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POSEIDON

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

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Final specification table for light source for PIC

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Executive Summary

With help of the EAB feedback two potential applications fitting better the type of sources developed within Poseidon have been identified: quantum photonics and Mid-IR spectroscopy. The specification table for ICT has been rendered obsolete, as the sources developed within Poseidon are not promising for this application. New specification table for single photon emitters for quantum technologies has been prepared. Further, a new specification table for Mid-IR sources has been also prepared.

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1. Introduction

The aim of this deliverable is to review the simulated and experimental results of the project and compare them with the specification table reported in D1.1. The specification table is then updated and the project goals are modified accordingly

It has been identified that the nanoemitters developed by the Poseidon consortium, due to the simple fact that they have small active areas, provide low output power. First experimentally characterized sources have output power or order of nW. This output power cannot be also simply scaled up by increasing the emitter area as the coupling of emission to waveguides will become inefficient. It has been discussed with the EAB members that the consortium should focus on different applications than originally planned. This mainly concerns application for ICT (data transfer) where high power and coherent emission is needed. It has been identified that self-assembled colloidal emitters are suitable for emitting single photons, which is desired for applications in quantum photonics. Colloidal quantum dots used in Poseidon have already shown single photon emission (UCAM), albeit without waveguide integration yet. Hence, the consortium will focus on development of waveguide integrated single photon emitters with both optical and electrical pumping.

POSEIDON consortium has also decided that the developed emitters are still suitable for sensing applications, where the demands on the emission characteristics are less strict compared to the ICT. With the help of the EAB Mid-IR wavelength range (e.g. 4 µm) has been identified as interesting for molecule detection.

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 the table 2.1 has been modified to take into account different figures of merit that are relevant for single photon sources. Further, table 2.2 has been expanded 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.

For some parameters it does not yet make sense to estimate or demand precise values this early in the project. These will be marked with "*" in the specification table and are meant to specify only the target order of magnitude.

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

Table 1

Parameter	Minimum requirement	Optimum
Wavelength	650 nm	1260 nm -1600 nm
Brightness	0.05	0.5
Purity ($g^{(2)}(0)$)	0.2	0.02
Indistinguishability	0.5	0.9
Quality (Q) factor of loaded nanophotonic resonator*	10^4	10^6
Process compatibility	Light source last	Full
Integration with waveguide material	Si3N4	SOI
Wafer-scale processes	no	yes

The target **wavelength** has been chosen to match the classical telecommunication wavelengths to achieve best compatibility optical fibers and SOI photonics that can manipulate single photons. However, these targets do not exclude other wavelengths from being potentially useful with help of wavelength conversion. The silicon nitride platform has a broad transparent wavelength range, whereas the SOI platform is limited to wavelengths above 1.1 µm. Within this project, we concentrate on the communication bands for the O-band (1260 nm -1360 nm) and C-band (1530 nm - 1565 nm).

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. The designs will be optimised to maximise this parameter. **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 – high M value means that generated photons have identical energies and polarisation. This parameter can be also optimized by the design – for instance by coupling the emitter with a high Q single mode cavity, which will ensure that photons with distinct polarisation and energy are predominantly emitted[1].

The **process compatibility** of the light source has to allow fabrication on top of otherwise finished AMO photonic integrated circuits (PICs). Optimally the active material like quantum dots would be encapsulated by e.g. SiO2 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.

Since quantum technologies are still in an emerging technology **wafer scale processing** is not strictly required at this stage. However, Poseidon will focus on processes, which are in principle scalable and can be performed using more advanced tools, such as state of the art projection lithography.

2.2. Colloidal on-chip light source for sensing applications

It has been identified that integrated sources are promising for sensing applications in Mid-IR in the wavelength range from 3 µm to 10 µm. Therefore, new specification table for such sources has been prepared. The specification table for sensing applications in the visible wavelength range has been updated accordingly taking into account simulation and experimental results.

