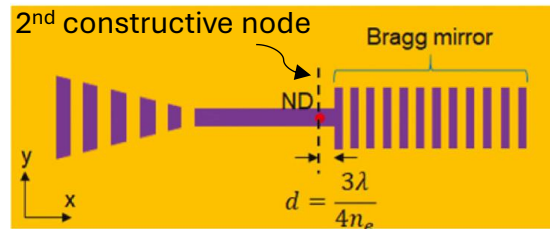
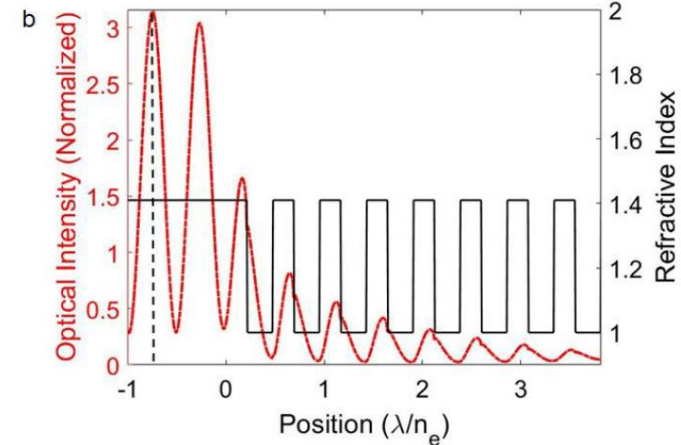
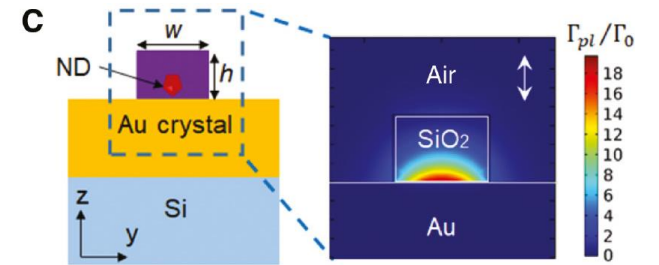


Figure-of-merit: The ability to achieve directional transmission of single photons.

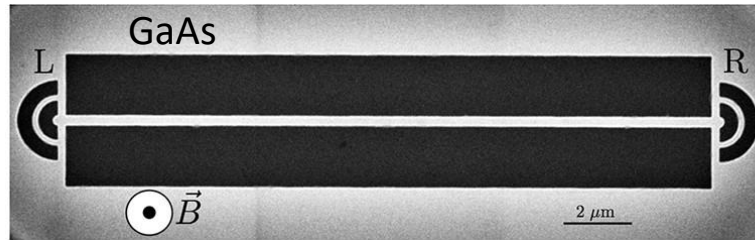
- High Purcell factor ($\frac{\Gamma_{tot}}{\Gamma_0}$)
- Greater propagation length (L_P)
- High directional coupling efficiency (β_d)

$$\text{FOM} = \frac{L_P}{\lambda_0} \times \frac{\Gamma_{tot}}{\Gamma_0} \times \beta_d$$



Propagation-direction-dependent (chiral) coupling

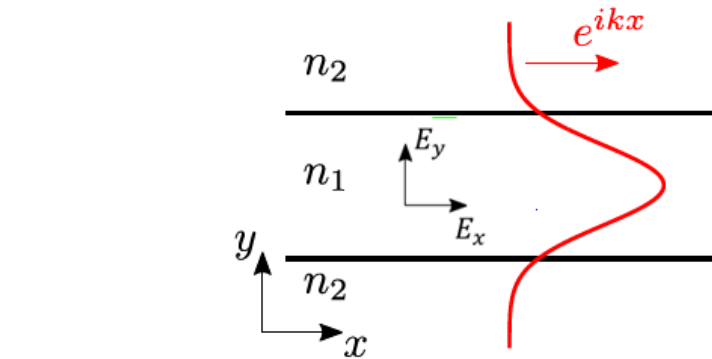
- Chiral effects induced by nanoscale confinement of guided modes



A typical nanobeam waveguide

$$\vec{E} = \begin{pmatrix} E_x \\ E_y \\ 0 \end{pmatrix} e^{ikx}$$

TE mode propagating in +x direction

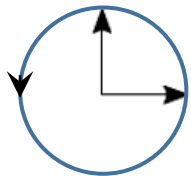


$$E_x = \frac{i}{k} \frac{\partial E_y}{\partial y}$$

E_x and E_y oscillate 90° out of phase

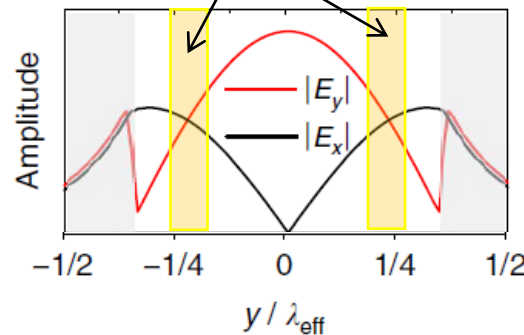
Magnitude is related to the mode confinement

