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Integrated nanophotonics for the development of fully functional quantum circuits based on on-demand single-photon emitters

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INTRODUCTION
Motivated by the great prospect of implementing a global quantum internet, the development of integrated quantum photonic circuits has become a central research area in emerging quantum technology over the past two decades. Here, the envisioned quantum internet will ensure secure data communication and unparalleled computing performance by enabling distributed quantum computing across interconnected quantum nodes. The enormous advantages of quantum information technology over classic digital technology are based on the use of qubits as information units and quantum mechanical phenomena such as superposition, quantum interference, and entanglement in quantum information processing and distribution. In this context, the photonic quantum technology, which uses single photons as information carriers or flying qubits, is of great interest.

Not only the quantum information transmission over large distances benefits from the low decoherence of these qubits and the fast transmission speed, for example, in the quantum repeater concept, but also local quantum operations can be implemented very efficiently in integrated quantum photonic circuits (IQPCs) with single photons. Especially in the field of linear optical quantum computing, great successes could be achieved on the way to functional quantum nodes and optical quantum computers. In fact, Knill, Laflamme, and Milburn showed in their pioneering work in 2001 that it is possible to realize universal quantum computers...
without the use of non-linear couplings solely on the basis of linear optical elements.\textsuperscript{11} The corresponding KLM protocol only requires sources of entangled photon pairs, linear optical elements, phase shifters, and single-photon detectors on the component side. The functionality is based on the use of "ancilla" photons, entanglement, quantum teleportation, and quantum error correction. An important basic element of this approach is the CNOT gate, which was first demonstrated in 2003 using conventional bulk optics.\textsuperscript{12,13} Going beyond simple proof-of-principle experiments, it is very attractive to implement quantum gates in integrated quantum circuits based on waveguide structures. Such circuits are also used in classic integrated optics and, in combination with spontaneous parametric down-conversion (SPDC) photon sources, made it possible to implement an integrated CNOT quantum gate for the first time in 2008.\textsuperscript{12} In recent years, such integrated quantum chips have become more and more complex and include nowadays more than 550 components to realize, for instance, multidimensional quantum entanglement with large-scale integrated optics.\textsuperscript{14,15}

An alternative, interesting approach to advance into the realm of quantum advantage is sampling. Although, unlike the KLM scheme, it is not universal, it poses a problem, which is believed to be beyond the ability of a classical computer. As such, boson sampling is believed to be an outstanding candidate for demonstrating the power of quantum computation in the near term. Boson sampling was suggested and analyzed by Aaronson and Arkhipov in 2010\textsuperscript{16} and has attracted great interest ever since. In particular, boson sampling is very suitable for demonstrating the power and performance of IQPCs. Here, the input state, which consists of a given number of indistinguishable photons, experiences single-photon interferences in a complex waveguide circuit to form a corresponding output state. It can be shown that the calculation of the expected output state is an extremely difficult task for a classical computer, and it is expected that a quantum advantage can be achieved by increasing the number of input photons to a few tens. Shortly after the theoretical suggestion of Boson sampling, this concept was implemented experimentally. Again, it started with discrete optics (for state preparation)\textsuperscript{7,18} and evolved to more monolithic networks and a larger number of input photons. Interestingly, for recent implementations of boson sampling, true single-photon sources (SPSs) based on semiconductor quantum dot sources (QDs) were used.\textsuperscript{19,20} In this context, the work of Wang et al. is remarkable, in which boson sampling with a 20 photon input state and a 60 mode 3D interferometer was demonstrated.\textsuperscript{21} This result was even exceeded in a current study using 50-photon Gaussian boson sampling in a 100-mode ultra-low loss interferometer. Here, Zhong et al. could outperform a state-of-the-art supercomputer by a factor of $\sim10^{24}$ in terms of the achieved sampling rate.\textsuperscript{22} In contrast to the frequently and in Ref. 21 used non-deterministic SPDC sources, quantum emitter based sources can generate individual photons with excellent quantum properties quasi on demand and at a high rate, which makes them extremely interesting active elements for future fully integrated quantum circuits.\textsuperscript{23} However, the input photons in the boson sampling experiments mentioned were generated via externally operated single-photon sources and fed to the interferometer chip via optical fibers. The necessary single-photon detectors were also not integrated on chip but consisted of external fiber-coupled superconducting nanowire single-photon detectors (SNSPDs) or single-photon counting modules based on Si avalanche photodiodes. This leads to an enormous experimental overhead and complicates both the scalability and the performance of such boson sampling approaches. For example, the approach demonstrated in Ref. 21 is based on the multiplexing of the photons emitted by a quantum dot (in a large-scale external cryostat), which greatly limits the achievable photon rate at the inputs of the interferometer and would further reduce this rate by at least the scaling factor with further scaling. These problems clearly motivate the development of fully integrated quantum circuits that contain all the necessary functionalities, and in particular the photon sources on chip, and have a scalable architecture.