Table 2 – Specification for sensing applications using visible and near infrared wavelengths

Parameter	Minimum requirement	Optimum
Wavelength	650 nm	450 -900 nm
Output power*	0.5-1 µW	100 µW
Internal quantum efficiency*	10 %	90 %
Coupling to waveguide*	10 %	30%
Coherent emission	no	filtering
Bandwidth	30 nm	30 nm
Quality (Q) factor of loaded nanophotonic resonator*	1,000	100,000
Process compatibility	Light source last	Full
Integration with waveguide material	Si3N4	Si3N4
Wafer-scale processes	no	yes

The minimum **wavelength** requirement has been chosen to match readily available CdSe quantum dots, whereas the optimum has been chosen as 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 400-900 nm to be reasonable for the fabrication and at the same time useful to many applications for future sensing devices.

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. The output power should not be generated by inefficient means, though. This is specified by the **internal quantum efficiency** of the emitters and the efficiency of their coupling to the photonic waveguides. For both values the minimum target is set to approximately 10 %, as below this value the emitters will probably never be used in real devices.

At this stage of the project, it becomes evident that obtaining typical laser emission from self-assembled emitters will be extremely challenging. Instead, the project will focus on obtaining some degree of temporal coherence by filtering the broad band emission or via enhancement of the emission to spectrally narrow resonance modes. Therefore, the **coherence** in the specification table has been updated to "filtering" in the optimal case.

The **gain bandwidth** of the material determines the flexibility to cover different wavelength with the same material. It is practically limited by the photoluminescence widths of the quantum dots, which have full-width at half maximum (FWHM) of approximately 30 nm. Obtaining broader FWHM from single material is not feasible, therefore the optimal case in the specification table has been updated to 30 nm.

The **process compatibility** of the light source has to allow fabrication on top of otherwise finished AMO photonic integrated circuits (PICs). Optimally the active material like quantum dots would be encapsulated by e.g. SiO2 so that after their deposition and encapsulation all fabrication steps could be performed as usual.

Wafer-scale processes are necessary for cost-effective production of the light sources and are aimed to be reached for the sensing light source.

Table 3 Specification for integrated source for sensing in Mid-IR range

Parameter	Minimum requirement	Optimum
Wavelength range	3 – 5 µm	3 – 10 µm
Bandwidth	100 nm	10 – 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

Mid-IR **wavelength** range is particularly useful for detection or organic molecules by measuring their absorption spectra. For this purpose, the light source has to emit light over a broad range that allows to capture molecule signatures. Minimum requirement is 3 µm to 5 µm range that would allow to identify e.g. CO2[2] and can be integrated with suspended Si waveguide platform developed by AMO. Ideally the source should be able to extend to 10 µm, which will allow to identify e.g. explosives such as TNT.

The minimum **bandwidth** needed to identify specific molecules is 100 nm. Ideally the bandwidth should reach 500 nm to increase the accuracy and allow for sensing of multiple molecules.

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

Quality factor of the nanoresonator is set to rather low values. Its mail role is to direct the emission into a waveguide without narrowing the spectrum. High Q factors would result in spectrally narrow emission, which is not favourable for Mid-IR spectroscopy applications.

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 for this application. Ideally, it should be possible to integrated these sources also with germanium waveguides, which are used for extended Mid-IR range down to up to 10 µm. In 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 layer, e.g. electrical connections, can be fabricated after the source.

3. Conclusions

This deliverable updates the specifications which have been set in the POSEIDON project for the integrated colloidal light source.

Two new fields of application have been identified: quantum photonics replacing ICT and sensing in Mid-IR. Both of them require different parameters from the light source. For both, a monolithically integrated light source, which can be fabricated in scalable wafer-based processes would boost the state of the art tremendously. The two spec sheet tables summarize the minimum and optimal requirement for each light source.

4. Degree of progress

The development of "Specification table for light source for PIC" is 100% fulfilled.

5. Dissemination level

The Deliverable D1.1 "Specification table for light source for PIC" is public and therefore it will be available to download on the project's website and on demand.

6. References

[1] N. Somaschi *et al.*:*Nat. Photonics*, vol. 10, no. 5, pp. 340–345, 2016.

[2] F. Ottonello-Briano, C. Errando-Herranz, H. Rödjegård, H. Martin, H. Sohlström, and K. B. Gylfason:*Opt. Lett.*, vol. 45, no. 1, p. 109, 2020.