$$E_x \approx -iE_y$$

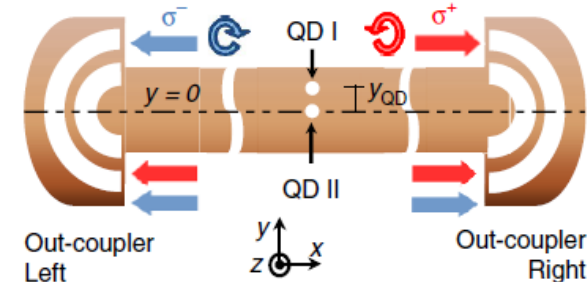


Circularly polarized light field

Chiral regions



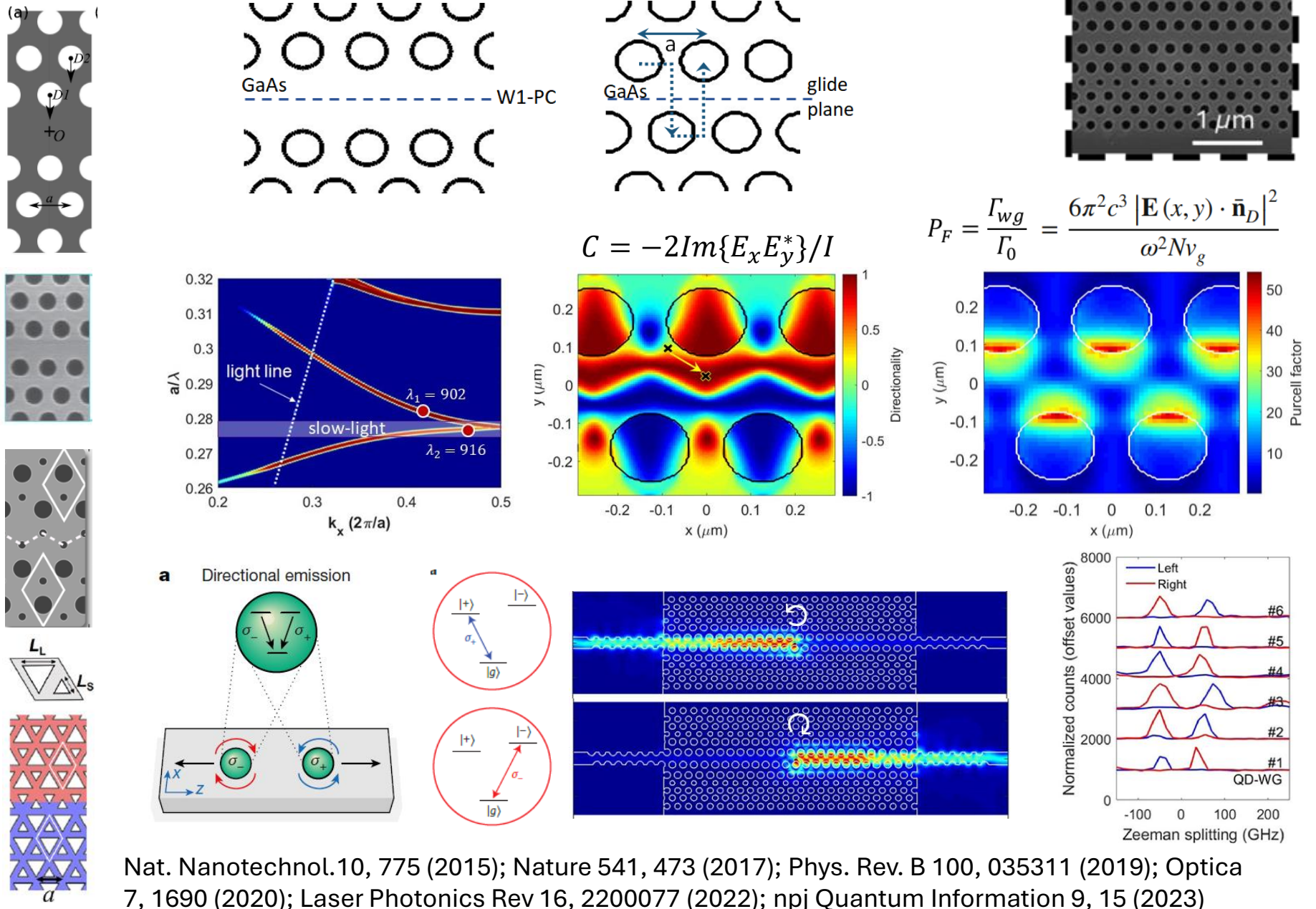
Spin-momentum locking of light



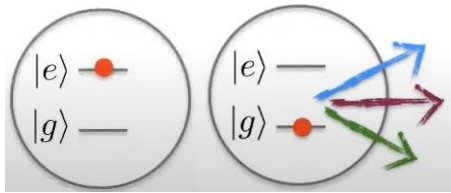
Coles et al., Nat. Commun. 7, 11183 (2016)

× Limited β and Purcell factor

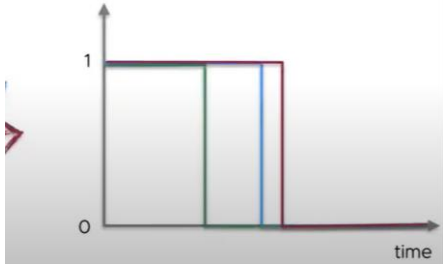
Engineering chiral interactions in waveguides



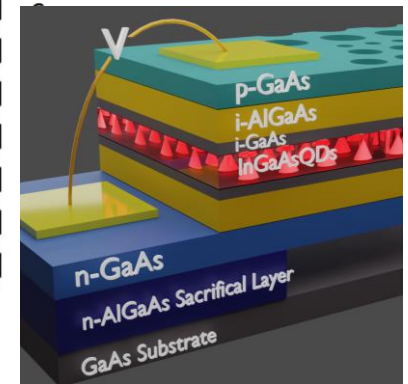
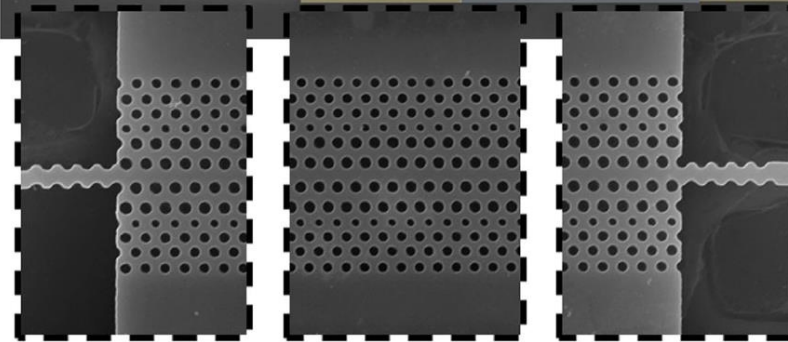
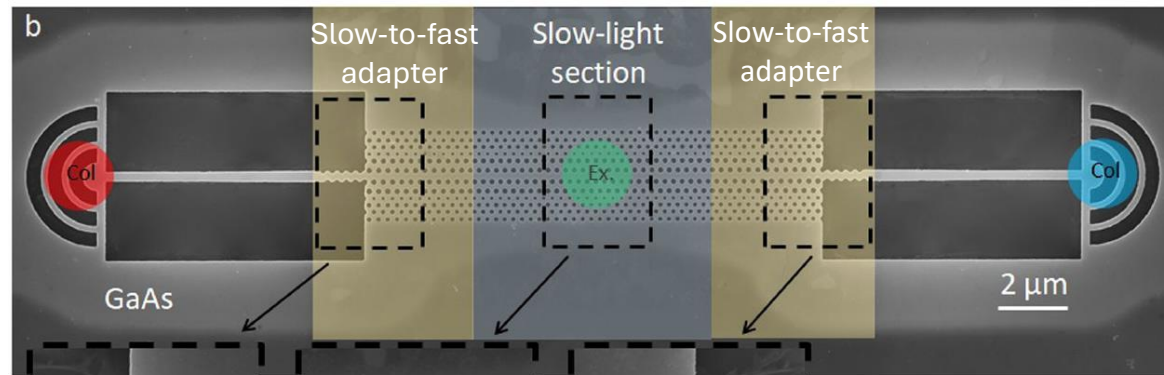
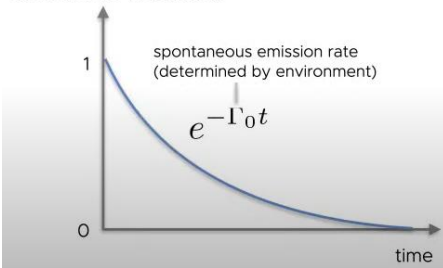
Purcell enhancement in the slow-light regime



excited-state population



excited-state population



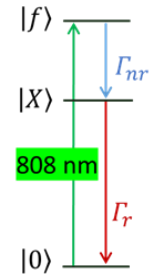
✓ A record Purcell factor of 20-fold and near-unity β in chiral waveguide