The examples discussed show the high relevance and application potential of integrated photonic quantum circuits in quantum technology. They also give an insight into the major developments that this field of modern quantum optics has experienced in recent years. At the same time, a closer look reveals not only the enormous opportunities but also extreme technological and experimental challenges that have to be solved in the near future on the way to photonic quantum computers and multipartite quantum networks. In this context, this perspective first summarizes the status of the technology used in IQPCs in order to provide an outlook on future developments based on this. Here, bottlenecks are identified that are currently inhibiting further progress and possible ways of circumventing them are shown. The focus is on developments toward fully functional IQPCs, with an emphasis on architectures based on on-demand single-photon emitters, which in addition to all optically active elements and complex waveguide systems also contain detectors and are also directly fiber-coupled for modular operation in global quantum networks. Here, the term "on-demand" refers to emitters that are in principle able to produce a single-photon deterministically per optical or electrical trigger event, in contrast to intrinsically probabilistic SPDC sources. In the context, it is important to note that present day quantum emitters only approximate the "on-demand" character because different shortcomings such as non-ideal internal quantum efficiency and non-ideal photon-extraction efficiency lead to the fact that not every trigger event results in usable photons. Best (quasi) on-demand single-photon sources based on self-assembled quantum dots nowadays yield a single-photon generation probability per trigger event in the range of 65%–85% in combination with a photon indistinguishability exceeding 90%.\textsuperscript{24–26} Interestingly, time multiplexing of heralded SPDC can also approximate the "on-demand" character, however, with a large experimental overhead. For instance, 66.7(24)% probability of collecting a single photon with high indistinguishability exceeding 90% into a single-mode fiber per cycle was demonstrated using this approach.\textsuperscript{27} It should be mentioned that SPDC sources have the advantage of room temperature operation, while on-demand sources need to be operated at cryogenic temperatures to achieve a high photon indistinguishability. This Perspective is not meant to be a comprehensive review, and we recommend the following articles and references listed in these papers for a more comprehensive insight into the state of the art in the field: Refs. 2–4, 7, 23, and 28.

Central elements of IQPCs for linear optical operations are waveguide systems that contain beam splitters and phase shifters. The aim is to transmit single photons as flying qubits with little loss from the input of the circuits to the output and to manipulate them according to the desired quantum function. In the case of boson sampling, the waveguide system simulates a unitary matrix, the elements of which are implemented using combinations of beam
splitters that manipulate the $n$-photons at the input in $m$-optical modes via quantum interference, thereby generating the output state that is analyzed via $m$ single-photon detectors.\textsuperscript{16,25} In the field of integrated quantum photonics, there are various approaches for implementing corresponding single-mode waveguide systems. In III/V semiconductor technology, for example, waveguide architectures based on self-supporting photonic crystal membrane structures have been developed that use the photonic bandgap in these engineered optical systems to control the emission properties of integration quantum emitters.\textsuperscript{17} These WGs can be combined comparatively easily with integrated nanoresonators to use cavity quantum electrodynamics (cQED) effects,\textsuperscript{3,22} have a small size footprint, and allow quantum emitters with a high coupling constant to be integrated monolithically.\textsuperscript{30} However, their fabrication is very demanding, and they are mechanically fragile, and with their self-supporting geometry, scaling to complex systems is difficult to imagine. III/V ridge waveguide structures are very popular for proof-of-principle experiments.\textsuperscript{2,34} They can be easily prepared with electron beam lithography (EBL) and dry chemical etching and can also include monolithic integrated quantum emitters. Nevertheless, their coupling efficiency to integrated emitters is only in the range of 10% and they have comparatively high optical transmission losses of $> 1$ dB/cm. Recently, it was shown that the optical losses of (Al)GaAs waveguides can be reduced to about 0.4 dB/cm by heterogeneous integration on a SiO\textsubscript{2} platform,\textsuperscript{35} which might be an interesting option for the future development of IQPCs if such low losses can be maintained for structures with integrated quantum emitters.

