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POSEIDON

NanoPhOtonic devices applying Self-assembled colloIDs for novel ON-chip light

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Executive Summary

In this deliverable the updated target specifications for our POSEIDON light sources are compared to the achieved experimental results for sensing in the visible spectrum and for single photon emitters, whereas the case of Mid-IR sensing is discussed.

For the visible spectrum sensing we reached or got close to many goals. However, as expected since the proposal phase, the most challenging aspect is scaling up the useable output power of such tiny emitters. Furthermore, we were able to build and characterize electrically pumped "quantum emitters", which are in principle suitable for single photon emission and wafer scale fabrication.

Outside of POSEIDON there has been remarkable progress on chip-scale integrated light emitters and lasers, be it optically or electrically pumped, even though the perfect solution does not yet exist. The area where the progress from POSEIDON is unique is to extract the maximum emission from each QD via the plasmonic antennae, in a configuration that is suitable for wafer-scale waveguide integration.

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1. Introduction

The aim of this deliverable is to review the simulated and experimental results of POSEIDON and compare them with the specification table reported in D1.2. This includes considerations on manufacturing scalability of the POSEIDON emitters and an updated overview of the competition.

Compared to the first version of the specification table, listed in deliverable D1.1, the telecommunication use case has been dropped. The reachable output power was a major concern, as well as the lack of stability of available infrared quantum dots (QDs) based on PbS. Instead, in addition to the originally foreseen sensing in the visible range, two new use cases were added: Mid-IR sensing and single photon emission for photonic quantum technology. These adjustments were discussed and developed together with the project's External Advisory Board (EAB). Some early results on quantum emitters will be presented, whereas for practical trials towards the Mid-IR we were lacking a suitable active emitter material.

2. Results and discussion

The requirements of different application fields of integrated on-chip light sources differ significantly. In the original specification table from D1.1 it was chosen to focus on two application fields: 1. information and communication technology (ICT) and 2. sensing. Separate specification tables were created for them. Since the Consortium has identified single photon emitters as a promising application instead of ICT, table Table 3 has been modified to consider different figures of merit that are relevant for single photon sources. Furthermore, Table 2 has been added to include the Mid-IR range.

For each individual property a "minimum requirement" value and the "optimum" are specified. The reasoning behind this is that compromises are possible to work round certain "non-optimal" aspects of a light source, including limiting its application scope, whereas certain basic specifications have to be fulfilled in order for the solution to be seriously considered.

2.1. Colloidal on-chip light source for visible sensing applications

The main work in POSEIDON has focused on optically pumped light emitters for the visible wavelength range. Table 1 shows a comparison of the experimentally reached values and the targeted specifications, based on deliverable 1.2.

Table 1: Comparison for target specifications and experimental results for optically pumped visible and near infrared sensing. Color coding: green for "well achieved", orange for "reasonably close to the target" and red for "still insufficient" properties.

Parameter	Minimum requirement	Optimum	Achieved
Wavelength	650 nm	450 -900 nm	**640 nm**
Luminescence bandwidth	30 nm	30 nm	**30 nm**
Plasmonic antenna enhancement	10	100	**7 – 40**
Output power at 1 mW input power	1 µW	100 µW	**50 pW – 0.5 nW**
Internal quantum efficiency	10 %	90 %	**?**
External quantum efficiency	0.1%	10%	**0.01%**
Coupling to waveguide	10 %	30%	**5 – 20%**
Emission lifetime	-	-	**2 ns**
Coherent emission	no	filtering	**?**
Quality (Q) factor of loaded nanophotonic resonator	1,000	100,000	**?**
Process compatibility	Light source last	Full	**Light source last**
Integration with waveguide material	Si_3N_4	Si_3N_4	**Si_3N_4**
Wafer-scale processes	no	yes	**Partly**

The minimum **wavelength** requirement has been chosen to match readily available and stable CdS/CdSe QDs. This goal was reached because we chose exactly such QDs and we could extend the spectral coverage by shifting to other sizes of the same QD type. The optimum range has been chosen as approximately the complete visible spectrum to allow a broad range of potential applications. However, these targets do not exclude other wavelengths from being potentially useful for sensing. We chose the wavelength range 450-900 nm as longer wavelengths are not easily detected with cheap Si photodetectors and for wavelength shorter than about 450 nm the losses of integrated waveguides, especially made of Si_3N_4, increase significantly.