Electrical tuning, Stark shift

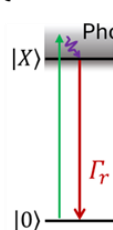
Purcell factor $\propto \frac{\Gamma_{wg}}{\Gamma_0} \propto \frac{n_g}{A_{wg}}$

group index n_g
mode area A_{wg}

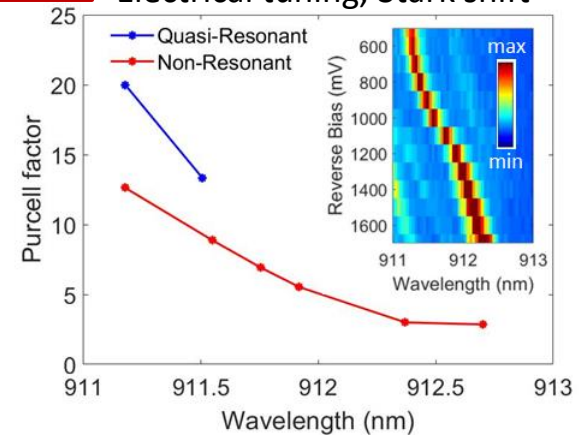
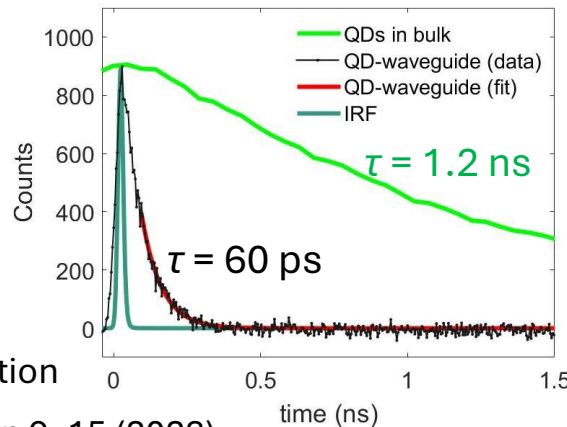
Non-Resonant



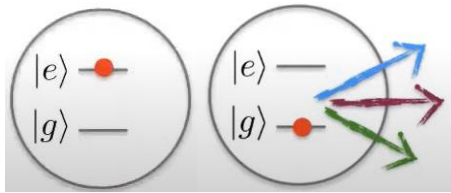
Quasi-Resonant



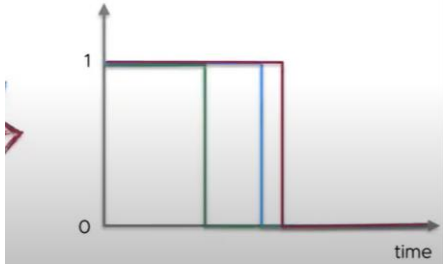
To eliminate intradot relaxation



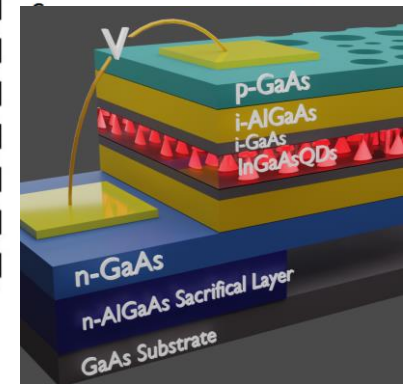
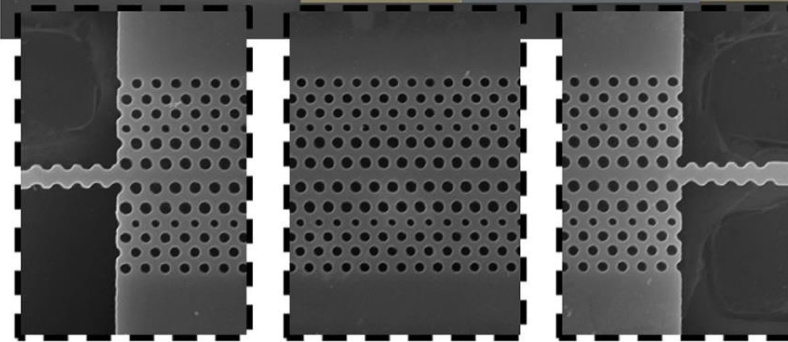
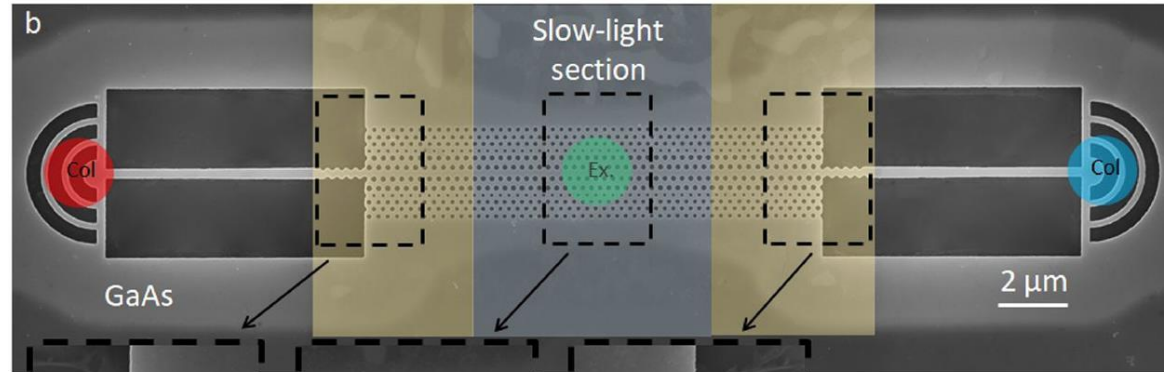
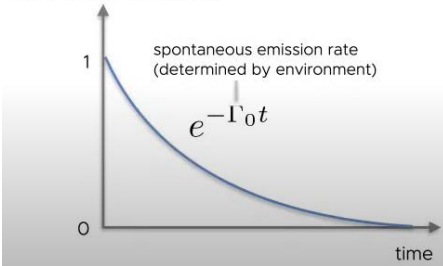
Purcell enhancement in the slow-light regime