Waveguide systems that are written into fused silica by direct laser writing are also attractive candidates.\textsuperscript{29} These exhibit low optical losses down to 0.1 dB/cm\textsuperscript{29} and can be manufactured in a flexible arrangement in 2D and 3D, precisely, scalable and inexpensive. They have been used successfully for the implementation of boson sampling\textsuperscript{17,29} and, more recently, topological photonics,\textsuperscript{37} but quantum emitters cannot be directly integrated in this platform. The latter was achieved through direct laser writing of polymer structures and diamond that contain NV centers as quantum emitters,\textsuperscript{38–40} with guiding losses of around 10 dB/cm higher than that with the waveguides in fused silica mentioned above. With regard to the level of development, the achievable complexity, and the optical properties, Si-based waveguide systems are certainly the most promising system for the further development of IQPCs. They include structures based on SiO\textsubscript{2} on Si, Si-on-insulator (SOI), and SiN on SiO\textsubscript{2} with up to several hundreds of components.\textsuperscript{14,15,41–43} In addition to passive elements such as directional couplers and phase shifters, complex Si-based IQPCs often also contain externally pumped non-deterministic photon pair sources based on SPDC\textsuperscript{37} or spontaneous four wave mixing (SFWM).\textsuperscript{36–40}

Against this background, there are a number of challenges that must be addressed on the way to fully functional and modularly integrable larger quantum networks. In the ideal image of an IQPC, on-chip-excited on-demand single-photon emitters with identical emission energy and high photon indistinguishability, low-loss waveguides, and beam splitters as well as phase shifters and filter elements would be included in a scalable architecture. Furthermore, either single-photon detectors have to be integrated on chip or on-chip fiber couplers have to be implemented to efficiently detect photon output states or to integrate the IQPC modularly into a larger quantum network. A prototype of such a fully functional IQPC is illustrated in Fig. 1, and the highlighted parts and functionalities define important topics that will be of utmost relevance for the further development of IQPC:

\begin{itemize}
  \item[i] Deterministic integration of on-demand quantum emitters and spectral fine-tuning solutions For an optimal performance of the IQPCs, individual photons are ideally generated on demand by on-chip integrated quantum emitters. Color centers in diamond such as NV and SiV centers; defect centers in SiC, ZnO, and BN;\textsuperscript{23} and
\end{itemize}

![FIG. 1. Schematic illustration of important parts of a fully functional IQPC as discussed in the text. The modular quantum device with scalable architecture includes (i) deterministically integrated quantum emitters in combination with spectral fine tuning by using the quantum confined Stark effect; (ii) integrated electrically driven microlasers, which are evanescently coupled to WGs to resonantly excite quantum emitters acting as high-performance on-demand single-photon emitters; (iii) heterogeneous and scalable low-loss waveguides systems (in magenta) in which the target quantum operations such as boson sampling and linear quantum computing are performed via directional couplers and phase shifters before analyzing the output state with attached superconducting single-photon detectors; and (iv) on-chip fiber coupling elements to connect to other nodes of a large-scale quantum network.](image-url)
semiconductor QDs are particularly suitable as non-classical emitters. Both species have a random spatial distribution per se and show an inhomogeneous broadening of the ensemble emission well above the homogeneous linewidth of the individual emitters.\textsuperscript{44–46} As a result, conventional nanotechnology platforms such as standard EBL are not suitable for the scalable fabrication of quantum circuits based on these emitters. In particular, the process yield would be negligible even for the integration of only a few QDs or NV centers in multi-emitter waveguide systems.\textsuperscript{27} To make matters worse, the emitters have to generate individual photons with identical energy on a scale of the homogeneous linewidth and inject them into waveguides with high coupling efficiency. These high technological demands require the development and application of novel deterministic manufacturing processes for the spatially and spectrally controlled integration of on-demand quantum emitters and methods in order to be able to bring them precisely into spectral resonance.\\n\\ni Solutions for on-chip resonant excitation of quantum emitters to generate indistinguishable photons