The **luminescence bandwidth** of the material determines the flexibility to cover different wavelengths with the same material. It is practically limited by the photoluminescence bandwidth of the QDs, which have full-width-at-half-maximum (FWHM) of approximately 30 nm. Obtaining broader FWHM from a single material is not feasible, therefore the target in the specification table has been set to 30 nm and reached experimentally.

For the **plasmonic antenna emission enhancement** a factor between 10 and 100 is targeted. The reasoning is that with a factor of 10 one gains an order of magnitude compared to simpler emitters, which may already warrant the additional fabrication complexity. The optimum target of 100 is chosen to consider that while enhancements larger than 1000 can be computed for some configurations, such structures are often notoriously difficult to fabricate and require a high level of perfectness, which is not going to be present in fabricated devices. Experimentally we have achieved an enhancement factor of 7 to 40 compared to QDs without antennae, well within the target range.

The **optimal output power** target is set to a value readily available from commercial light emitting diodes. The minimum specification is set significantly lower, targeting applications which prefer lower cost over maximum sensor performance. On the experimental side the output power is a pain point, as expected from the beginning of the project. We have focussed on optimizing small, almost point-like emitters via plasmonic antennae and reached about 50 pW output power through the waveguide for 1 mW of input power, exciting with 500 – 550 nm light. Using 405 nm excitation we have reached about 0.5 nW of output power due to higher absorption of the QDs. The antenna gain drops to a factor of 4 compared to reference samples with pure QDs, as 405 nm is out of resonance of our DoD antenna. With antenna geometry adjustments to create a resonance for 405 nm excitation a further enhancement of a factor of 10 would yield 5 nW output power, which is two orders of magnitude below the target specification.

Generally, the output power should not be generated by inefficient means. This was specified by the **internal quantum efficiency** of the emitters and the **efficiency of coupling** them to the photonic waveguides. For both values the minimum target is set to approximately 10 %, as below this value the emitters will probably not be used in real devices. Based on our simulations the coupling efficiency is well within the target range, depending on the specific emitter configuration. Experimentally we have been able to estimate the external quantum efficiency of our plasmonically enhanced emitters as 0.01%. This number seems small compared to the targeted internal quantum efficiency, but it includes all non-idealities of the experiment, i.e. everything from the pump laser output until the entrance of the detector.

For the luminescence **emission lifetime,** we cannot deduce a meaningful target. However, we were able to characterize our emitters and saw a reduction from 20 ns for pure QDs to about 2 ns for our plasmonically enhanced emitters due to the Purcell effect. This shorter lifetime increases the radiative yield compared to non-radiative recombination and allows faster direct modulation of the emitters.

At this stage of the project, it becomes evident that obtaining typical laser emission from self-assembled emitters will be extremely challenging. Instead, in the optimum case it may be realistic to obtain some degree of temporal **coherence** by filtering the broad band emission or via enhancement of the emission to spectrally narrow resonance modes. Due to the low output power of our emitters, we were not able to check them for any (partial) coherence.

The **quality factor** of nanophotonic resonators drops once they are loaded with POSEIDON emitters, or more generally any material causing additional loss. The target is to minimize the loss of Q, i.e. the absorption of pump light by the QDs should dominate over losses from scattering or other imperfections. While we have fabricated Si_3N_4 resonators and loaded them with POSEIDON QDs, we were not able to pinpoint the effect on the Q factor.

The **process compatibility** of the light source has to allow “light source last”, i.e. the fabrication on top of otherwise finished photonic integrated circuits (PICs). Optimally, full integration could be enabled by encapsulating the active material like QDs by e.g. SiO_2, so that all further fabrication steps could be performed as usual. We have achieved “light source last” integration, with a severe limitation being the lack of stability of deposited QDs to the harsh environments during semiconductor fabrication, like high temperatures and high-density plasmas.

