EUROPEAN CONFERENCE ON INTEGRATED OPTICS

Integration of quantum light sources, circuits and superconducting detectors on nanophotonic chips.

Invited paper

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Integrated optics holds great potential for overcoming scaling challenges and realizing complex functionalities in quantum technology. Here we show how large numbers of solid-state single photon sources and superconducting nanowire single-photon detectors can be integrated on nanophotonic chips. We further demonstrate a reinforcement learning-based inverse design method that allows for scaling down nanophotonic circuit components.

Keywords: *Single photon sources, SNSPD, inverse design, reinforcement learning*

INTRODUCTION

Quantum Technology promises tremendous advances in information processing, communication, and sensing, but many current implementations do not yet integrate all essential building blocks and neither scale to large system size. Here we focus on photonic approaches, which are a frontrunner for quantum communication applications but also hold promise for optical quantum computing, simulation, and remote sensing [1]. We identify quantum light sources, nanophotonic circuit components and single-photon detectors as essential building blocks and show how these can be replicated in large numbers on semiconductor chips by leveraging modern nanotechnology. Combining single photon sources and detectors with configurable optical, electrical and mechanical nanophotonic functionalities thus provides new means for realizing networks of quantum sensors, photonic information processors and quantum communication devices.

SINGEL PHOTON SOURCE INTEGRATION

Single-photon sources are of outstanding importance for a wide variety of tasks in quantum technology that employ photonic degrees of freedom for quantum information encoding. While several single-photon sources have shown excellent performance, they typically are individual single-emitter devices. Future quantum technology however will require large numbers of such quantum emitters that are integrated into a network architecture for sensing, computing, or communication tasks. This will be challenging to achieve with approaches relying on placing an individual emitter system under a high-numerical aperture objective for efficient fluorescence collection. Integrating single-photon emitters into nanophotonic circuits instead provides opportunities for scaling photonic quantum systems with multiple emitters to significantly smaller size, while maintaining functionality as a single-

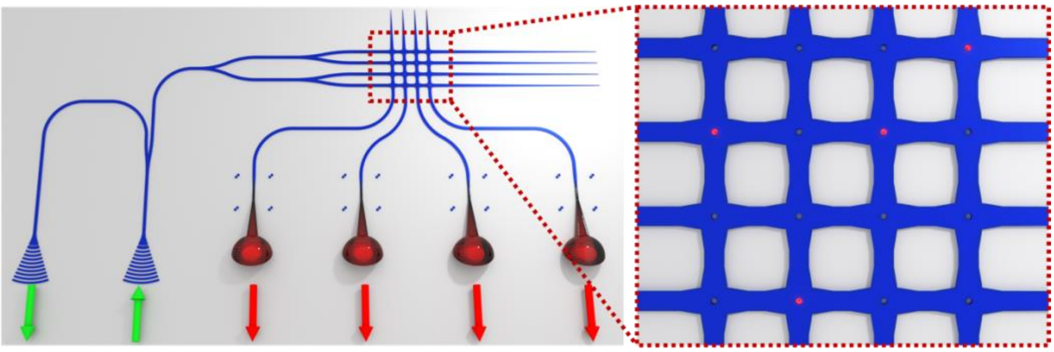

Fig. 1. Nanophotonic device that probabilistically integrates lithographically positioned colloidal quantum dots at the intersections of (horizontal) excitation and (vertical) collection waveguides. Electron beam and focused laser exposure allow for eliminating excess emitters. Upon optical excitation with 532 nm laser light, supplied from optical fibers via narrow bandwidth grating couplers (left), the quantum dots emit single photons into perpendicular collection waveguides that connect to optical fibers via efficient, broad bandwidth 3D polymer coupling interfaces (red).

photon source. Here we show how nanoscale solid-state quantum emitters, such as colloidal quantum dots, can be embedded into photonic integrated circuits [2]. Our approach allows for simultaneously addressing several emitter systems individually, but independently of one another from nanophotonic waveguides that connect to an optical fiber array via efficient and broadband coupling interfaces, as shown in Fig. 1. We increase integration yield of individual single-photon sources by processing colloidal quantum dots in solution, removing excess emitters via electron beam and focused laser exposure, and lithographic pattering for achieving high positioning accuracy. Our approach paves the way for integrating single photon sources at any desired position in a photonic integrated circuit where optical excitation and photon collection can be realized via independent waveguide-channels.