excited-state population



excited-state population



✓ A record Purcell factor of 20-fold and near-unity β in chiral waveguide

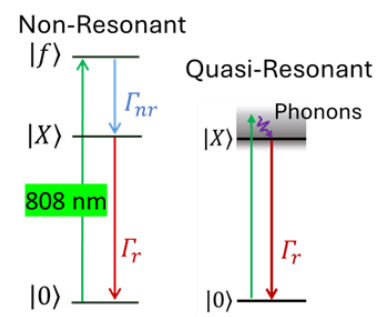
✓ Single photon emitter

Purcell factor

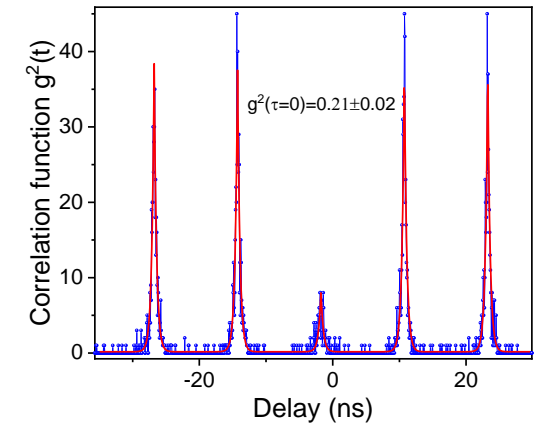
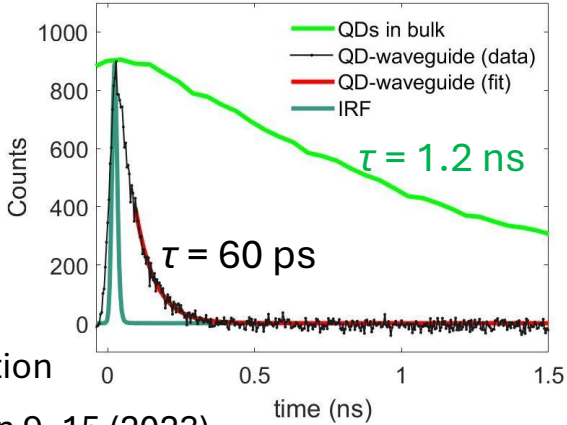
$$\frac{\Gamma_{wg}}{\Gamma_0} \propto \frac{n_g}{A_{wg}}$$

group index

mode area



To eliminate intradot relaxation



Chiral quantum optical waveguide systems

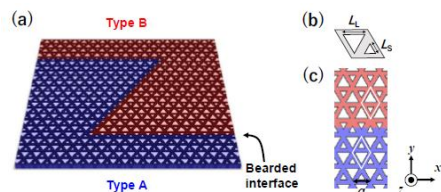
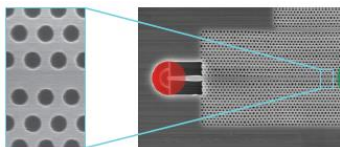
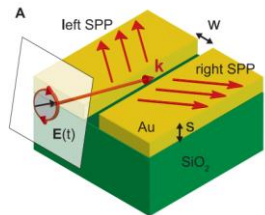
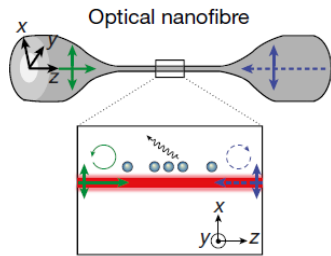
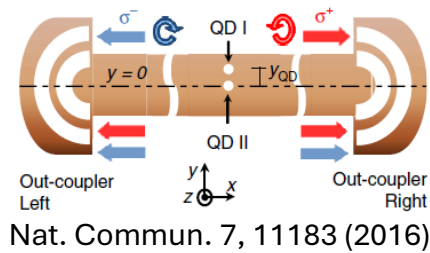
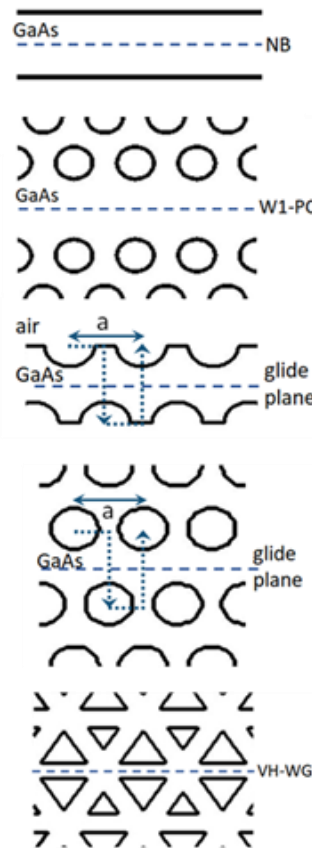


Figure-of-merit: The ability to achieve efficient directional coupling of spin-carrying photons.

- Large chiral area (scalability)
- High Purcell within the chiral area
- High coupling efficiency (β)

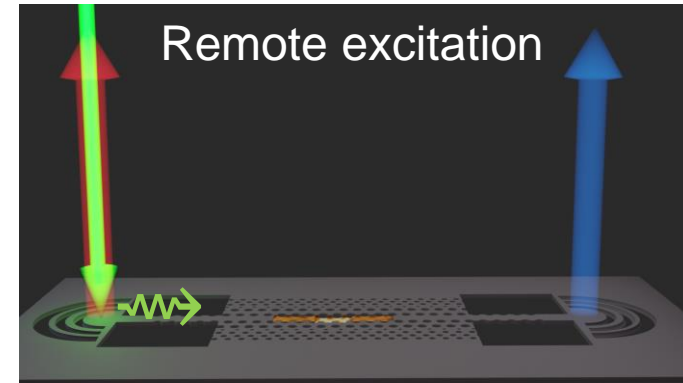
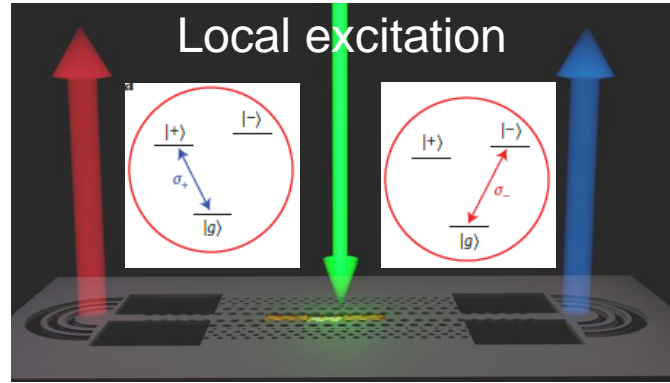
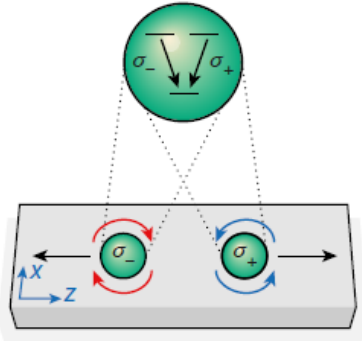
$$\text{FOM} = A_{chiral} \cdot \frac{\Gamma_{tot}}{\Gamma_0} \cdot \beta$$



