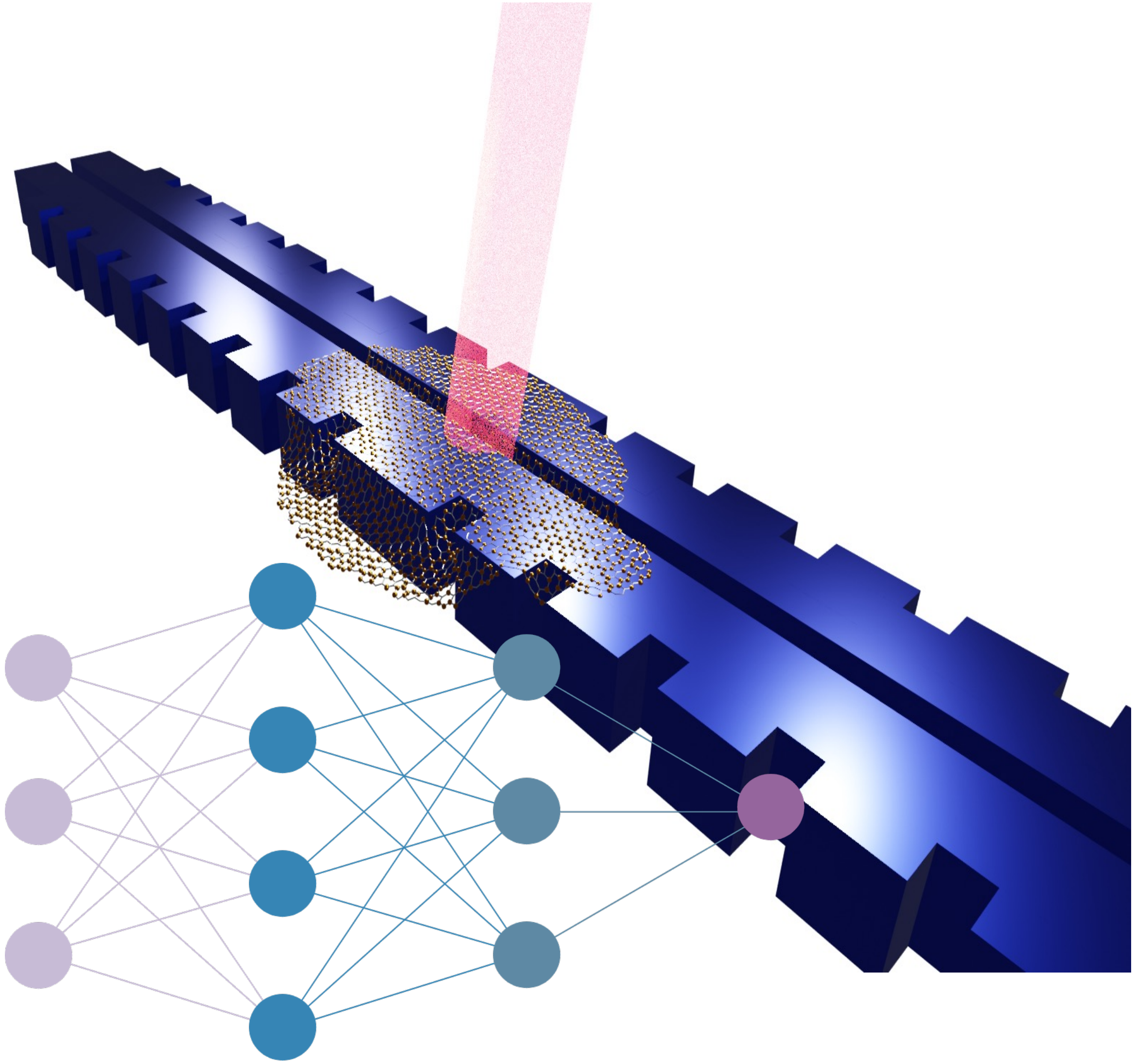
Towards Room-Temperature Integrated Quantum Photonics through Reduction of the Quantum Decoherence Using Machine Learning



PABLO A. POSTIGO

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QMP Morning Coffee by PerovsQuTe

Goal: CMOS-compatible quantum photonics at RT

- Photonic Quantum Networks will only meet its expectation as a ground-breaking technology when integrated into a **scalable fashion**.[1] The solution lies in **quantum photonic integrated circuits (QPICs)**

- **QPICs** must implement **on-chip**, **deterministic**, **high brightness**, **high-purity, indistinguishable** single-photon sources and, ideally, at **Room Temperature**. This is one of the main barriers to developing the full potential of quantum photonic technologies.

- **The number of deterministic quantum emitters** (QEs) for single photon sources (SPS) has increased in the last years with emitters based on color centers, QDs, defects in 2D semiconductors, single atoms, single ions, and single molecules, color centers (diamond, SiC, SiN, Si, ZnO…), perovskites…

How to integrate any deterministic QE with CMOS-compatible photonic platforms is of paramount importance (at least technologically).

[1] The rise of integrated quantum photonics. Nat. Photonics 14, 265 (2020).

Indistinguishable Photons in Quantum Photonics

Two photons are said to be “identical particles” when they cannot be discerned based on their “modal” properties (momenta, frequency, and polarization).

Indistinguishability arises from the existence of such identical properties along with the symmetrization of the wavefunction. Symmetrization ensures that the states remain identical upon particle interchange.

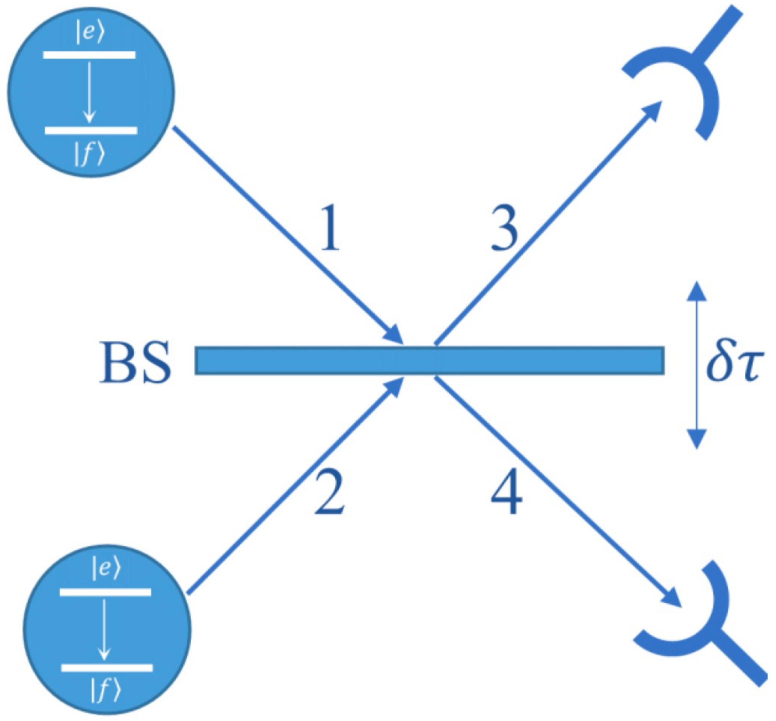
Why Indistinguishable Photons are essential:

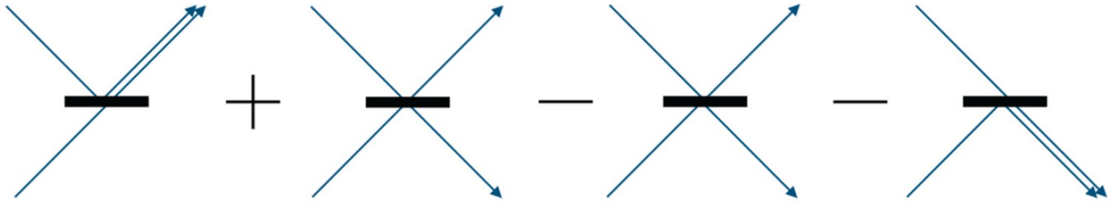
- Indistinguishability gives rise to quantum interference
- Realizing quantum logic gates
- Boson sampling
- Quantum communication (characterize entanglement - identify any compromises in the communication channel due to eavesdropping - entanglement in spatially overlapping identical particles realizes many quantum information protocols)
- Quantum networks (characterize entanglement as well as identify any compromises in the communication channel due to eavesdropping)
- Generation of random numbers
- Noise-free entanglement generation

Indistinguishable photons are crucial in quantum computing, communications, networks, entanglement, and teleportation.

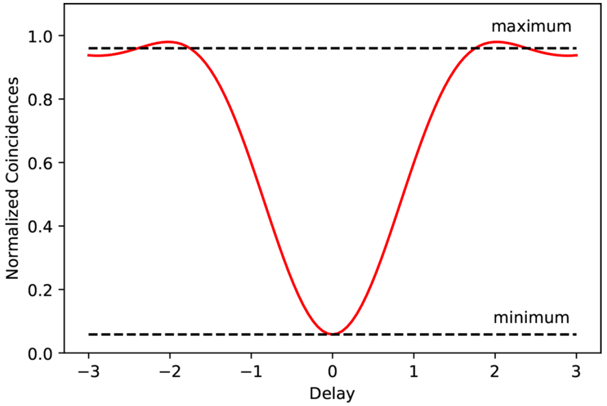
AVS Quantum Sci. 4, 021701 (2022)

The HOM interferometer





When it comes to **identical** photons, both the photons exit through the same output port together



C.-K. Hong, Z.-Y. Ou, and L. Mandel, Phys. Rev. Lett. 59, 2044 (1987).