In addition to the controlled integration of the quantum emitters into waveguide systems, the high quantum optical quality of the emitted photons is of decisive importance for the functionality of the IQPCs. In fact, a high indistinguishability of individual photons is the basic requirement for linear optical quantum operation. Depending on the application, different lower limits for the indistinguishability are to be considered. In the case of boson sampling, the limited indistinguishability of photons affects the hardness of the boson sampling problem. Taking the available computer power of a state-of-the-art supercomputer into account, Renema et al.\textsuperscript{48} inferred that for 50 photons and an error threshold of 10\%, the degree of indistinguishability of the interfering photons must be higher than 94.7\%. Even higher values of $>99\%$ apply for cluster-state quantum computing and all-optical quantum repeaters, both applications requiring also $g^{(2)}(0) < 0.001$.\textsuperscript{23} In this context, it is important to note that while the single-photon emission character in the sense of low $g^{(2)}(0)$ values is comparatively easy to guarantee, the requirement of a high level of indistinguishability is much more difficult to meet. In fact, there are many influences such as spectral diffusion that can lead to non-ideal indistinguishability.\textsuperscript{49} Here, in addition to technological aspects, the excitation scheme also plays an important role and it has been shown that strictly resonant excitation of quantum emitters is the method of choice for the generation of photons with maximum indistinguishability of $99.5\%$.\textsuperscript{50,51} Unfortunately, the resonant excitation scheme is not compatible with the intrinsically non-resonant on-chip excitation of the emitters via conventional pin-junctions, as is required for a compact electrically driven device concept. At the same time, the use of external lasers for the resonant excitation of the integrated quantum emitters is not very targeted in terms of practical applications of the IQPCs. Thus, solutions are required that allow resonant on-chip excitation of quantum emitters.\\n\\niii Development of heterogeneous architectures for highly functional low-loss waveguide systems

Due to the high complexity of functional IQPCs, various requirements are placed on the underlying design, which as a rule cannot be met by a single material base. For instance, Si-based waveguide systems feature very low optical losses, but quantum emitters cannot be implemented directly in silicon with an indirect bandgap, and efficient single-photon detectors are usually based on superconducting materials. Thus, in order to exploit the full potential of IQPCs, it is almost essential to combine different materials with the desired properties in a heterogeneous manner. This places great demands on the design and requires innovative nanotechnology solutions in order to pave the way for high-performance IQPCs with high quantum functionality.\\n\\ni\textsuperscript{v} Realization of on-chip fiber couplers

Although the actual functionality of the IQPCs is concentrated on the chip itself, they also have to be optically coupled to external components. For instance, if detectors are not monolithically integrated, it is essential to transmit the output signals to external single-photon detectors using suitable means. Fiber optics connections are preferably used, which are also required for later integration in large-scale quantum networks. For this purpose, it is crucial to develop technical solutions for the direct fiber optics coupling of IQPCs via robust and efficient on-chip fiber couplers.\\n
In the following, we highlight the current status of these central challenges and discuss open questions and further perspectives on them. The focus is on IQPCs, which are based on quantum emitters acting as integrated on-demand sources for single photons.

**Deterministic Integration of On-Demand Quantum Emitters Including Spectral Finetuning Solutions**

A central aspect of fully functional IQPCs is the scalable integration of suitable photon sources. A fundamental distinction must be made between probabilistic photon sources and quantum emitters acting as on-demand photon emitters. Probabilistic photon sources use optical nonlinearities, e.g., the $\chi^{(3)}$ nonlinearity in silicon for the generation of entangled photon pairs. From a technological point of view, corresponding sources can be integrated comparatively easily into optical chips and can be operated at room temperature.\textsuperscript{15,42} However, the probabilistic emission processes in these sources follow a classical statistic and can only approximate the quantum character of the single-photon emission.\textsuperscript{52} Furthermore, they are pumped with external lasers with high optical power in the mW range, which introduces a pronounced scattered light problem and requires very efficient on-chip filter elements with suppression ratios in the range of 100 dB in order to separate the single-photon signal from the pump laser signal.\textsuperscript{52}

In contrast to probabilistic sources, quantum emitters naturally function as non-classical light sources with corresponding emission statistics.\textsuperscript{28} They contain defects in crystals,\textsuperscript{45} QDs,\textsuperscript{71} and, recently, also localized emission centers in 2D quantum materials.\textsuperscript{14–16} Due to their pronounced quantum character, QDs, in particular, have almost ideal multiphoton suppression and photon indistinguishability in combination with high emission rates, which makes them ideal for applications in integrated quantum photonics.\textsuperscript{3} What these quantum emitters have in common, however, is that during fabrication, they form at random locations in the active layer. Furthermore, they exhibit a pronounced...
inhomogeneous broadening of the ensemble emission, significantly larger than the homogeneous spectral broadening of the individual emitter. This complicates their controlled integration in IQPCs using conventional nanotechnology methods such as EBL and makes the scalable realization of quantum circuits virtually impossible.