Wafer-scale processes are necessary for cost-effective production of the light sources and are aimed to be reached for the sensing light source. We partly succeeded in this goal. The sample-wise steps needed in POSEIDON can be performed on wafer-scale: the disk-on-disk (DoD) fabrication would simply need evaporation and sputtering chambers sufficiently large for the nanophotonic wafers, and the monolayer QD deposition would need a sufficiently large chemical setup or the option to deposit thin multilayers, which would be suitable for e.g. the DoD configuration.

2.2. Colloidal on-chip light source for Mid-IR sensing applications

The current section received minor updates compared to the corresponding one in deliverable 1.2, as we did not have an active material for Mid-IR emission available.

Table 2: Target specifications for integrated light source for sensing in the Mid-IR range.

Parameter	Minimum requirement	Optimum
Wavelength range	3 – 5 µm	3 – 10 µm
Bandwidth	100 nm	1 – 500 nm
Output power	1 µW	1 mW
Coupling to waveguide	10 %	90 %
Quality (Q) factor of loaded nanophotonic resonator	10	100
Process compatibility	Light source last	Full
Integration with waveguide material	Si	Si + Ge
Wafer-scale processes	no	Yes

The Mid-IR **wavelength** range is particularly useful for detection of organic molecules by measuring their absorption spectra. For this purpose, the light source has to emit light over a broad spectral range that allows to capture molecule signatures. The minimum requirement is 3 µm to 5 µm range that would allow to identify e.g. CO_2 [1] and can be integrated with the suspended Si waveguide platform developed by AMO. Ideally, the source or variations thereof, should be able to extend to 10 µm, which will allow to identify e.g. explosives such as TNT.

The minimum **bandwidth** needed to conveniently identify specific molecules is approximately 100 nm. Ideally the bandwidth should reach 500 nm to increase the accuracy and allow for sensing of multiple molecules. Alternatively, narrow-band emitters can be used to probe only specific gas absorption lines.

The **output power** is crucial to ensure high signal to noise ratio of the sensor. 1 µW is the bare minimum, which may still be useful for sensing using state of the art detectors. In a practical device it should reach values closer to 1 mW.

The **Quality Factor** of photonic resonators is set to comparably low values. Its main role is to direct the emission into a waveguide without narrowing the spectrum. Too high Q factors would result in spectrally narrow emission, which may be difficult to align precisely with molecular resonances.

As a minimum requirement the source should be **integrated** with silicon waveguides on a single chip level, which is necessary to demonstrate the feasibility of this approach. Ideally, it should be possible to integrate these sources also with germanium waveguides, which are used to extend the Mid-IR range covered down to 10 µm wavelength. In the optimal case this should be possible on a wafer scale.

Initially, the sources could be integrated last. Ideally however they should be fully compatible with the wafer **fabrication process**, so that additional layers, e.g. electrical connections, can be fabricated after the source.

2.3. Colloidal on-chip light source for single photon emission

In this section we compare the specification wish list of integrated single photon emitters with the devices fabricated and characterized in POSEIDON based on a recent publication by the consortium [2]. The measured devices are electrically pumped Nanoparticle-on-Mirror (NPoM) devices based on commercially available CdSe/CdS QDs, described in detail in deliverable 4.3. It is safe to call them quantum emitters, as the QDs are known to emit from well-defined quantum states and can be used for single photon emission, as shown in Fig. S6 of reference [2]. However, it was experimentally not yet possible to verify the single photon emission on the NPoM device. The explanation as given in [2] is:

"*To confirm that the device can provide single-photon emission, photon correlation experiments were developed; however, the typical Purcell enhancement in such plasmonic nanocavities is predicted to reduce the radiative lifetime by ~10^3-fold. This effect is anticipated to be significant in the NPoM geometry due to the strong field confinement. Given the bare QD lifetime τ_0 ~ 30 ns, we estimate cavity-enhanced lifetimes to be <10 ps, which is far below the resolution limit (1 ns) of our single-photon detectors, preventing so far the effective characterization of $g^{(2)}$ correlations in EL (Figure S6).*"

Table 3: Comparison for target specifications and experimental results for POSEIDON quantum emitters. Color coding: green for "well achieved", orange for "reasonably close to the target" and red for "still insufficient" properties.