The second-order correlation function

$$g^{(2)}(\tau) = \frac{\langle\langle \hat{E}_3^\dagger(t)\hat{E}_4^\dagger(t+\tau)\hat{E}_4(t+\tau)\hat{E}_3(t)\rangle\rangle}{\langle\langle \hat{E}_3^\dagger(t)\hat{E}_3(t)\rangle\rangle\langle\langle \hat{E}_4^\dagger(t+\tau)\hat{E}_4(t+\tau)\rangle\rangle}$$

50–50 beamsplitter T = R = 1/2, so that at zero-time delay, $\delta\tau = 0$

$$g^{(2)}(0) = 1 - \frac{\gamma}{\gamma+\gamma^*} \qquad [1]$$

Where γ is the lifetime rate and $\gamma*$ the dephasing rate of the single photon emitter

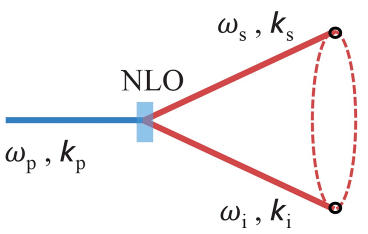
The quotient $\gamma/\gamma+\gamma*$ is the "coalescence degree" and it describes the experimental measurement of independent photons, so it is also called the **degree of Indistinguishability**

For practical use, I > 0.5

[1] Bylander, J., Robert-Philip, I., & Abram, I. (2003). Interference and correlation of two independent photons. The European Physical Journal D-Atomic, Molecular, Optical and Plasma Physics, 22(2), 295-301.

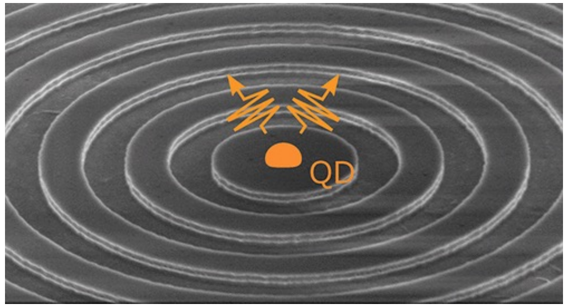
Examples of Sources of Indistinguishable Photons

1. **Nonlinear crystal-based sources**
spontaneous parametric down-conversion (SPDC)

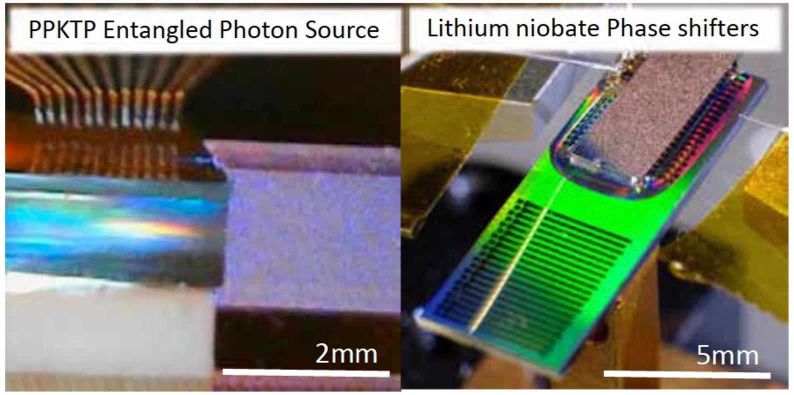


2. **Solid-state sources**: atoms, molecules, ions and quantum dots

ACS Photonics 2022, 9, 9, 3060–3066, 2022

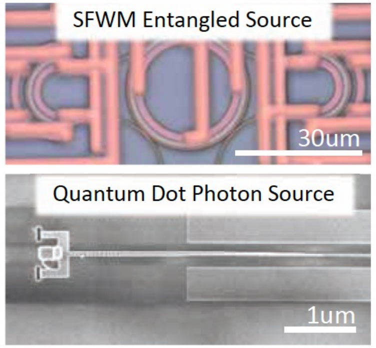


Heterogeneous Integration of Materials and Quantum Transduction

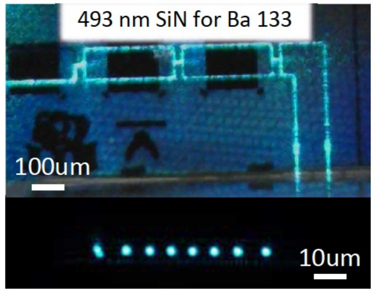


M.L. Fanto, QIPG, AFRL/RITQ

Single/Entangled Photons Sources



Visible Photonics for Solid State/Trapped Ion Qubits



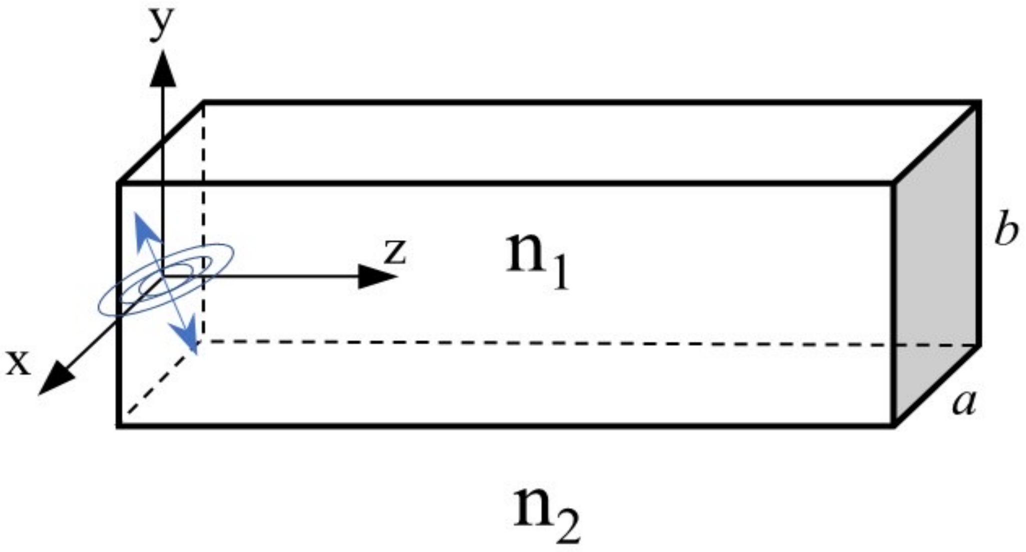
All of them have an **Indistinguishability > 0.7, most I > 0.9** and they share the goal of **on-chip integration**

Indistinguishable Photons in Integrated Photonic Circuits

What happens for single photons generated inside a waveguide?

Are they indistinguishable?

Can their indistinguishability be enhanced?



$$I = \frac{\Gamma_0}{\Gamma_0 + \Gamma^*}$$

A “bad” QE: $\Gamma^*/\Gamma_0 \approx 1$ and $I \approx 0.5$

J. Guimbao et al., Enhancement of the indistinguishability of single photon emitters coupled to photonic waveguides, Opt. Express 29, 21160-21173 (2021)

Indistinguishable Photons in Integrated Photonic Circuits II

In the “bad cavity” regime we can use an effective quantum emitter with decay rate (Γ+*R*) where *R* is the population transfer between the emitter and the cavity:

$$I = \frac{\Gamma_0}{\Gamma_0 + \Gamma^*} \longrightarrow I = \frac{(\Gamma_0 + R)}{(\Gamma_0 + R) + \Gamma^*} \; ; \; R = \frac{4g^2}{\Gamma_0 + \Gamma^* + \kappa} \qquad \boxed{R = \Gamma_0 \cdot P_f}$$

$$\boxed{I = \frac{(1 + P_f)}{(1 + P_f) + \frac{\Gamma^*}{\Gamma_0}}} \qquad \frac{\Gamma}{\Gamma_0} = \frac{P}{P_0}$$ is the Purcell Enhancement P_f

J. Guimbao et al., Enhancement of the indistinguishability of single photon emitters coupled to photonic waveguides, Opt. Express 29, 21160-21173 (2021)

Indistinguishable Photons in Integrated Photonic Circuits III

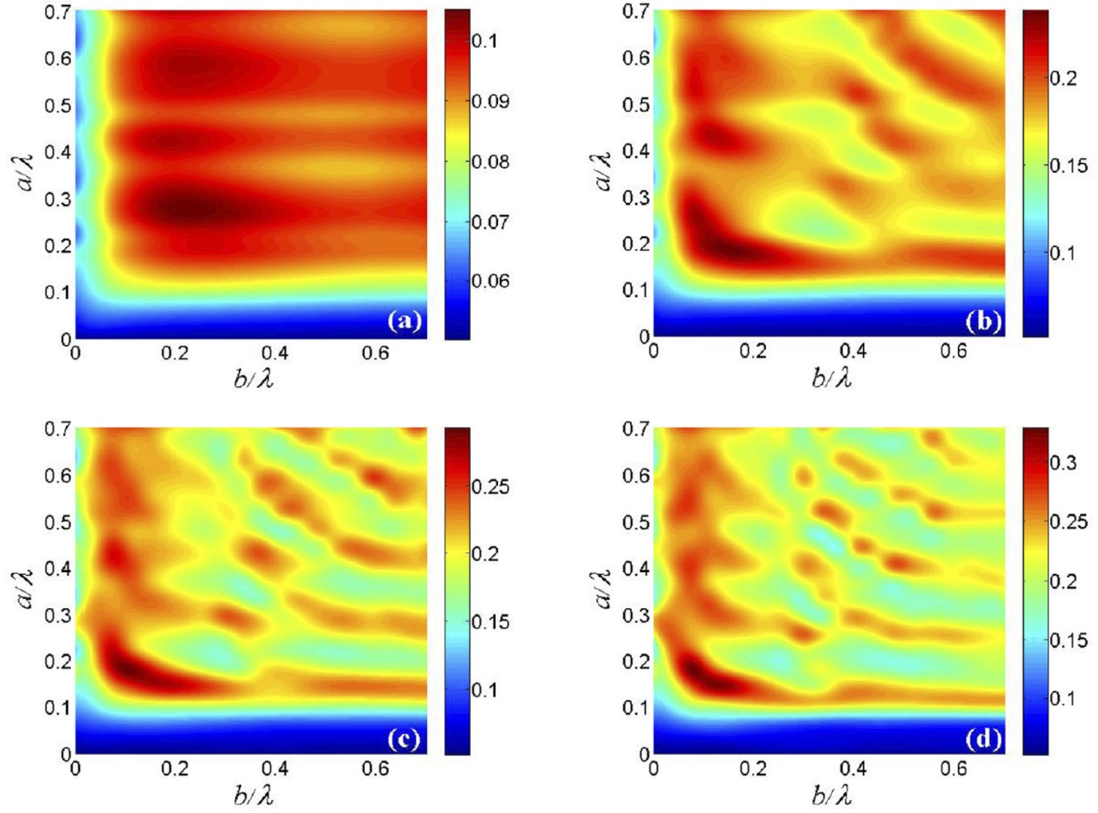


Fig. 9. $I\,\beta$ value as a function of the normalized width, a/λ, and thickness, b/λ, when the s-source is placed at the edge of the waveguide with $n_2 = 1.44$ calculated with the analytical model. (a) $n_1 = 2$, (b) $n_1 = 3.4$, (c) $n_1 = 4$, (d) $n_1 = 4.5$.