In order to be able to use the outstanding optical quality of the quantum emitters mentioned, and at the same time to guarantee a scalable fabrication of IQPCs, deterministic nanotechnology processes were developed. Two different approaches are currently being pursued, which can be subdivided into methods for positioning the quantum emitters and methods for spectral preselection of the quantum emitters, each followed by a possible integration in nanophotonic components. The first family of methods mentioned includes the positioned growth of QDs,\textsuperscript{7,47–49} the targeted implantation of defect centers in diamond,\textsuperscript{40,47} and strain engineering of single-photon emitters in 2D quantum materials.\textsuperscript{64} These approaches can basically be combined with conventional nanotechnology methods for the scalable manufacturing of quantum circuits with integrated quantum emitters. However, they have the disadvantage that the positions but not the spectral properties of the emitters are controlled, which, in turn, considerably reduces the process yield for the integration of spectrally identical quantum emitters. Furthermore, tight position control is usually associated with a reduced optical quality of the quantum emitter, e.g., due to the spatial proximity of an etched surface in the case of site-controlled QDs based on nanoarray arrays.\textsuperscript{66}

The aim of the second type of deterministic manufacturing methods is to pre-select quantum emitters with regard to their spectral properties and to integrate them precisely into nanophotonic elements. It includes pick-and-place techniques and \textit{in situ} lithography techniques. In the case of pick-and-place techniques, a large number of optical elements that contain quantum emitters are initially produced using conventional nanotechnology methods.\textsuperscript{6–68} Subsequently, suitable structures are selected based on their optical properties and are transferred, e.g., to waveguide structures,\textsuperscript{69} using precise transfer methods. Recently, this technique has been used for the large-scale integration of artificial atoms in hybrid photonic circuits, which highlights its application relevance.\textsuperscript{70} Notably, the process yield of the pick-and-place technique can be very high here, but the process is comparatively complex and leads to a large overhead of unusable structures.

In the case of \textit{in situ} lithography techniques, suitable quantum emitters, so far mainly semiconductor QDs, are identified using luminescence mapping and their respective positions are recorded in order to define the desired nanophotonic structures at the emitter’s positions. In addition to optical \textit{in situ} lithography,\textsuperscript{70,71} which is particularly suitable for the deterministic realization of microstructures, \textit{in situ} electron beam lithography has also been developed and established in recent years,\textsuperscript{72,73} which defines sub-micrometer structures flexibly and is aligned with great precision to the positions of pre-selected quantum emitters. This nanostructure technology is therefore ideally suited for the deterministic fabrication of complex quantum emitter waveguide structures with a high process yield. Notably, although the positions of the selected quantum emitters do not follow regular patterns, a high degree of scalability can still be guaranteed in that the waveguides can be routed to regularly arranged waveguide systems starting from the determined positions of the quantum emitters. It should be noted that also multi-step marker-aided nanotechnology methods do exist.\textsuperscript{74–78} They usually utilize (gold) markers or topographic structures on the sample’s surface to address single emitters in different setups for optical characterization and lithography. This also enables the deterministic integration of quantum emitters with high alignment accuracy, but using different systems for luminescence mapping and lithography requires a laborious matching of coordinate systems on a nanometer scale and the markers may be obstacles for the processing of extended waveguide circuits.

Against the background of the extremely successful advances in deterministic nanotechnology processes, it is now time to demonstrate the scalability by integrating several quantum emitters, which need to be spectrally identical for many applications, into complex waveguide systems. In fact, only individual emitters have so far been integrated deterministically, while, e.g., for on-chip boson sampling, the largest possible number $n$ of identical quantum emitters of indistinguishable photons at the input channels of the Haar-interferometer, i.e., an interferometer implementing a random unitary matrix,\textsuperscript{79} are required to pursue the quantum advantage. The developed methods have to face this challenge, and it will be exciting to see which concept will be best suited for the deterministic and scalable integration of quantum emitters in IQPCs in the future.

In any case, it can be foreseen that the deterministic integration of spectrally preselected quantum emitters alone will not be sufficient to fully meet the requirements of quantum applications with regard to multi-emitter photon indistinguishability. In fact, the spectral accuracy of the preselection, together with the observation that the emission energy of the emitters, at least in the case of QDs, changes slightly with each cooling cycle due to different charge configurations in the vicinity of the QD, results in an overall accuracy in the range of $1 \text{meV}$, which is about three orders of magnitude above the homogeneous linewidth of about $1 \mu \text{eV}$ of typical semiconductor QDs.\textsuperscript{79} The latter value defines the (very challenging) figure of merit for the spectral correspondence of several on-chip integrated quantum emitters.