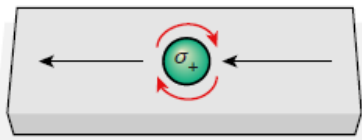
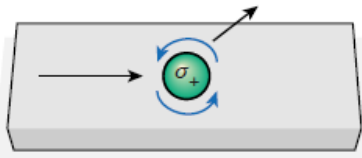
Waveguide device	Chiral area	β -factor	Purcell factor	FOM
NB	28%	83%	1.1	0.31
W1	0.8%	99%	2.8	0.02
GPN	28%	83%	2.2	0.61
GPW	36%	99%	30	10.8
Topological Valley-Hall	21%	57%	0.68	0.14

Directional absorption in chiral waveguides

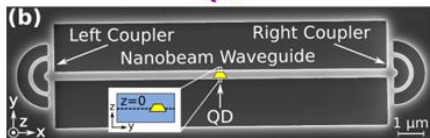
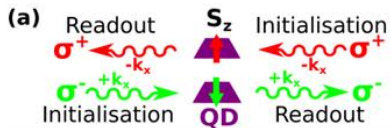
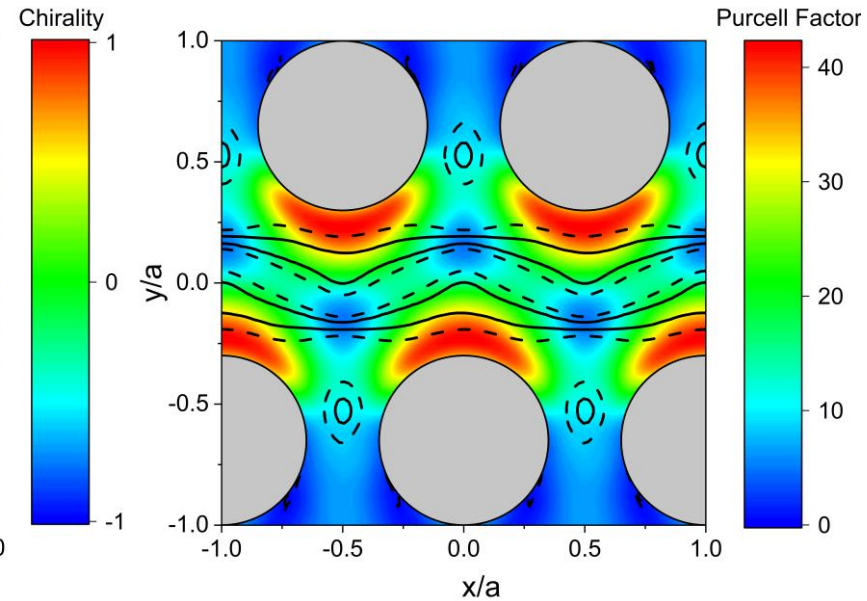
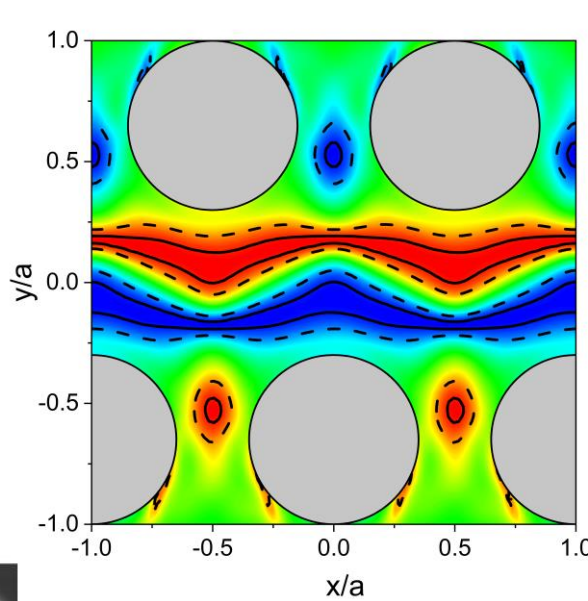
a Directional emission



c Non-reciprocal absorption



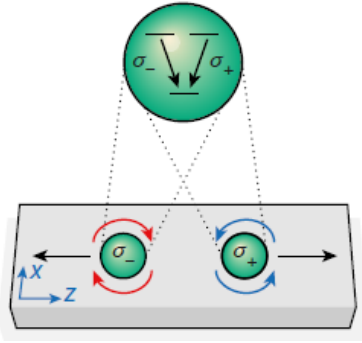
Nature 541, 473 (2017)



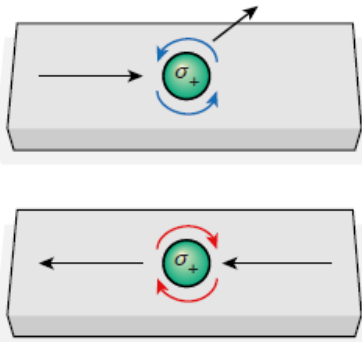
Germanis et al., arXiv:2502.00218 (2025)

Directional absorption in chiral waveguides

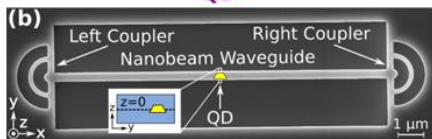
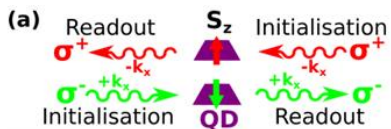
a Directional emission