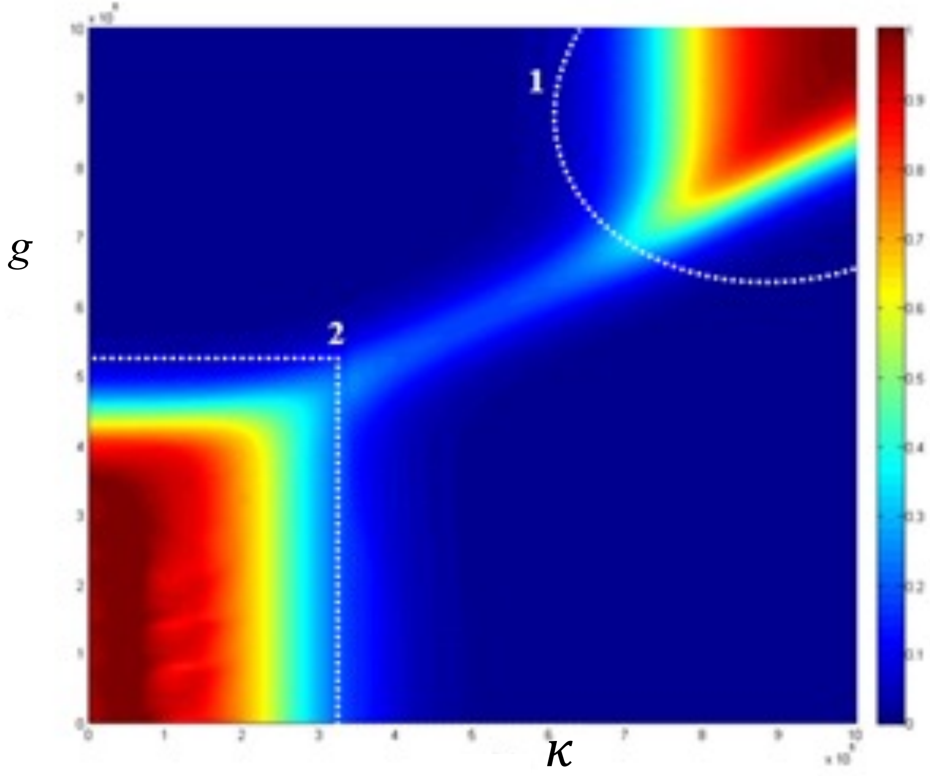
The Indistinguishability **depends strongly on the position** of the quantum source in respect to the waveguide.

Surprisingly, **the best Indistinguishability is found outside the waveguide, close to the walls of it.**

For low dissipative emitters with $\Gamma^*/\Gamma_0 \approx 1$ (like GaAs QDs) the indistinguishability can be enhanced up to a **30%** and reach **values I ≈ 0.8.** For InAs quantum dots with Γ^*/Γ_0=2.6 **up to 40%.**

J. Guimbao et al., Enhancement of the indistinguishability of single photon emitters coupled to photonic waveguides, Opt. Express 29, 21160-21173 (2021)

Indistinguishable Photons in Photonic Cavities



$$\kappa \sim 1/Q \text{ and } g \sim 1/\sqrt{V_{\text{eff}}}$$

Solve

$$\frac{\partial \hat{\rho}}{\partial t} = \mathcal{L}[\rho]$$

Compute

$$I = \frac{\int_0^\infty dt \int_0^\infty d\tau |\langle \hat{a}^\dagger(t+\tau)\hat{a}(t)\rangle|^2}{\int_0^\infty dt \int_0^\infty d\tau \langle \hat{a}^\dagger(t)\hat{a}(t)\rangle\langle \hat{a}^\dagger(t+\tau)\hat{a}(t+\tau)\rangle}$$

[1]

Coherent regime (1):

$$2g > \kappa + \gamma + \gamma^* \qquad I_{\text{cc}} = \frac{(\gamma+\kappa)(\gamma+\kappa+\gamma^*/2)}{(\gamma+\kappa+\gamma^*)^2}$$

I does not depend on g

Incoherent regime (2) and right-side (1): *"good" and "bad" cavities*

$$I_{\text{bc}} = \frac{\gamma + R}{\gamma + R + \gamma^*}$$

"bad" cavity: high k, high g

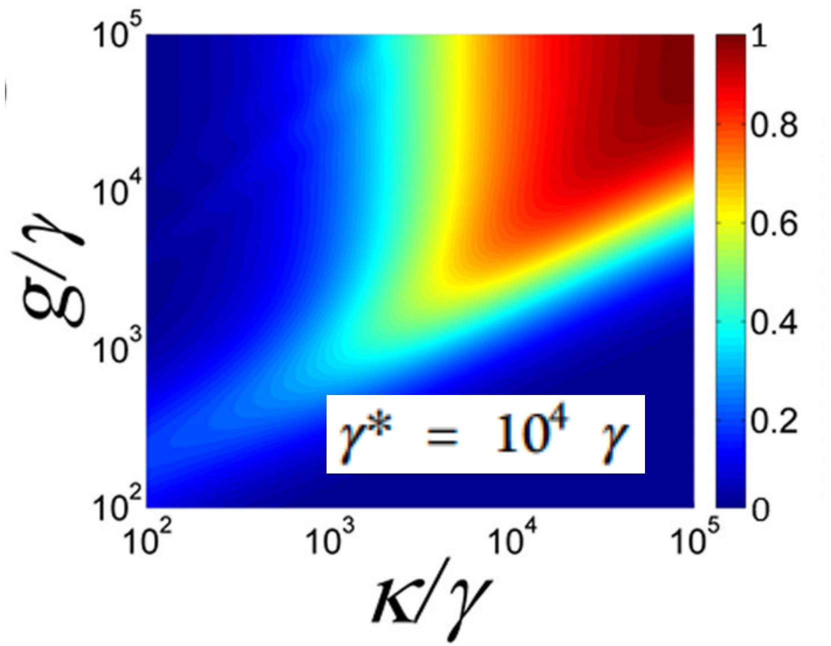
$$I_{\text{gc}} = \frac{\gamma + \frac{\kappa R}{\kappa + R}}{\gamma + \kappa + 2R}$$

"good" cavity: low k, but low g: only
"Funneling" can help for a high emission rate [2]
Also "Cascaded Cavities" [3]

[1] J. Guimbao et al. ACS Photonics (2022), 9, 6, 1926-1935
[2] Grange, et al. (2015). PRL,114(19)
[3] Choi, H., Zhu, D., Yoon, Y., & Englund, D. (2019). PRL, 122(18)

Indistinguishable Photons in “not-too-bad” Photonic Cavities

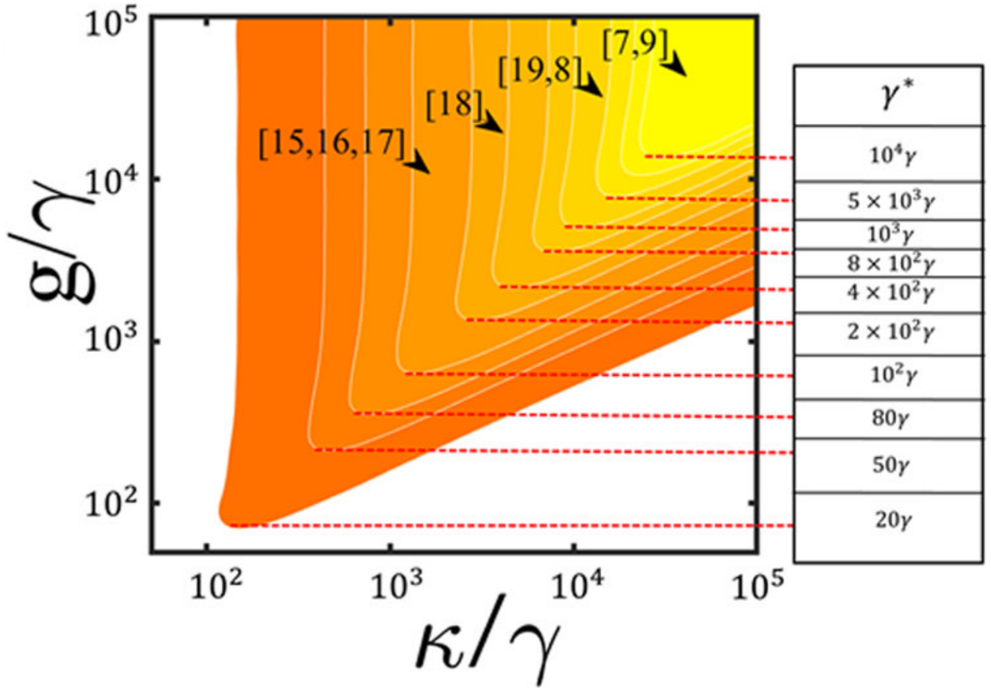
$$I = \frac{\int\int_0^\infty dt d\tau \,|< \hat{a}^\dagger(t+\tau)\hat{a}(t) >|^2}{\int\int_0^\infty dt d\tau < \hat{a}^\dagger(t)\hat{a}(t) > <\hat{a}^\dagger(t+\tau)\hat{a}(t+\tau)>}$$



$\kappa \sim 1/Q$ and $g \sim 1/\sqrt{V_{eff}}$.