There are various possibilities for the precise spectral control of quantum emitters, and especially of QDs, using external tuning knobs. They include the spectral tuning of QDs via temperature,\textsuperscript{81} strain,\textsuperscript{82,83} magnetic field,\textsuperscript{84,85} and electrical field,\textsuperscript{86,87} which modify the electronic band structure or emitter properties. Among them, (global) strain tuning\textsuperscript{88} was implemented in QD-WG systems to control the wavelength of the emitters. For IQPCs, the local spectral tuning is of particular interest, for which local temperature tuning,\textsuperscript{89} strain variation via structured piezoelements,\textsuperscript{90,91} nanomechanical tuning,\textsuperscript{92,93} and the quantum confined Stark effect\textsuperscript{94} in electrically contacted structures come into question. The third approach seems to be the most promising since electrical contacts can be realized flexibly and precisely with conventional nanostructuring methods on chip, and compared to strain tuning, only low control voltages are required. In addition, electric fields can also reduce the charge noise in the QD environment and thus contribute to an increase in photon indistinguishability. Finally, highest modulation bandwidths beyond $1 \text{GHz}$ are expected in the case of Stark tuning.\textsuperscript{95} Stark tuning has already been used in a variety of ways for the spectral control of QDs\textsuperscript{96–98} and time will tell whether this can also
be successfully used in the future with multi-emitter IQPCs without scaling.

Notably, in addition to the required spectral resonance of multi-emitters for a scalable IQPC architecture, the high joint indistinguishability has to be ensured for the on-chip integrated quantum emitters. This aspect is also highly relevant in quantum communication and has been tested in a number of experiments.\textsuperscript{100–104} Here, it has been shown that despite the almost ideal indistinguishability of successively emitted photons of an individual source, the indistinguishability in Hong–Ou–Mandel experiments of remote QD single-photon sources is limited to a maximum of about 50%\textsuperscript{105}. The causes for this are manifold and include, for example, spectral jitter from the sources. This problem and possible solutions are discussed in Ref. 53.

**SOLUTIONS FOR ON-CHIP RESONANT EXCITATION OF QUANTUM EMITTERS TO GENERATE INDISTINGUISHABLE PHOTONS**

A major goal of integrated quantum nanophotonics is to include all of the required components on chip. Here, the high quantum optical quality of the photon sources must be preserved so that ideal and individual photons can be coupled on demand with a high level of indistinguishability into waveguide systems. High photon indistinguishability has so far been achieved almost exclusively with external lasers as coherent excitation sources.\textsuperscript{50,51} In general, the indistinguishability can be increased by using the Purcell effect for QDs coupled to low mode volume resonators by eliminating the effect of pure dephasing and suppressing the influence of spectral wandering. Purcell-enhanced indistinguishability was recently also shown for WG-coupled QDs, where 94% and 95% indistinguishability were reported for QDs coupled to a photonic crystal cavity\textsuperscript{106} and a ring resonator.\textsuperscript{107} respectively.

Notably, Purcell enhancement also increases the single-photon emission rate of quantum emitters in IQPCs. While this rate is limited to about 1 GHz for a typical spontaneous emission lifetime of $T_1 = 1 \text{ ns}$ for self-assembled QDs, it can be significantly increased by the Purcell factor in cavity-enhanced WD-WG systems. For instance, in Ref. 106, a Purcell factor of $43$ associated with $T_1 = 23 \text{ ps}$ was reported under resonant excitation, which would allow for single-photon emission rates well beyond 10 GHz. Notably, such short single-photon pulses are also beneficial and important when considering the photon transit time in waveguide circuits. Considering a typical refractive index $n_{WG}$ of about 2–4 for typical WG materials, photons travel about 10 cm in $T_1 = 1 \text{ ns}$. The Purcell effect helps to reduce this length by the associated Purcell factor $F_P$ and to shrink the size of the IQPC accordingly, when considering that in the case of multiple integrated on-demand quantum emitters, the quantum circuit size should be on the order of $c/n_{WG} \times T_1/F_P$ (with the velocity of light $c$) to ensure that the photons emitted (with a suitable large coherence time of typically a few 100 ps) within one excitation pulse can interact jointly in the coupled WG system implementing, e.g., boson sampling. As a positive side effect, shrinking the chip size in the case of Purcell-enhanced emitters also mitigates photon losses in the WG due to smaller traveling distances.