REINFORCEMENT LEARNING-BASED INVERSE DESIGN OF NANOPHOTONIC CIRCUIT COMPONENTS

As the complexity of photonic integrated circuits increases, scaling nanophotonic devices to smaller footprints becomes ever more important. Inverse design methods have shown to yield compact layouts for a wide variety of nanophotonic functionalities employing convex optimization techniques [3]. However, the topology of the solution space accessible with standard nanofabrication techniques is nonconvex, as evident from large numbers of local optima. Here we explore the possibility of interpreting nanophotonic black-box optimization problems as reinforcement learning (RL) tasks. We develop an algorithm, which shows stable and scalable learning behavior applicable to any pixel-discrete nanophotonic design problem that allows for assessing device performance via electromagnetic simulation to evaluate reward functions. Several interfaces to the data flow enable us to incorporate design constraints, for example to account for limitations of state-of-the-art nanofabrication capabilities. To demonstrate the universality of our approach we apply our RL-algorithm to a wide range of nanophotonic functionalities, such as mode converters and directional couplers, as shown in Fig. 2. 3D finite difference frequency domain simulations show that excellent device performance is achievable for extremely compact footprints. A silicon-on-insulator mode converter for transverse electric (TE) modes, shown in Fig. 2 a), achieves 95.3% conversion efficiency from the fundamental TE00 to the TE20 mode with minimal 0.1% crosstalk into the TE00 mode. If state-of-the-art nanofabrication constraints are taken into account by the algorithm the performance only decreases slightly to 93.7% TE00-to-TE20 conversion with 1.8% crosstalk to the fundamental mode, as shown in Fig. 2 b). In addition to functionality, the algorithm also allows for varying pixel size, material system, and operation wavelength, as shown for a 50:50 power splitter in tantalum pentoxide (Ta2O5) on insulator for 775 nm wavelength in Fig. 2c), achieving 84% transmission. If smaller pixels and nanofabrication constraints are considered the transmission improves to 91.4%, as shown in Fig. 2 d). While our RL-based inverse design algorithm already provides exciting prospects for dramatically increasing device density in photonic integrated circuits we anticipate that exploration mechanisms in delayed-reward environments, such as artificial curiosity, can lead to further improvements.

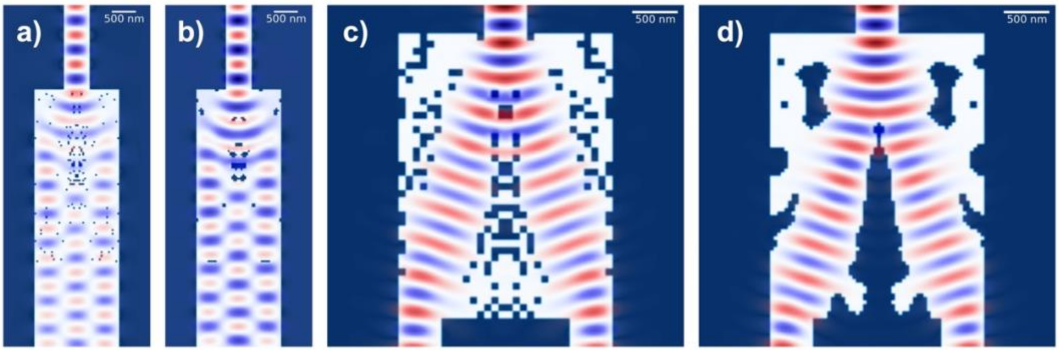

Fig. 2. a) Electrical field distribution in a TE00-TE20 mode converter in SOI for 1550 nm wavelength as calculated via reinforcement learning-based inverse design (top view). b) Same as in a) after incorporating realistic nanofabrication constraints into the inverse design algorithm. c) Electrical field distribution in a 50:50 power splitter in SOI for 1550 nm wavelength as calculated via reinforcement learning-based inverse design for 100 nm pixel size. d) Same as c) for a reduced pixel size of 50 nm and after incorporating realistic nanofabrication constraints into the inverse design algorithm