For a high I, the photon must escape out of the cavity before the emitter dephases it.

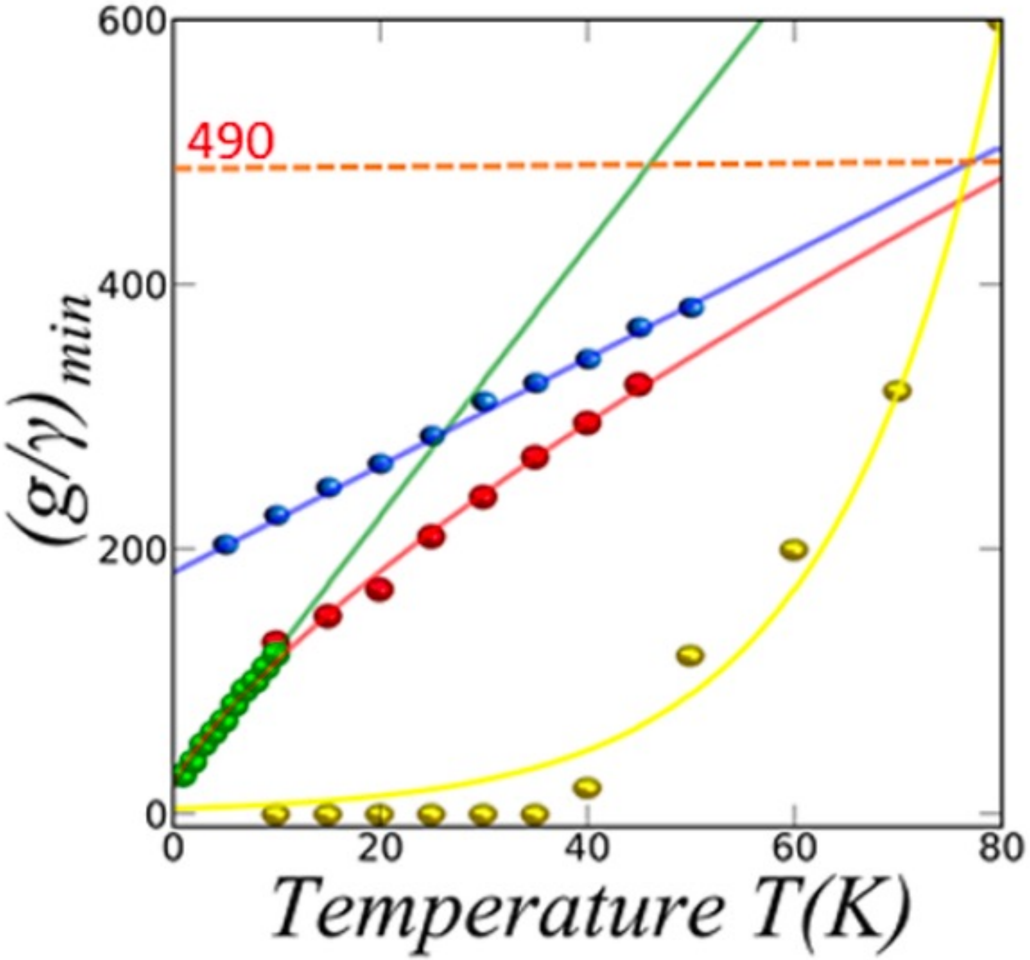
Contour maps of the region with $I > 0.9$ as γ^* changes



Dielectric cavities can potentially achieve the region with $I > 0.9$ for high dissipative emitters (i.e., QE at RT) just by increasing its cavity decay rate κ

J. Guimbao et al. ACS Photonics (2022), 9, 6, 1926-1935

Indistinguishable Photons from Temperature-Dephased Emitters



Variation of the (g/γ)min with T for I > 0.9 and different SPS:
QDs GaAs (red)
QDs InAs (yellow).
Molecules (green)
Two-dimensional (2D) materials (blue)

For the technologically relevant T of liquid nitrogen (77 K), the same value (g/γ)min = 490 works for InAs and GaAs QDs and 2D materials.

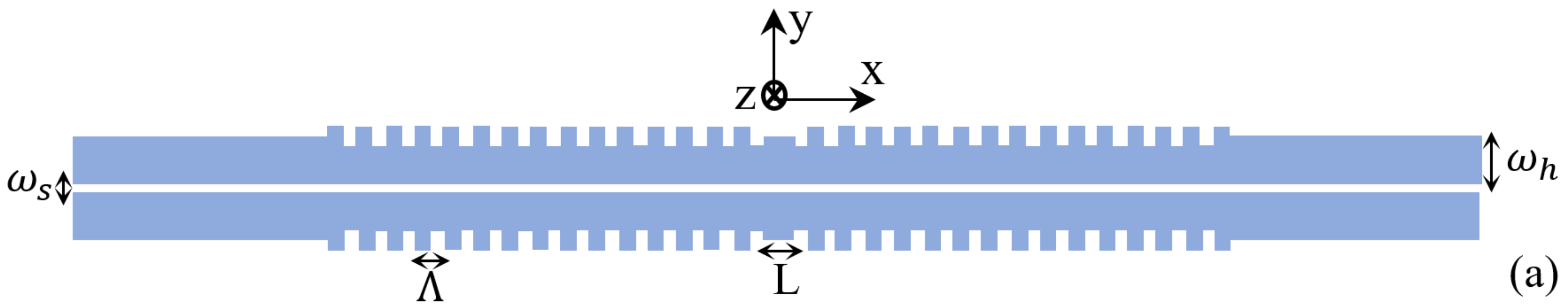
J. Guimbao et al. ACS Photonics (2022), 9, 6, 1926-1935

Indistinguishable photons in Nanophotonic Resonators

Our Photonic Cavity should therefore meet the following goals:

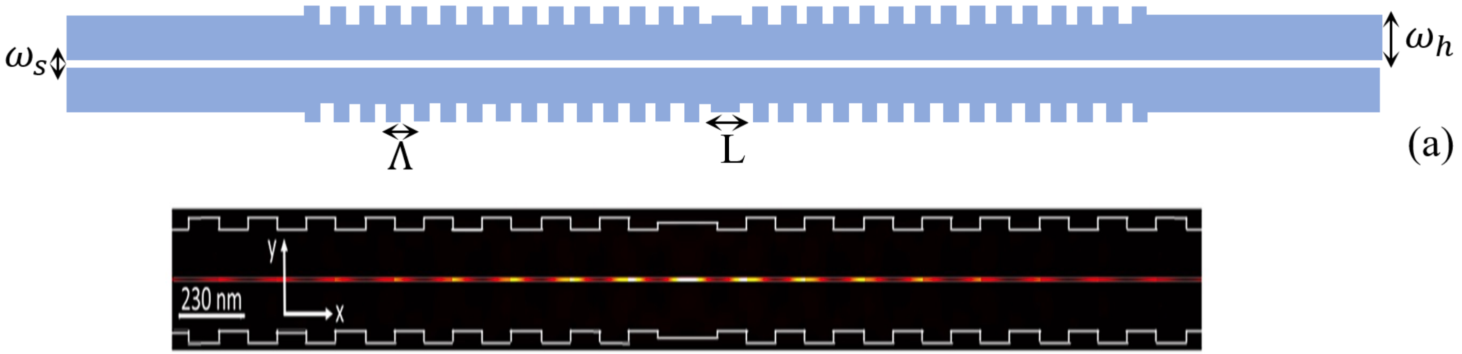
- Keeping the κ/g ratio inside the region with a high I by increasing g and adjusting Q
- On-chip integrated cavity, CMOS-compatible with photonic integrated circuits (PICs) used in silicon photonics

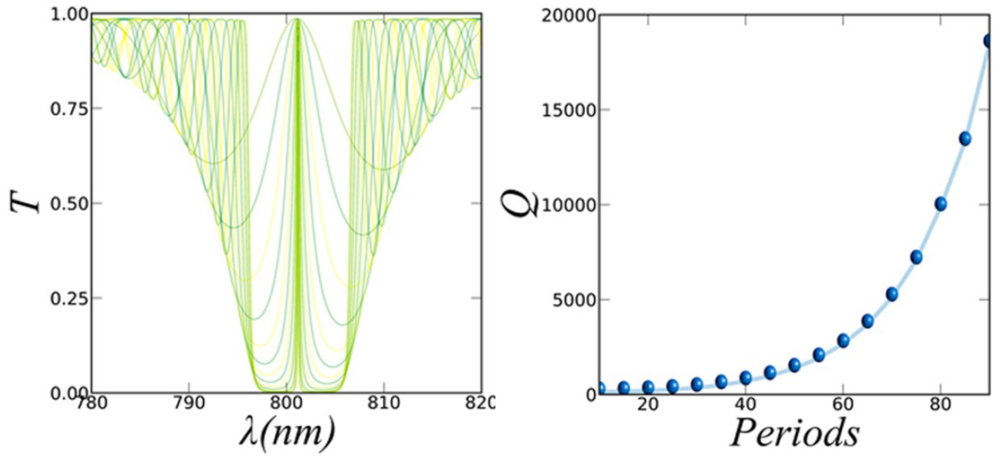
A good candidate is a *hybrid slot-Bragg cavity*, where Q changes by the number of periods of the Bragg reflector section.