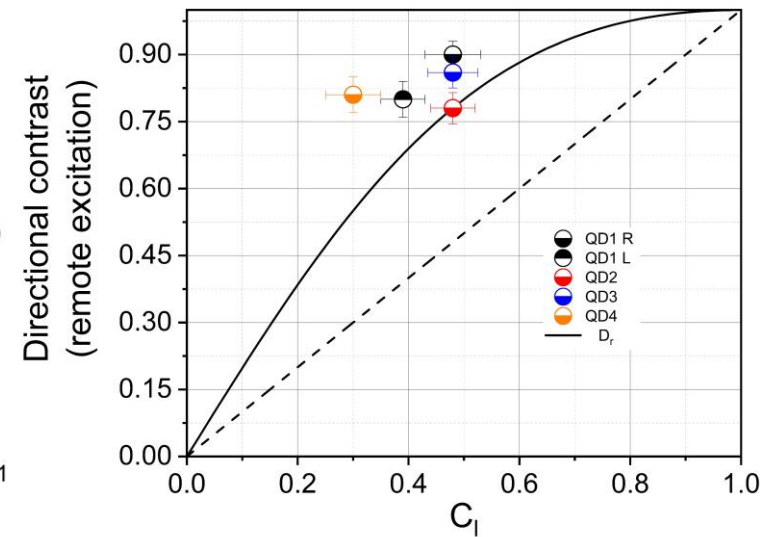
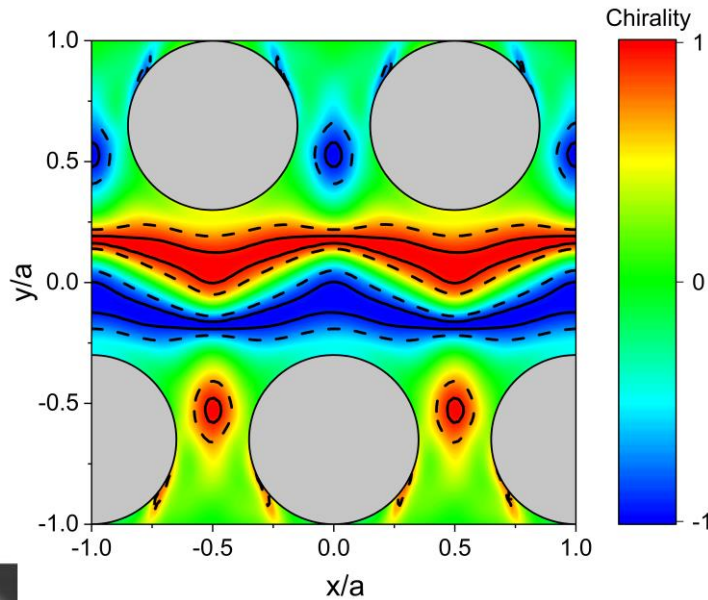
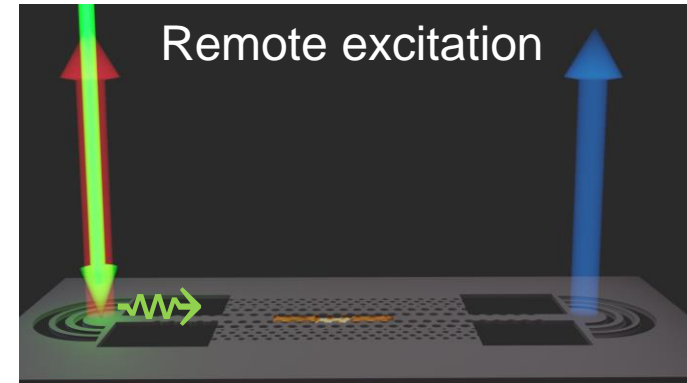
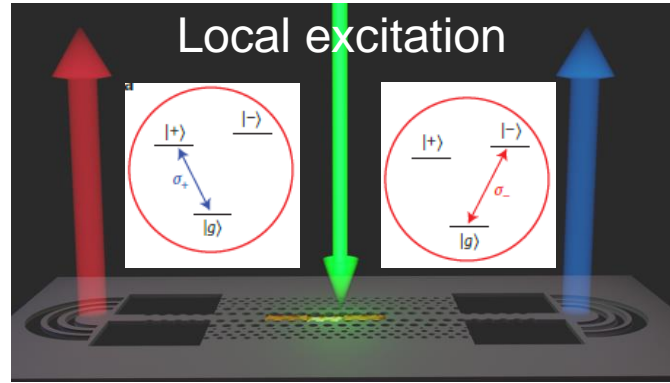
c Non-reciprocal absorption



Nature 541, 473 (2017)



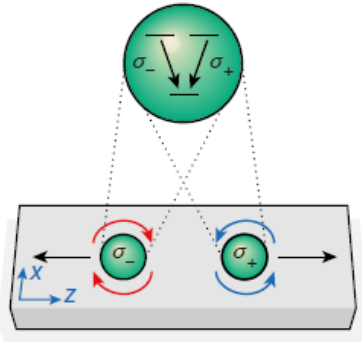
Phys. Rev. B 95, 121401 (2017)



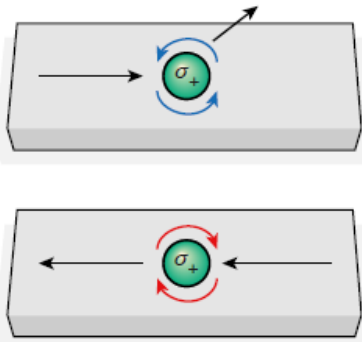
Germanis et al., arXiv:2502.00218 (2025)

Directional absorption in chiral waveguides

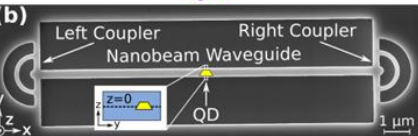
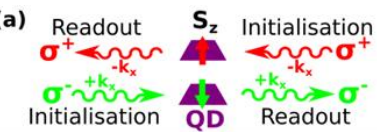
a Directional emission



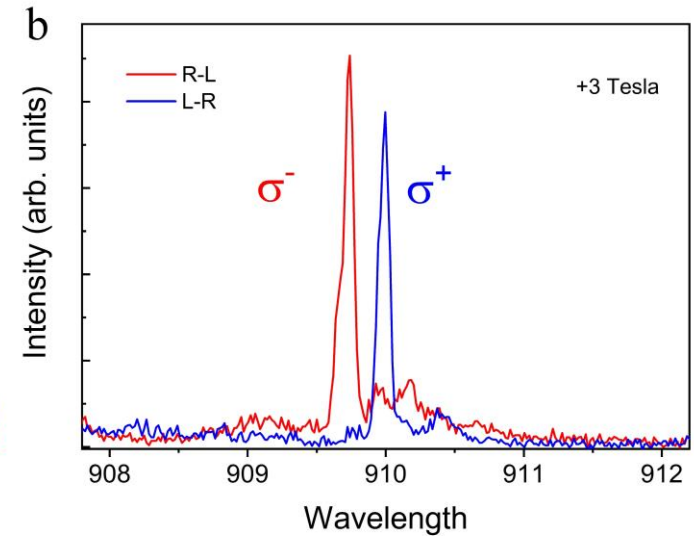
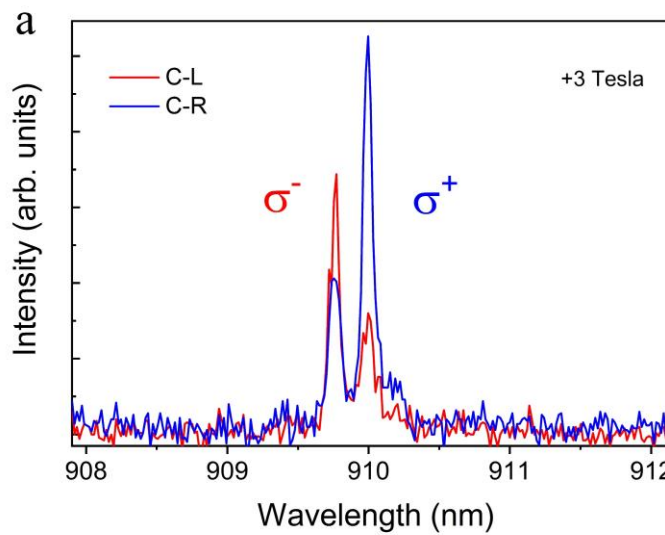
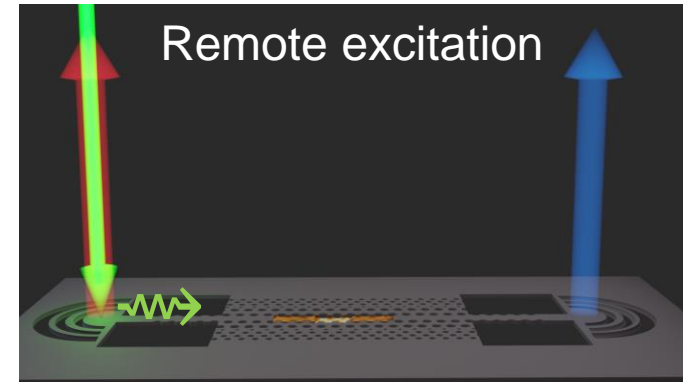
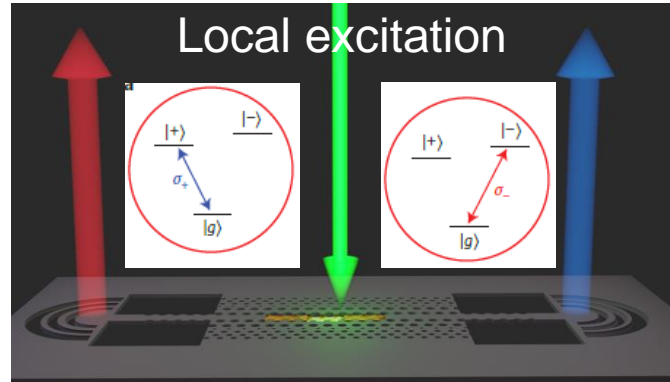
c Non-reciprocal absorption