Parameter	Minimum requirement	Optimum	Achieved
Wavelength /nm	650	1260 - 1600	**620 - 750, bias dependent**
Count Rate /s	10^3 - 10^6	10^6 - 10^9	**10^4 - $3{\cdot}10^5$**
Output power	0.3 fW – 0.3 pW	0.16 pW - 120 pW	**0.1 pW**
Brightness	0.05	0.5	**?**
Power efficiency	-	-	**10^{-4}%**
Purity ($g^{(2)}(0)$)	0.2	0.02	**?**
Indistinguishability	0.5	0.9	**?**
Emission lifetime	-	-	**<100 fs**
Quality (Q) factor of loaded nanophotonic resonator	10^4	10^6	**?**
Threshold turn-on voltage	<100 V	<3 V	**2.0 V**
Process compatibility	Light source last	Full	**Light source last**
Integration with waveguide material	Si_3N_4	SOI	**Feasible**
Wafer-scale processes	no	yes	**Partly**

The target optimum **wavelength** has been chosen to match the classical telecommunication wavelengths to achieve best compatibility to optical fibers and SOI photonics that can manipulate single photons. However, these targets do not exclude other wavelengths from being potentially useful, e.g. for sensing or with the help of wavelength conversion. In the project we are sticking to the same wavelength range as for the emitters for sensing due to using the same type of QD emitters.

The **count rate** is the single photon emission rate, as counted by single photon detectors. Values in the kHz to MHz range are already useful, whereas some reports in the GHz range have already appeared. Our NPoM emitters based on single QDs have achieved 10^4 counts/s using single photon detectors. However, due to problem of the employed detectors being too slow to resolve the dynamics of these emitters, each such detection event may contain multiple photons. We have thus estimated the photon rate based on the **average emitted power** of 0.1 pW, which yields $3{\cdot}10^5$ photons/s, i.e. a factor of 30 more. These values are close to our "Optimum" target specifications.

Brightness is the ratio of useful photons collected by the waveguide to the number of generated photons per excitation pulse. This figure of merit is mainly affected by the efficiency of coupling of the emitter to the waveguide. As our emitters do not yet have a waveguide (and no **nanophotonic resonator**), we are not able to state a meaningful number. However, we have estimated the **power efficiency** to be around 10^{-4}%, which would not yet allow us to get close to the brightness targets.

Purity describes the ability of the source to emit single photons instead of multiple photons. The $g^{(2)}(0)$ is the 2nd order correlation function that characterises the source. Values close to 0 represent high purity. **Indistinguishability** is another important parameter – a high value means that generated photons have identical energies and polarisation. We were not able to measure these properties in our devices due to the estimated **emission lifetime** below 100 fs.

A property of practical importance is the **turn-on voltage threshold** to drive the emitter. We've set the minimum requirement to less than 100 V to be compatible with typical lab equipment and not to run into high risk of breakdowns, whereas in the optimal case of less than 3 V the emitters can be driven by simple CMOS output drivers. Our devices have a typical threshold of 2.0 V, fulfilling this requirement.

The **process compatibility** of the light source has to allow fabrication on top of otherwise finished PICs, as we have achieved in POSEIDON. Optimally the active material like QDs would be encapsulated by e.g. SiO_2 so that after their deposition and encapsulation all fabrication steps could be performed as usual.

The light source is targeted for integration with silicon nitride waveguides, but **compatibility** with silicon on insulator (SOI) would be a strategic advantage. This is of high importance to demonstrate feasibility of the colloidal light source approach via integration of lasers into silicon based photonic and electronic chips. The approach chosen in POSEIDON uses gold (Au) for plasmonic enhancement, which is problematic in SOI integration, but safe for the "light source last" approach, especially at temperatures which the QDs still survive.