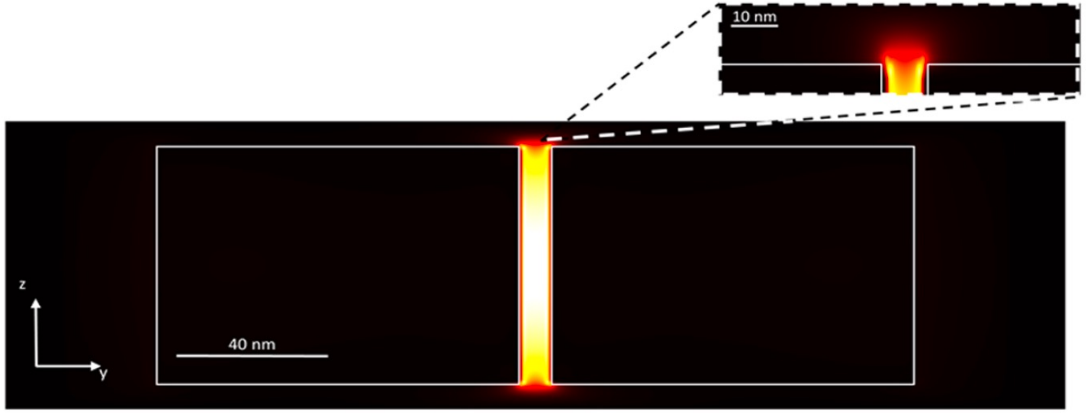


J. Guimbao et al. ACS Photonics (2022), 9, 6, 1926-1935

Indistinguishable photons in Slot-Bragg hybrid cavity





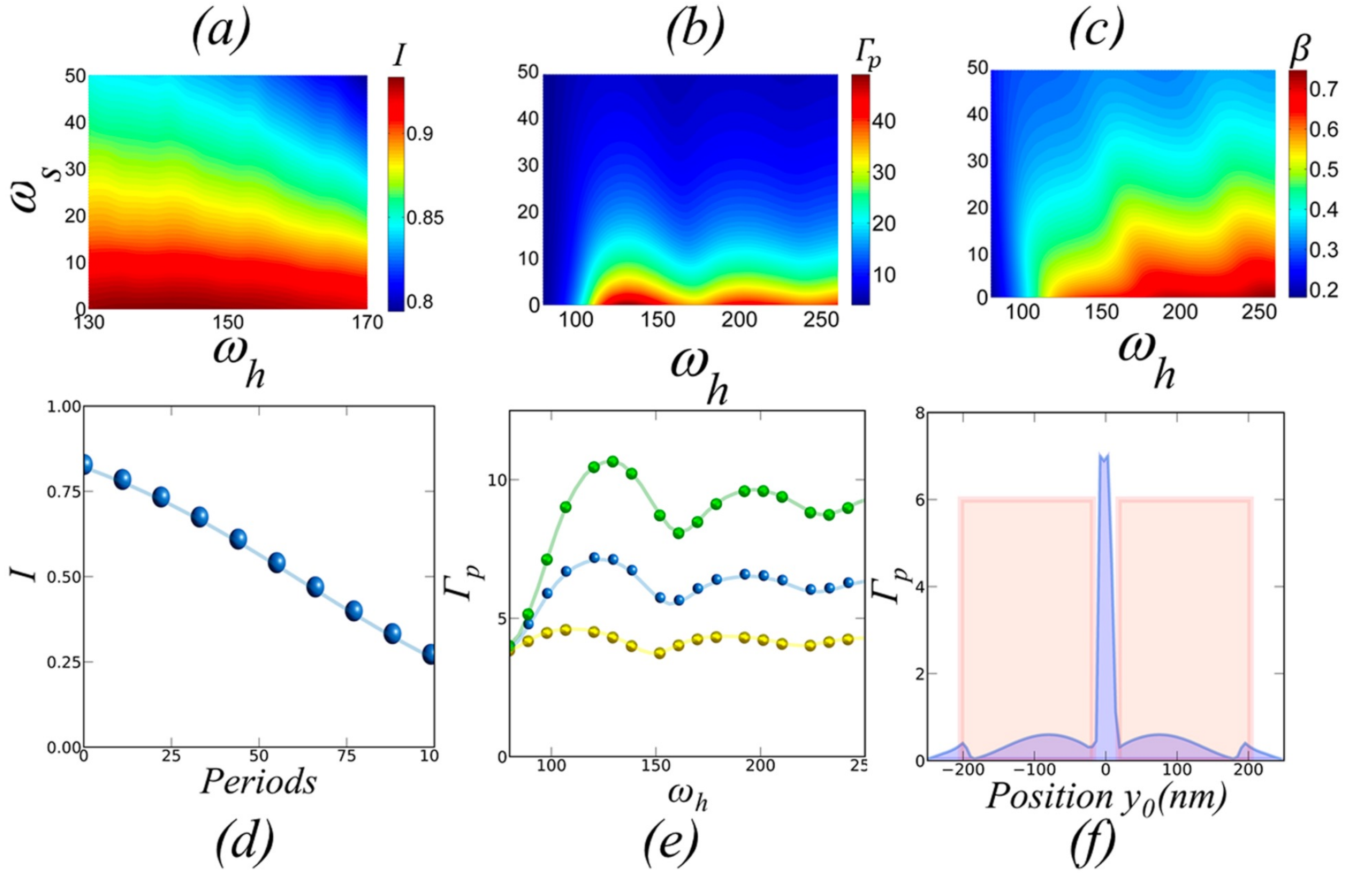


Obtaining (g/γ)min for I > 0.9 for different Q-emitters

Emitter	λ (nm)	t(nm)	L(nm)	Λ(nm)
QDs InGaAs	915	900	263	263
QDs GaAs	916	900	263	263
TMDC	728	710	210	210
S.molecules	785	770	225	225
Diamond c.c.	685	680	195	195

J. Guimbao et al. ACS Photonics (2022), 9, 6, 1926-1935

Indistinguishable photons in Slot-Bragg hybrid cavity II



(a) Cavity-induced I when $\gamma/\gamma^* = 10^4$ versus waveguide width (ωh) and slot width (ωs) for #p = 10

(b) Purcell enhancement (Γp) versus waveguide width (ωh) and slot width (ωs)

(c) Coupling efficiency (β) versus waveguide width (ωh) and slot width (ωs) for #p = 10

(d) I versus number of grating periods (#p) for (ωs, ωh) = (5 nm, 140 nm).

(e) Γp versus ωh for three ωs (green, ωs = 15 nm; blue, ωs = 20 nm; yellow, ωs = 25 nm)

(f) Γp versus source position (y_0)

Indistinguishable photons in Slot-Bragg hybrid cavity III

Table 1. Maximum (ω_s (nm), #p) for $I > 0.9$ Using InGaAs QD, GaAs QD, TMDCs, and Single Molecules as QE

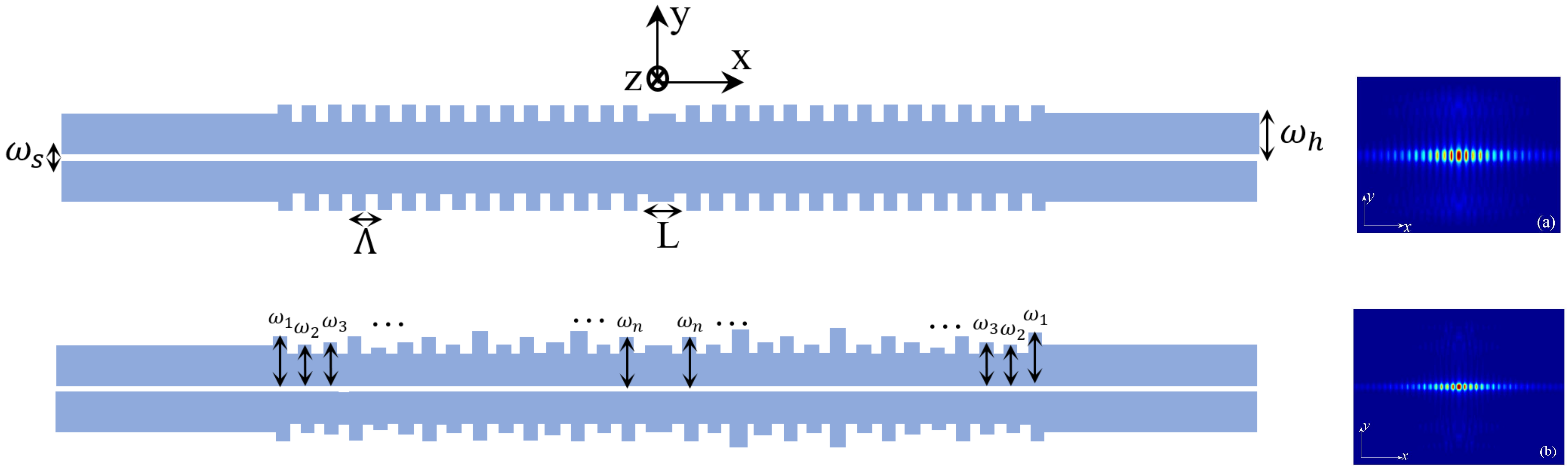
	$\gamma^* = 10^2\gamma$	$\gamma^* = 10^3\gamma$	$\gamma^* = 10^4\gamma$
InGaAs	(43,100)	(36,50)	(15,10)
GaAs	(41,100)	(30,50)	(9,10)
TMDC	(36,120)	(25,60)	(5,12)
S.molecules	(40,120)	(28,60)	(8,12)
Diamond	(45,100)	(38,50)	(15,10)

For high dissipative emitters with $\gamma^* = 10^4\gamma$, the width of the cavity slot must be $\omega s < 10$ nm for $I > 0.9$. Similarly, $\omega s < 10$ nm is needed for $\beta > 0.7$. Also, the emitter's position plays a critical role, giving very low coupling when the emitter is outside the slot region.