WAVEGUIDE-INTEGRATED SUPERCONDUCTING NANOWIRE SINGLE PHOTON DETECTORS

Chip-scale quantum photonic technology benefits strongly from integrating single-photon detectors into the nanophotonic circuitry, thus avoiding interface losses to separate stand-alone photon counting solutions. This is achievable by integrating superconducting nanowire single photon detectors on top of nanophotonic waveguides. Resulting devices have demonstrated >90% on-chip detection efficiency, dark count rates below 1 count per second and timing accuracies of a few 10 ps [4]. However, simultaneous operation of large numbers of independent devices on the same chip, efficient interfaces to fiber optic quantum communication channels and photon number resolving

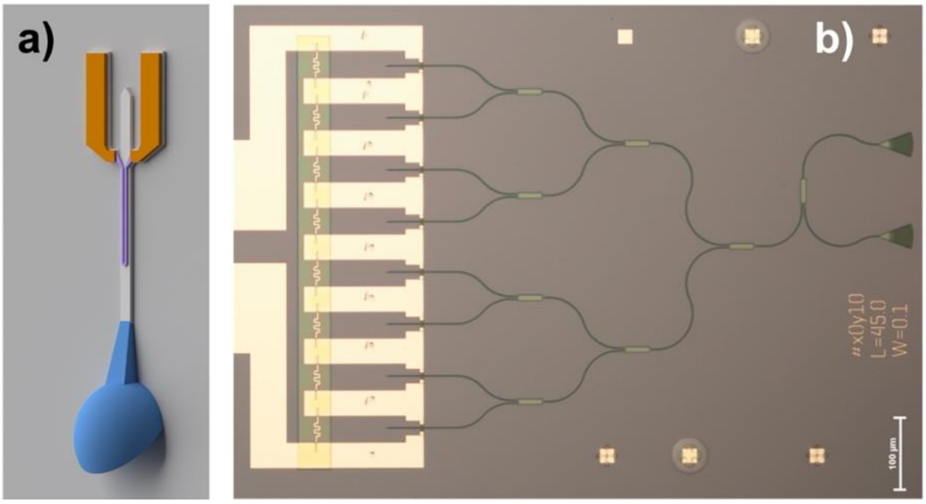

Fig. 3. a) Waveguide-integrated superconducting nanowire single photon detector (purple) with broad bandwidth 3D polymer coupling interface (blue). b) Photon number resolving superconducting nanowire detector architecture that translates optical input photon number into electrical output pulse height via parallel connected normal (Au) resistors.

capabilities have remained challenging. Here we show how direct laser writing allows for realizing 3D polymer coupling structures via two-photon polymerization to facilitate efficient fiber-chip interconnects, as shown in Fig. 3 a). We exploit these capabilities for enabling independent fiber access to up to 64 waveguide-integrated SNSPDs [5]. Simultaneous operation of these detectors has allowed us to perform quantum key distribution experiments that realize secret key rates of up to 3 Mbit/s on parallelizable channels [6]. We further configure SNSPDs and corresponding nanophotonic access to achieve quasi-photon number resolution. By connecting several nanowires in series with each individual nanowire connected to a parallel normal resistor, as shown in Fig. 3 d), it is possible to infer photon number in the input mode from the electrical output pulse height. We successfully realize these photon number resolving (PNR) capabilities for up to 16 nanowire elements. PNR-SNSPDs will be crucial for generating non-Gaussian states via photon number subtraction in fully integrated fashion and provide novel detector solutions to advanced quantum information processing and simulation tasks, such as Boson sampling.

CONCLUSION

We present progress towards realizing all essential ingredients for integrated quantum photonic technology, namely single photon sources, circuit components, and detectors, with compact form factor and individual addressability on integrated optical platforms. The favorable scaling properties of our approach have already enabled high rate quantum key distribution [6] and offer several exciting prospects for developing next generation quantum communication systems, sensors and information processing protocols.

ACKNOWLEDGMENTS

Acknowledgements: We acknowledge support from the Ministry for Culture and Science of North Rhine-Westphalia (421-8.03.03.02–130428), the German Research Foundation (DFG, CRC 1459), the Federal Ministry of Education and Research (BMBF, QuPAD Grant No. BMBF 13N14953) and the European Union's Horizon 2020 Research and Innovation Action under grant agreement no. 899824 (FET-OPEN, SURQUID) and the Münster Nanofabrication Facility (MNF).

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