Since quantum technologies are still an emerging technology, **wafer scale processing** is not strictly required at this stage. In POSEIDON we have achieved partial compatibility, in the sense that the sample-scale process steps could be developed into wafer-scale processes (see section 2.1).

3. Updates to the state of the art

In the quest for compact integrated photonic components, the focus extends to on-chip light sources. Trapping light on the nanometer scale using metals, and generating highly localized hotspots, gives rise to the field of plasmonics. This domain has significantly contributed not only to sensing and metamaterials but also serves as light sources through Purcell-enhanced modification of emitter emission rates. There have been over 2 decades of advancement in spasers and plasmonic nanolasers [3,4]. Even though being electrically injected, almost all of them are III-V semiconductor based and bring with them fabrication and cost related challenges for integration with silicon-based PICs. Multiple options for III-V integration of lasers and light emitting diodes (LEDs) onto silicon chips, ranging from hybrid to monolithic integration are being pursued by companies and institutes like Cisco, Rockley Photonics, Intel, Tower Semiconductor, IMEC, Ghent University, etc. Some of these established methods include flip-chip integration, pick and place of packaged lasers, hetero-epitaxial growth, die-to-wafer bonding, and micro-transfer printing [5–7]. Although many of them have progressed since the beginning of POSEIDON, some unresolved challenges persist such as cost, low throughput due to sequential integration, scalability to multiwavelength sources, risk of Si fab contamination, risk of yield and reliability during multi module alignment, etc. Hence simple and cost-effective wafer-scale integration of colloidal semiconductor quantum emitters has gained a considerable interest owing to its potential to revolutionize optoelectronic and quantum photonic technologies [2]. For spectrally broad lasing applications like comb lasers or widely tuneable lasers and advanced modulation schemes, QDs as emitters or gain medium have higher performance than quantum wells (QW), resulting in a giant leap towards monolithic integration of light sources on Si [5,7]. Moreover, despite the tremendous success of lasers based on III-V semiconductors, there are certain technologies that could benefit from the availability of lasers and LEDs based on solution-processable material [8].

Placing radiative emitters in Purcell enhanced cavities and waveguide integration has been reported in works like [9]. However, this involves ion implantation of rare earth metal Er^{3+}. There have been similar attempts to create a hybrid of plasmonic and photonic modes using selectively deposited CdSe/ZnS QDs [10]. Nevertheless, these nano-focusing structures necessitate an extremely precise gap control of a few tens of nanometers, thus presenting a significant challenge for top-down fabrication. But using simple colloidally deposited QDs and integrating them with Au based metal-insulator-metal (MIM) cavities on configurations like NPoM was shown very simple and cost-effective by our consortium [2,11,12]. Within POSEIDON we have for the first time experimentally demonstrated the integration of such NPoM based light sources with silicon nitride (Si_3N_4) waveguides on a silicon PIC (see section 2.1). However, the upper metal being deposited via colloidal gold nanoparticles (AuNPs) there is an inherent randomness associated with NPoMs. Hence, we have also experimentally demonstrated for the first time a patch nanoantenna called disk-on-disk (DoD) nanoantenna integrated with the same Si_3N_4 waveguides using a structured and deterministic top-down patterning. Some numerical feasibility studies on similar patch nanoantennae were done earlier by Esteban et. al. [13,14].

An overview of recent progress on integrated lasers based on colloidal QDs is given in references [8,15]. Noteworthy developments include the creation of a near-IR laser based on self-assembled Ag_2Se QDs and a visible laser based on self-assembled CdSe/CdS core-shell QDs [16,17]. This validates our goal of using self-assembly to create such optically pumped light sources, even though the authors have used the "coffee ring" effect, which is neither well controllable nor scalable to wafer size. There have also been demonstrations of electrical pumping to reach amplified spontaneous emission, albeit not yet reaching lasing in this recent Nature publication from 2023 [18]. Important material related bottlenecks have been overcome in that work, reaching 170 µW of output power. The main problem we see with this approach is that the material stack is rather exotic, and the emitter is not well suited for integration with classical photonic platforms or the back-end-of-line CMOS chips. In a slightly earlier work the same group has used very similar structures to achieve optically pumped lasing at liquid nitrogen temperature with the help of electrical injection, combining both pumping schemes in one device for enhanced control [19]. In any case, the QD engineering for maximum gain is key to build successful light emitters, which is an area where the POSEIDON approach could benefit from e.g. graded index QDs as used in the last two references.