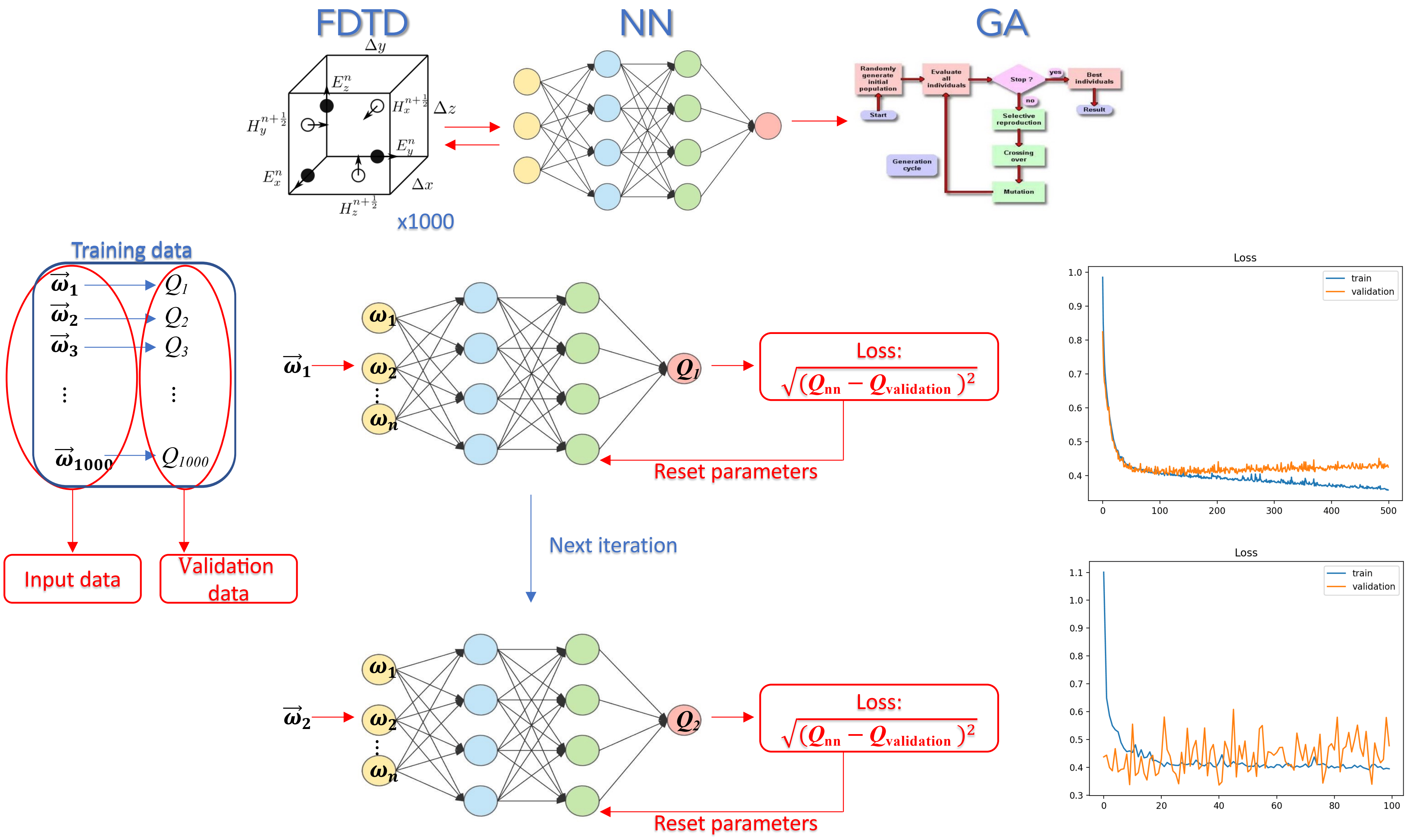
These requirements make complex both the fabrication and the emitter integration. Achieving slot widths below 10 nm is technologically very demanding, and deterministic deposition of a QD with that accuracy can be complicated.

Can we do something to reduce those limitations?-> Further optimization of the geometry

Slot-Bragg hybrid cavity optimization my Machine Learning

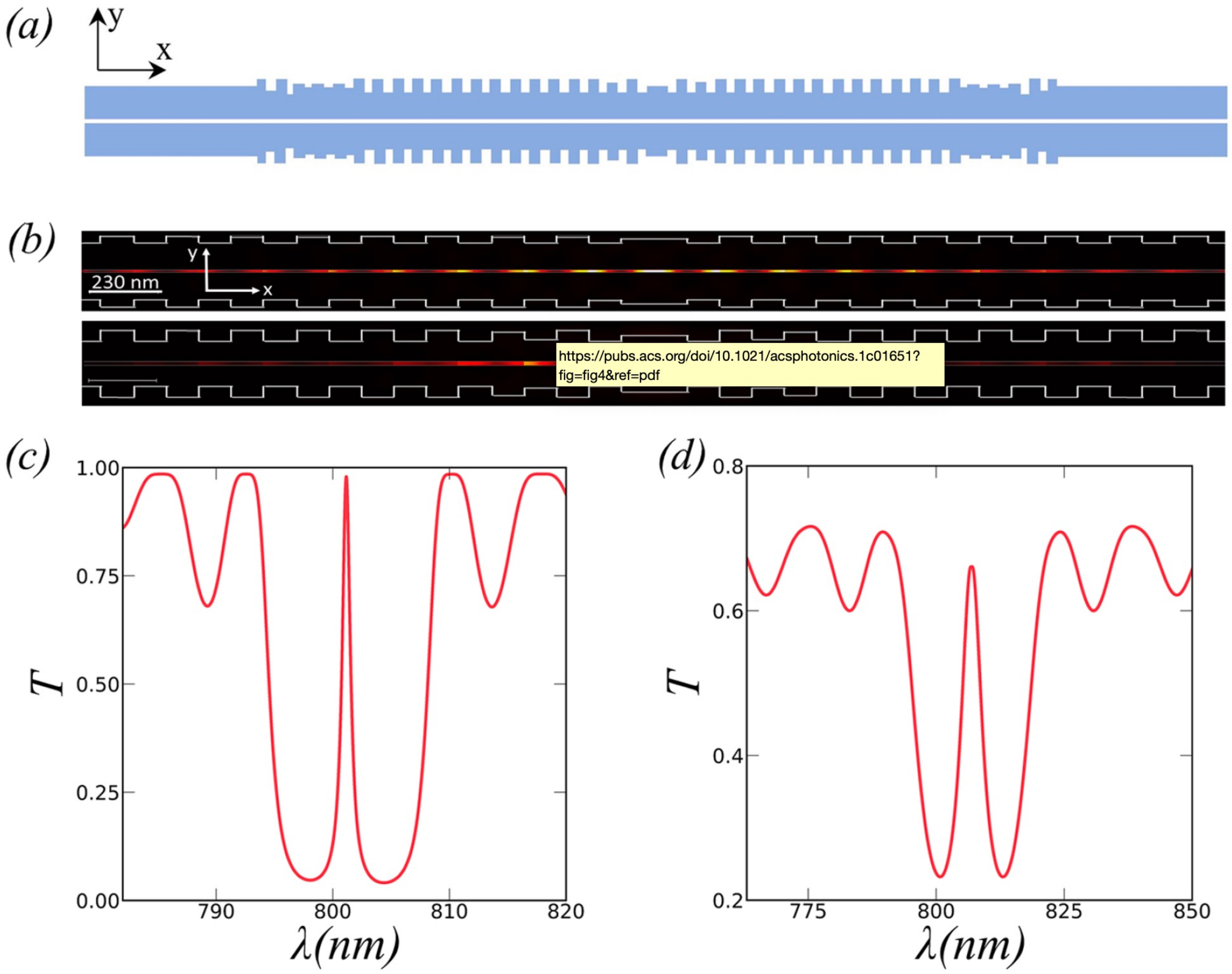


- We perform a hybrid GA-NN optimization of the Bragg corrugation geometry.
- The GA-NN optimization must deal with the trade-off between reducing the cavity modal volume (to increase g) and maintaining the Q to achieve I > 0.9 with $\gamma^* = 10^4\gamma$



J. Guimbao et al. CLEO Europe (2022)

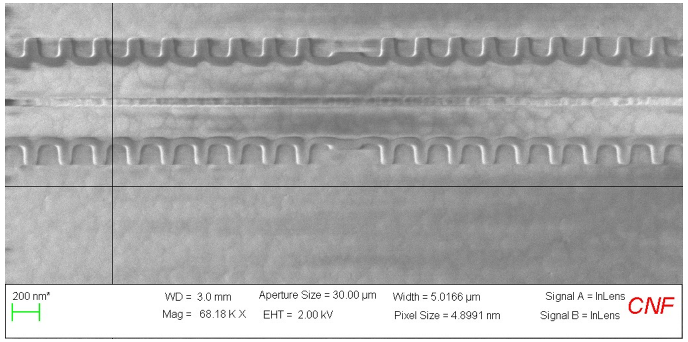
Results



We set ωs = 20 nm and #p = 20.