Nature 541, 473 (2017)



Phys. Rev. B 95, 121401 (2017)

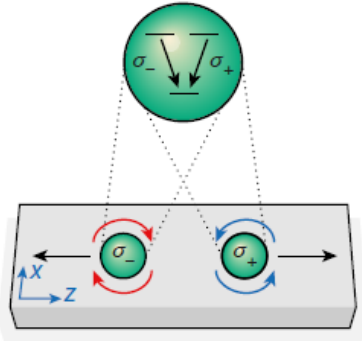


Spin memory under quasi-resonant p-shell excitation is close to 100%.

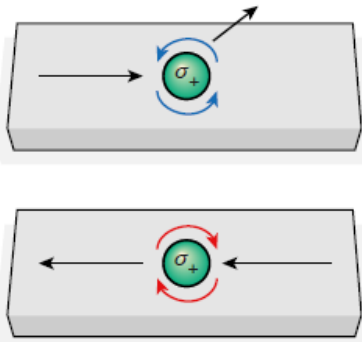
Germanis et al., arXiv:2502.00218 (2025)

Directional absorption in chiral waveguides

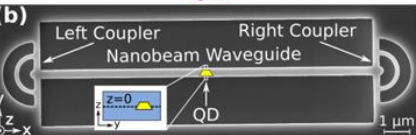
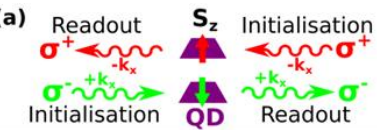
a Directional emission



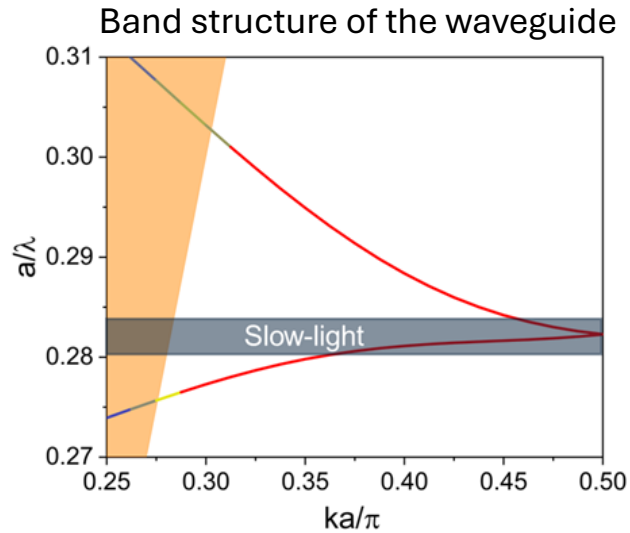
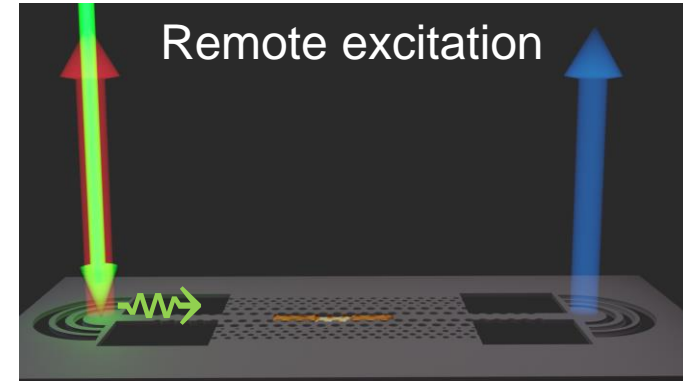
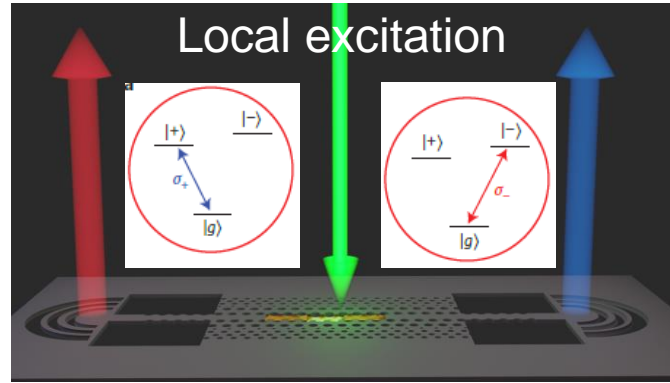
c Non-reciprocal absorption