Furthermore, there is also a report on Mid-IR electroluminescence from QDs [20]. Since stable semiconductors with suitable band gaps are not readily available, the authors have chosen to use intra-band transitions, like in a quantum cascade laser. This may be the active media needed to apply the plasmonic enhancement from POSEIDON to the Mid-IR range.

It is also noteworthy that beyond academic research, the use of QDs has sprouted to industries as well. Quandela, a company of French origin who specializes in the production of photon-based quantum computing and cloud solutions uses semiconductor QDs placed in a cavity with electrical contacts to tune the QD emission via the Stark effect. Sparrow Quantum, of Denmark origin, has shown a single-photon source based on self-assembled InAs QDs coupled to a slow-light photonic-crystal waveguide.

4. Conclusions

In this deliverable the updated target specifications for our Si_3N_4 POSEIDON light sources are compared to the achieved experimental results for sensing in the visible spectrum and for single photon emitters, whereas the case of Mid-IR sensing is discussed.

For the visible spectrum sensing we reached our goals in terms of spectral coverage, gain bandwidth, plasmonic antenna enhancement, waveguide coupling efficiency and integration with Si_3N_4 waveguides and got reasonably close to the targets in terms of best-case output power, external quantum efficiency, wafer scale processing and process compatibility. As expected since the proposal phase, the most challenging aspect is scaling up the useable output power of such tiny emitters.

Furthermore, we were able to build and characterize electrically pumped "quantum emitters", in the sense that single NPoM emitters should emit single photons, albeit at a rate so high that we were not able to resolve this with our existing measurement equipment. As a final strong point, wafer scale fabrication of such emitters coupled to waveguides seems feasible.

Outside of POSEIDON there has been remarkable progress on chip-scale integrated light emitters and lasers, be it optically or electrically pumped, even though the perfect solution does not yet exist. The area where the progress from POSEIDON is unique is to extract the maximum emission from each QD via the plasmonic antennae, in a configuration that is suitable for wafer-scale waveguide integration.

5. Degree of progress

The development of "Specifications compared to D1.2, state of commercialization & scalability" is 100% fulfilled.

6. Dissemination level

The Deliverable D5.4 "Specifications compared to D1.2, state of commercialization & scalability" is public and therefore it will be available to download on the project's website and on demand.