Optimization by GA-NN gives a reduction in the modal volume of 2.8

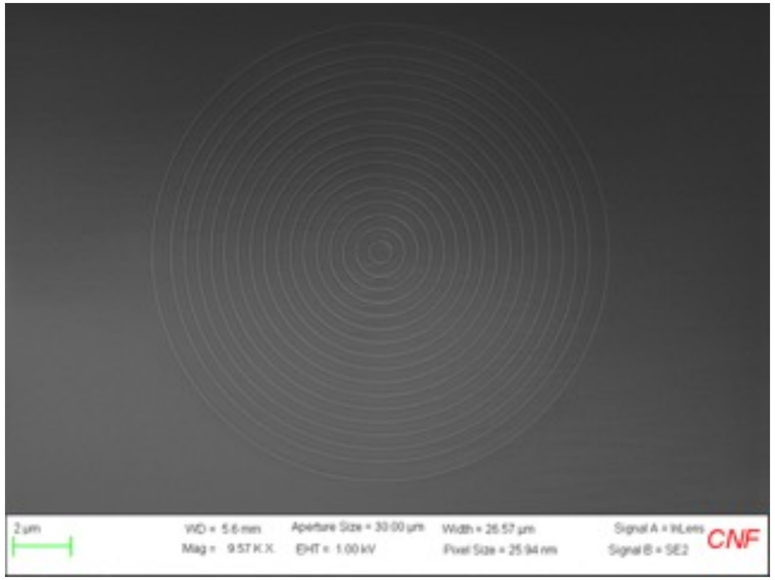
With this design, we can successfully achieve **I > 0.9 with γ^* = $10^4\gamma$ and duplicate the slot width to 20nm**

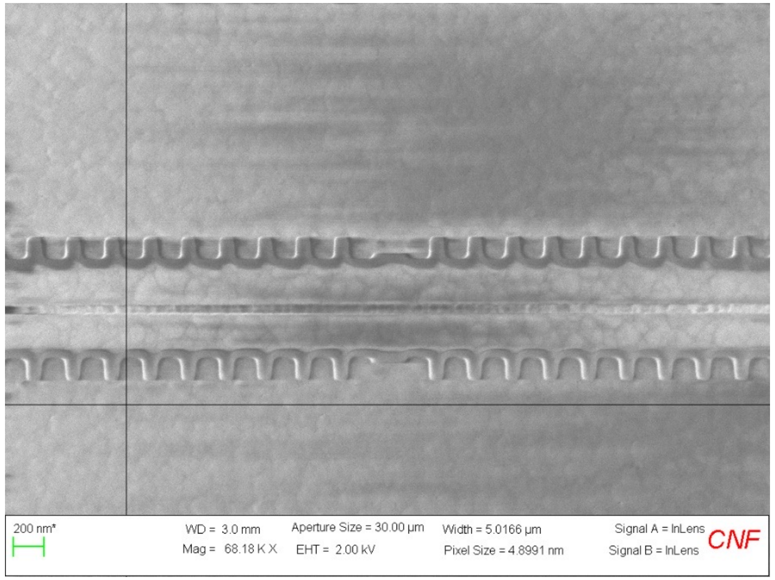


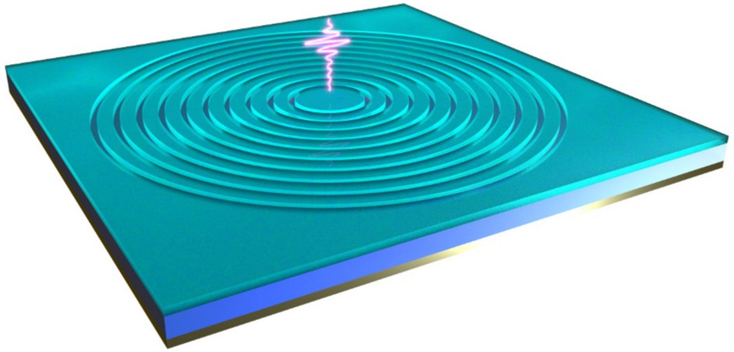
In collaboration with Prof. J. Cardenas and M. Song, UoR

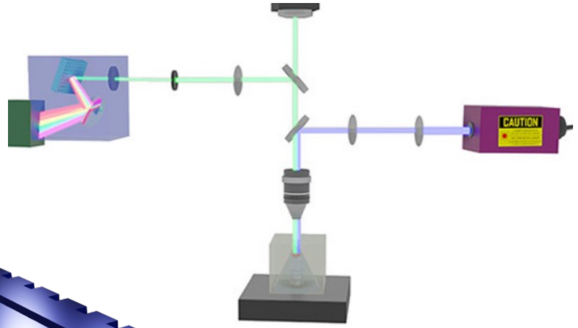
J. Guimbao et al. ACS Photonics (2022), 9, 6, 1926-1935

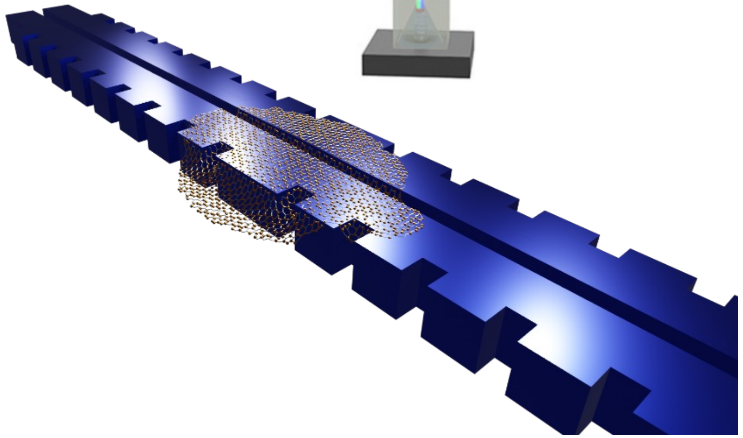
Work in progress





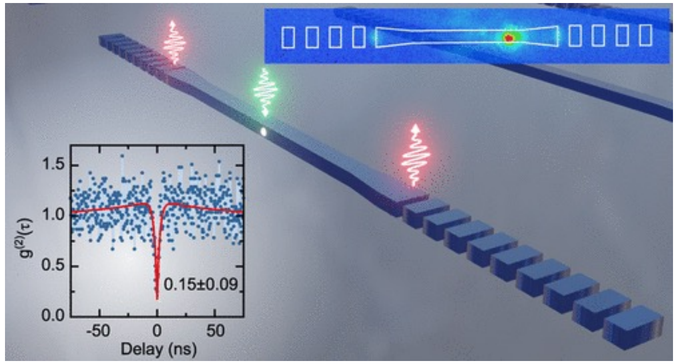




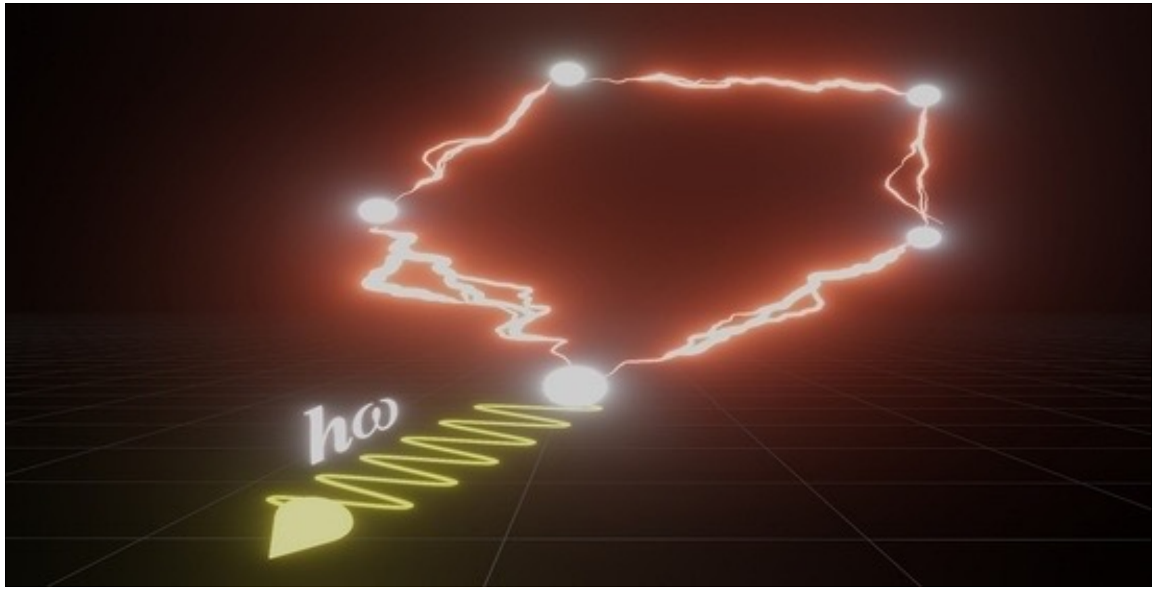


In collaboration with **Prof. J. Cardenas, Prof. N. Vamivakas, Prof. S. Lukishova, Yi Zhang, R. Johnson, N. Achuthan, M. Sanchez and Dr. M. Song, UoR**

Room-temperature single-photon emitters in silicon nitride
Senichev et al., Sci. Adv. 7, (2021)
ACS Photonics (2022), 9, 10, 3357–3365