Coming back to the aspect of resonant excitation, although this type of excitation delivers photons of the highest quality, it is not expedient in terms of the desired full integration and practical applications. In order to meet this requirement and to pave the way for modular IQPCs, it is obvious to use electrical excitation in doped and contacted structures. In fact, in recent years, especially in the case of semiconductor QDs, it has been possible to develop electrically operated single-photon sources at cryogenic temperatures\textsuperscript{108–111} and even at room temperature,\textsuperscript{112,113} however, the latter with significantly reduced optical quality. These sources are usually based on QDs that are embedded in the intrinsic layer of pin diodes and are excited to emit photons via charge carrier injection from the n and p regions. Highest device efficiencies of up to 61% with excitation rates up to 1.2 GHz have been achieved in electrically driven QD microcavity cavities, which use the Purcell effect to maximize the single-photon emission rate.\textsuperscript{114}

Apart from the fact that QD microcavity cavities emit in the direction normal to the sample surface and are therefore better suited for applications in quantum communication than in integrated quantum nanophotonics, simple electrical excitation in pin diodes is an intrinsically non-resonant method. If it is only about the on-demand generation of individual photons, the non-resonant excitation is usually not a problem. However, the large number of free charge carriers in the vicinity of the QDs results in charge noise and spectral jitter.\textsuperscript{115} This has a disadvantageous effect on the indistinguishability of photons and disqualifies the direct electrical excitation if a high quantum optical quality of the photons is required.

In order to solve this problem and at the same time meet the requirements for compact IQPCs, it is necessary to combine simple electrical operation with resonant excitation of QDs. One possible approach to this can be based on charge carrier injection in resonant tunnel diodes.\textsuperscript{116} However, this concept requires a complex layer design and it has not yet been proven whether it is really effective in terms of achieving high photon indistinguishability. An alternative approach for the on-chip generation of individual photons with a high degree of indistinguishability uses integrated and electrically operated microlasers that excite neighboring QDs in resonance.\textsuperscript{117} This approach combines hitherto largely independent scientific developments of high-beta microlasers and quantum light sources in a very elegant way and at the same time shows for the first time the great application potential of micro- and nanolasers in quantum nanophotonics.

The said on-chip excitation concept was first implemented in 2012.\textsuperscript{118} In the variant presented, an electrically operated whispering gallery mode (WGM) microcylinder is used to quasi-resonantly excite a QD in a neighboring microcylinder via its p-shell. In a further development of the concept, it was possible to trigger the emission of individual photons in an electrically tunable neighboring QD microcylinder via pulsed electrical operation of the WGM microcylinder.\textsuperscript{98} Independent of this, it could be shown that QD microcylinders are suitable for the strict resonant excitation of individual QDs and that they can generate individual photons with a high indistinguishability of 57%. Based on these results, it will be interesting to expand the excitation concept in such a way that an on-chip resonant excitation of QDs in waveguide structures is made possible. For this purpose, micro- or nanolasers could be integrated directly into photonic crystal waveguide structures via coupled defect cavities, or in the approach mentioned above, WGM microcylinders could be coupled evanescently to waveguide structures that include the target QDs.
The on-chip integration of micro- and nanolasers for the resonant excitation of WG-coupled QDs is a promising and powerful approach that can significantly contribute to the development of fully functional IQPCs. At the same time, it is technologically extremely demanding and there are some hurdles that have to be overcome for a successful implementation of the concept. These include, among other things, suitable opto-electrical designs of the lasers and corresponding excitation electronics in order to achieve the necessary emission pulse lengths in the range of 10 ps, which is required to maximize the excitation preparation fidelity and indistinguishability of QDs. When it comes to the epitaxial layer design, it must also be taken into account that at least in the case of a homogeneous IQPC architecture, the QD medium must provide sufficient optical amplification for laser operation via a suitable areal density and spectral distribution of the QD gain medium and, at the same time, enable single-QD waveguide structures. For this purpose, methods for positioned QD growth such as the buried stressor concept or the nanohole concept could be used, via which the QD density can be specifically controlled locally—for example, with a high density in the area of the laser and significantly lower density in the area of the WG structures. Alternatively, microlasers and single-QD structures could be grown separately and integrated into quantum circuits in a heterogeneous architecture (see the section titled "Heterogeneous IQPC architectures and integration of single-photon detectors"). Furthermore, an efficient suppression of background emission from the laser medium and laser stray light in the case of resonant excitation is necessary. This requires on-chip filter elements, for example, based on WGs with integrated Bragg gratings or crossed waveguides, which must achieve attenuation ratios in the range of 10⁶ in the case of strictly resonant on-chip excitation of QDs. Alternatively, two-photon resonant excitation of quantum emitters could be targeted, which relaxes a bit the stray light suppression issue, because the laser is not directly resonant with the target transition. Another challenge is the spectral resonance tuning between laser mode and QD transition. A rough coordination can already take place during the production via the geometry of the laser, for example, using the WGM laser diameter and the pre-selection of the QD using deterministic production methods. In addition, spectral fine tuning in the range of 1 nm is necessary in order to bring the QD and laser into resonance. If these technological challenges can be mastered, the on-chip integration of high-beta lasers can make a very important contribution to the development of highly functional and modular IQPCs that can do without an external laser infrastructure.