7. References

1. F. Ottonello-Briano, C. Errando-Herranz, H. Rödjegård, H. Martin, H. Sohlström, and K. B. Gylfason, "Carbon dioxide absorption spectroscopy with a mid-infrared silicon photonic waveguide," Opt. Lett. **45**, 109 (2020).
2. J. Huang, S. Hu, D. Kos, Y. Xiong, L. A. Jakob, A. Sánchez-Iglesias, C. Guo, L. M. Liz-Marzán, and J. J. Baumberg, "Enhanced Photocurrent and Electrically Pumped Quantum Dot Emission from Single Plasmonic Nanoantennas," ACS Nano (2023).
3. S. I. Azzam, A. V. Kildishev, R. M. Ma, C. Z. Ning, R. Oulton, V. M. Shalaev, M. I. Stockman, J. L. Xu, and X. Zhang, "Ten years of spasers and plasmonic nanolasers," Light Sci. Appl. **9**, (2020).
4. K. Liu, N. Li, D. K. Sadana, and V. J. Sorger, "Integrated Nanocavity Plasmon Light Sources for On-Chip Optical Interconnects," ACS Photonics **3**, 233–242 (2016).
5. S. Zhang, Y. Liu, R. Lu, B. Sun, and L. Yan, "Heterogeneous III–V silicon photonic integration: components and characterization," Front. Inf. Technol. Electron. Eng. **20**, 472–480 (2019).
6. A. De Groote, J. D. Peters, M. L. Davenport, M. J. R. Heck, R. Baets, G. Roelkens, and J. E. Bowers, "Broadband III-V on silicon hybrid superluminescent LEDs by quantum well intermixing and multiple die bonding," 2014 IEEE Photonics Conf. IPC 2014 **3**, 260–261 (2014).
7. D. Liang and J. E. Bowers, "Recent Progress in Heterogeneous III-V-on-Silicon Photonic Integration," Light Adv. Manuf. **2**, 59 (2021).
8. Y.-S. Park, J. Roh, B. T. Diroll, R. D. Schaller, and V. I. Klimov, "Colloidal quantum dot lasers," Nat. Rev. Mater. **6**, 382–401 (2021).
9. N. A. Güsken, M. Fu, M. Zapf, M. P. Nielsen, P. Dichtl, R. Röder, A. S. Clark, S. A. Maier, C. Ronning, and R. F. Oulton, "Emission enhancement of erbium in a reverse nanofocusing waveguide," Nat. Commun. **14**, 2719 (2023).
10. M. P. Nielsen, L. Lafone, A. Rakovich, T. P. H. Sidiropoulos, M. Rahmani, S. A. Maier, and R. F. Oulton, "Adiabatic Nanofocusing in Hybrid Gap Plasmon Waveguides on the Silicon-on-Insulator Platform," Nano Lett. **16**, 1410–1414 (2016).
11. R. Chikkaraddy and J. J. Baumberg, "Accessing Plasmonic Hotspots Using Nanoparticle-on-Foil Constructs," ACS Photonics **8**, 2811–2817 (2021).
12. R. Chikkaraddy, B. De Nijs, F. Benz, S. J. Barrow, O. A. Scherman, E. Rosta, A. Demetriadou, P. Fox, O. Hess, and J. J. Baumberg, "Single-molecule strong coupling at room temperature in plasmonic nanocavities," Nature **535**, 127–130 (2016).
13. R. Esteban and J.-J. Greffet, "Excitation of thin metallic disks and patch antennas by quantum emitters for single photon sources," in *Plasmonics: Metallic Nanostructures and Their Optical Properties VIII*, M. I. Stockman, ed. (2010), Vol. 7757, p. 775725.
14. R. Esteban, T. V. Teperik, and J. J. Greffet, "Optical Patch Antennas for Single Photon Emission Using Surface Plasmon Resonances," Phys. Rev. Lett. **104**, 026802 (2010).
15. J. Lin, G. He, Y. Hu, and J. Huang, "Advances in Colloidal Quantum Dot Laser Diodes," in *Optoelectronics - Recent Advances [Working Title]* (IntechOpen, 2023), Vol. 6, pp. 382–401.
16. C. Liao, N. Yao, L.-P. Tang, W.-H. Shi, S.-L. Sun, and H.-R. Yang, "Near-infrared self-assembled laser based on Ag2Se quantum dots," Acta Phys. Sin. **72**, 224204 (2023).

17. F. Di Stasio, J. Q. Grim, V. Lesnyak, P. Rastogi, L. Manna, I. Moreels, and R. Krahne, "Single-Mode Lasing from Colloidal Water-Soluble CdSe/CdS Quantum Dot-in-Rods," Small **11**, 1328–1334 (2015).

18. N. Ahn, C. Livache, V. Pinchetti, H. Jung, H. Jin, D. Hahm, Y.-S. Park, and V. I. Klimov, "Electrically driven amplified spontaneous emission from colloidal quantum dots," Nature **617**, 79–85 (2023).

19. N. Ahn, Y. Park, C. Livache, J. Du, K. Gungor, J. Kim, and V. I. Klimov, "Optically Excited Lasing in a Cavity-Based, High-Current-Density Quantum Dot Electroluminescent Device," Adv. Mater. **35**, 2206613 (2023).

20. X. Shen, A. Kamath, and P. Guyot-Sionnest, "Mid-infrared cascade intraband electroluminescence with HgSe–CdSe core–shell colloidal quantum dots," Nat. Photonics **17**, 1042–1046 (2023).