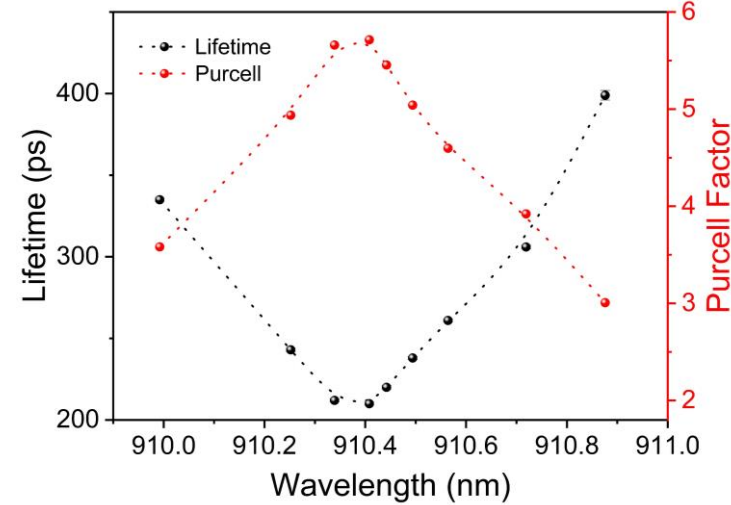
Nature 541, 473 (2017)



Phys. Rev. B 95, 121401 (2017)

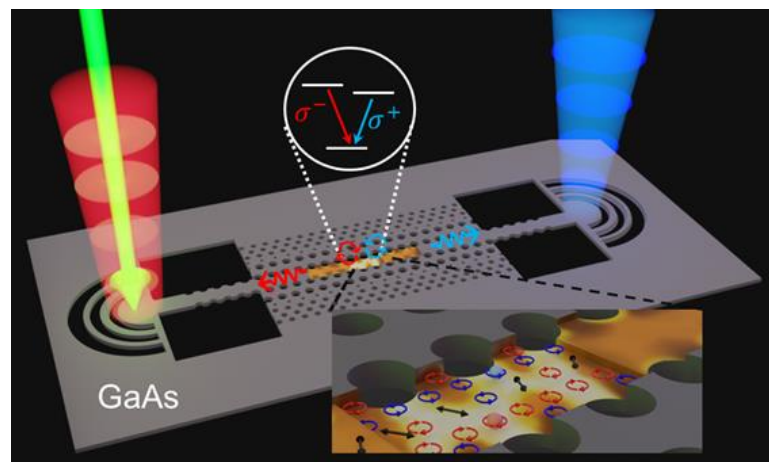
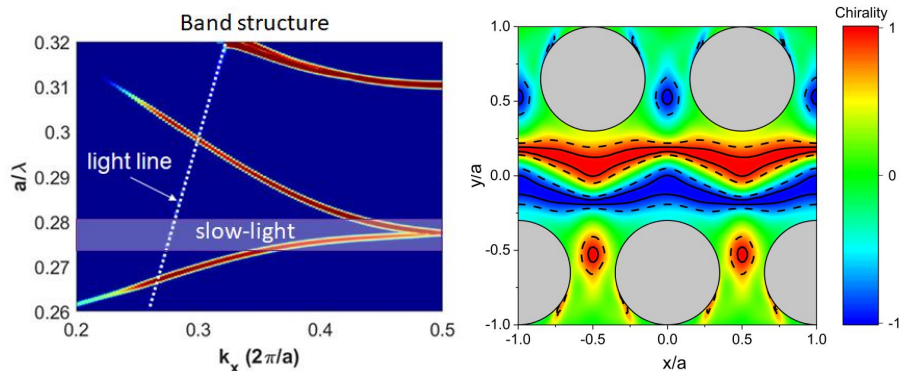


Electrical tuning, Stark shift



Germanis et al., arXiv:2502.00218 (2025)

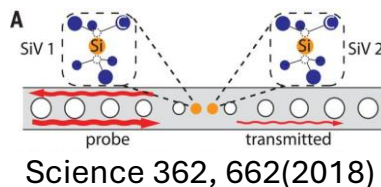
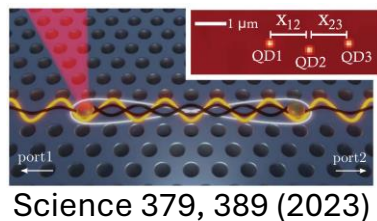
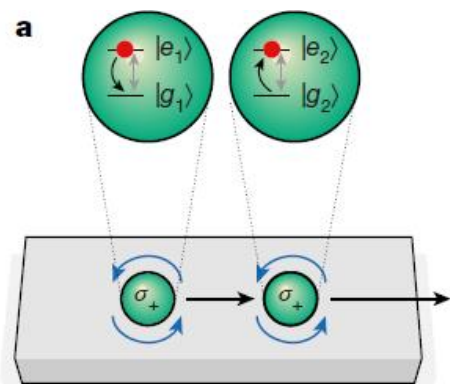
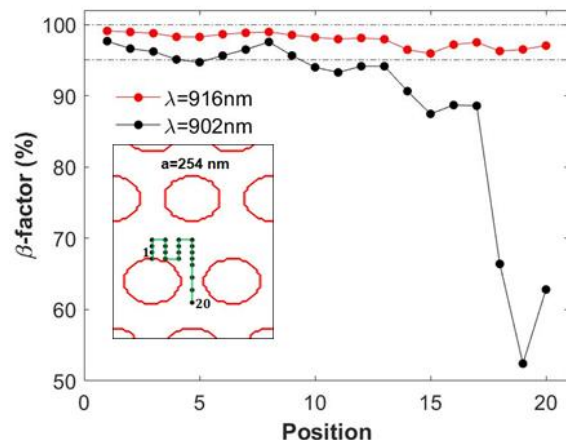
Summary and outlook



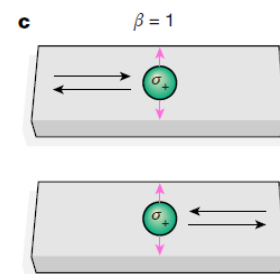
Cooperativity:

$$C = \frac{\beta}{1 - \beta}$$

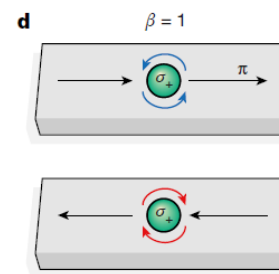
key ingredient
to scale up
the system



Symmetric (Isotropic)

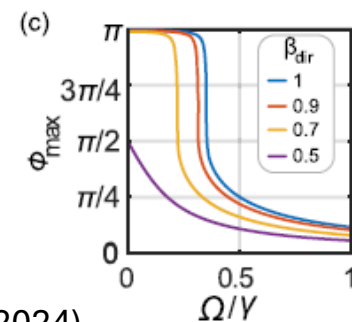
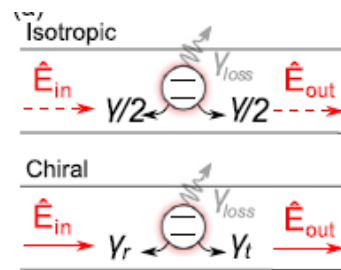


Chiral



Direction-Dependent Phase Shift:

- Chiral coupling transforms a perfectly reflecting emitter into a fully transparent one, inducing a non-reciprocal π phase shift in the light.



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PhD and non-UK Postdoc Fellowships Available

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