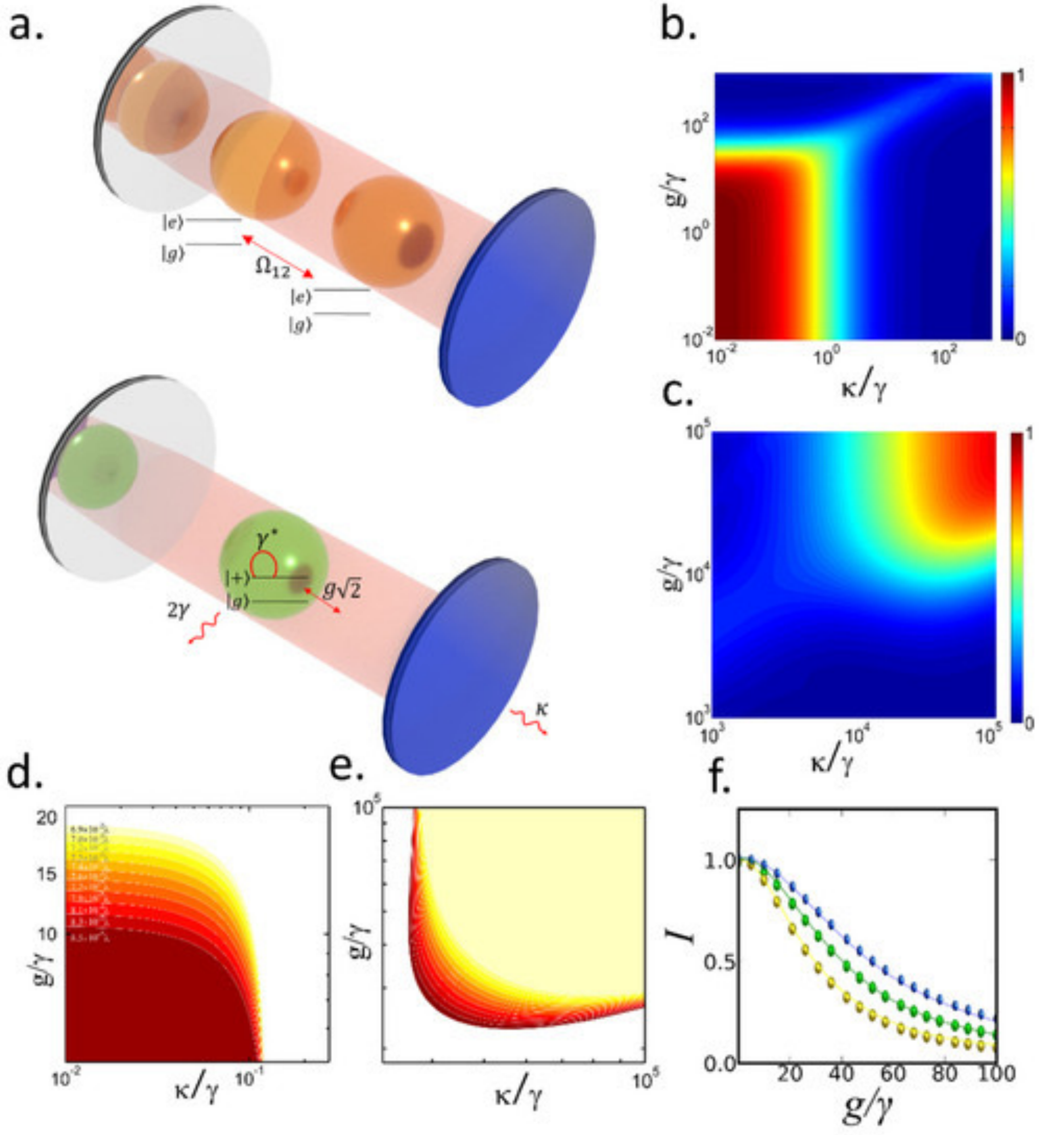


Indistinguishability from a Set of Dissipative Q-Emitters



- Can we estimate *I* in a two-emitter system with strong dephasing coupled to a single-mode cavity?
- Can we estimate *I* for even larger systems (i.e., systems with more than two emitters)?

Indistinguishability from 2 Dissipative Q-Emitters



I > 0.9 vs d, which ranges from d = 6.9x10^{-2} to d = 8.5x10^{-2} (λ units). Whereas the maximum g for I > 0.9 is about g = 10 γ when d = 8.5x10^{-2} , this value increases to g = 20 γ when d = 6.9x10^{-2} . In other words, the requirement for Q (i.e., $k < g$) remains unchanged and the R-reduction effect just enables high I for higher g values, which is not particularly interesting.

Therefore, the implementation of the two-QE system **does not provide any practical advantages** (coherent or incoherent regimes) in terms of Q and g with respect to the single-QE

d=6.9×10^{-2}λ (blue)
d=7×10^{-2}λ (green)
d=7.2×10^{-2}λ (yellow)

J. Guimbao et al. *Nanomaterials* **2022**, *12*(16), 2800

Indistinguishability with more than 2 Dissipative Q-Emitters

Incoherent regime, 2 emitters

$$R = \frac{4g^2\Gamma}{\Gamma^2 + \frac{\gamma^2}{(kd)^6}}, \; I = \frac{\gamma\kappa\left[\Gamma^3 + \Omega_{12}\right] + \left[4g^2(\gamma+1) + \Omega_{12}\frac{\kappa\gamma}{\Gamma}\right]\cdot\left[\Gamma^2 + \Omega_{12}\right]}{\left[\Gamma^2 + \Omega_{12} + 8g^2\right]\cdot\left[\kappa\Gamma^2 + \Omega_{12} + 4g^2\Gamma\right]}$$

For more than 2 emitters: we can derive analytic expressions of *I* for arbitrary large number of emitters without having to compute the ne-G. Instead, we obtain *I* from the determinant Δ and the trace τ of the matrix rate equations describing the single QE coupled to a single-mode cavity field:

$$\begin{pmatrix} \dot{P}_{QE} \\ \dot{P}_C \end{pmatrix} = \begin{pmatrix} -(\gamma+R) & R \\ R & -(\kappa+R) \end{pmatrix} \begin{pmatrix} P_{QE} \\ P_C \end{pmatrix}$$

which significantly simplifies the problem for systems with more than two emitters (or a single emitter and more than 1 cavity). This finding can be expressed as:

$$\boxed{\bar{\theta} = I = \frac{\overline{\Delta}}{\tau} = \frac{\gamma + \frac{\kappa R}{\kappa+R}}{\kappa + 2R + \gamma}}$$

J. Guimbao et al. *Nanomaterials* **2022**, *12*(16), 2800

Indistinguishability with more than 2 Dissipative Q-Emitters

Adding more subsystems (emitters and/or cavities) **provides additional paths** to maintain stability and relax the cavity requirements for high *I*.

Ok, lets go for a cluster of **five QEs** coupled to a single-mode cavity field: 10 transfer rates (Rij) etc.

highly non-trivial problem and computationally very time-consuming (!)

Solution: **ML scheme (NN-GA algorithm**) ->very short computational times ->best geometrical configuration for the emitters.

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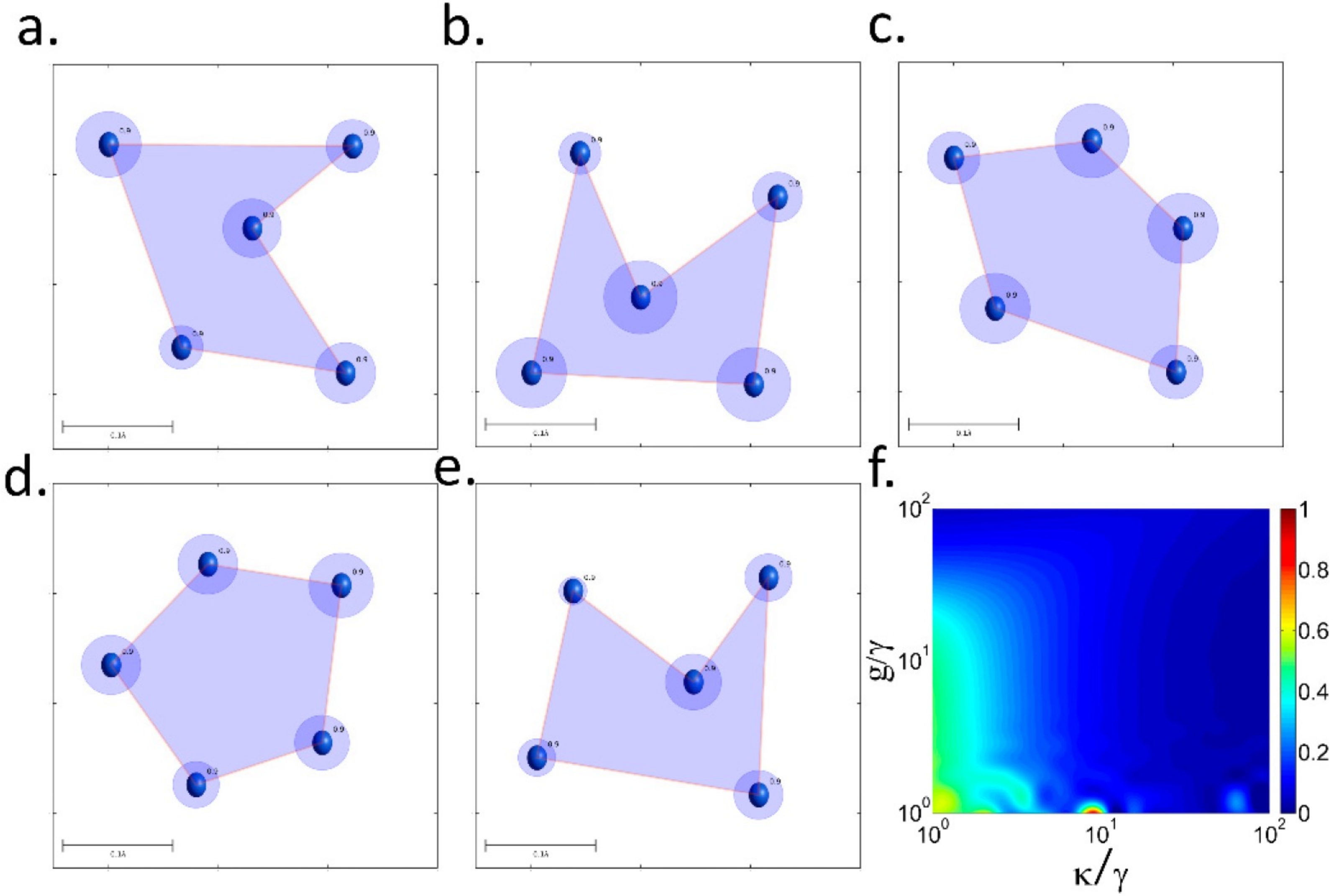
Indistinguishability with more than 2 Dissipative Q-Emitters



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CONCLUSIONS

Using ML may provide insights on optimizing different photonic structures for quantum information applications, such as the reduction of quantum decoherence in photonic cavities or clusters of coupled two-level quantum systems.

Thanks to J. Guimbao, L. Weituschat, J. Llorens, L. Sanchis, J. Cardenas, M. Song, Y. Zhang

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