HETEROGENEOUS IQPC ARCHITECTURES AND INTEGRATION OF SINGLE-PHOTON DETECTORS

A broad base of materials is generally available for the realization of IQPCs. This can basically be divided into III/V materials with a direct bandgap and silicon-based materials with an indirect bandgap. Moreover, there are approaches based, e.g., on thin-film diamond and 3D femtosecond laser written structures into bulk diamond, as well as structures written by a focused UV laser into Ge-doped SiO₂. Integrated Si-based architectures have the advantage that corresponding manufacturing methods and structural approaches are already established in classic large-scale integrated silicon photonics fabricated on an industrial scale. Furthermore, Si-based circuits are usually characterized by low optical losses, and with regard to photon generation, the pronounced nonlinearity of Si can be used effectively for SFWM processes to generate photon pairs. In contrast, III/V materials and, in particular, GaAs- and InP-based structures are ideally suited for the implementation and integration of quantum emitters due to the direct bandgap and the growth of semiconductor heterostructures. InGaAs QDs, in particular, stand out as almost ideal single-photon emitters that can be precisely integrated into waveguide structures (see above). A disadvantage is that the fabrication technology in this material system is less developed, especially with regard to complex quantum circuits, compared to Si-photonics. In addition, III/V waveguides tend to have higher optical losses compared to Si waveguides (see above). Moreover, defect-based quantum emitters such as NV centers in diamond, silicon, and silicon-carbide are interesting quantum emitters to be integrated in functional IQPCs.

In order to achieve optimal performance of IQPCs, it is therefore necessary to pursue heterogeneous architectures that combine the advantages of the materials involved. Of particular interest here is the integration of quantum emitters in heterogeneous Si platforms, as indicated above. This is technologically demanding and usually requires wafer bonding techniques in order to combine III/V and Si materials. In this regard, considerable successes have been achieved in recent years. For example, GaAs wafer containing InAs QDs were integrated with SiON photonic circuits via side bonding. In another approach, InP-based nanowires with integrated QDs were coupled to SiN waveguides. Here, in addition to the heterogeneous combination of materials, efficient photon coupling from the QD into the waveguide can also be ensured via a tapered waveguide geometry. In a similar way, InAs QDs in GaAs nanobeam resonators were coupled to Si waveguides, which were manufactured with CMOS compatible processes.

Even with heterogeneous IQPC concepts, it is essential to guarantee a high level of process control and manufacturing scalability for a further development towards high-performance IQPCs. In this context, deterministic manufacturing processes were used to manufacture heterogeneous quantum emitter waveguide systems. One example is the pick-and-place technique that was used to place a tapered nanobeam with a preselected InAsP/InP QD in a SiN waveguide. The in situ EBL technology has also been expanded and combined with conventional EBL in order to integrate preselected InGaAs QDs in tapered GaAs membranes with SiN₄ waveguide circuits. The tapered geometry of the GaAs membrane promises adiabatic coupling of the emitted photons into the SiN₄ waveguide with almost ideal coupling efficiencies of >45% per direction. An important question that arises particularly in the case of heterogeneous concepts with additional interfaces between different materials relates to whether maintaining a high level of photon indistinguishability is possible in such systems. For instance, charged interface states can in principle lead to increased spectral diffusion at the ns time scale, which reduces the indistinguishability. As shown in Ref. 135, first results under post-selection show a high Hong–Ou–Mandel visibility of 89% even in heterogeneous GaAs-SiN quantum circuits. Further investigations under pulsed excitation without post-selection are necessary in order to obtain a more detailed picture of the quantum optical quality of such circuits.
addition, as explained above, it is also crucial for the further development of heterogeneous IQPCs to demonstrate the scalability of the manufacturing process and, if necessary, to optimize them in order to realize spectrally tunable multi-emitter quantum circuits, for example, for boson sampling.

With regard to heterogeneous integration, single-photon detectors are also of great interest. They are generally necessary for the detection of the photonic output states of quantum gates and quantum circuits and are ideally integrated directly into the IQPCs. The on-chip integration of single-photon detectors enables a compact and modular design of the IQPCs and potentially reduces optical losses that typically occur when connecting via optical fibers to external detectors. However, on-chip fiber coupling solutions with high coupling efficiency become available, the use of external single-photon detectors may be an option for straightforward concepts such as boson sampling. Other quantum operations such as quantum machine learning may require fast on-chip feedback, which will clearly benefit from on-chip detector solutions, avoiding delays associated with signal transit time in optical fibers connecting to external detectors.

In recent years, single-photon detectors based on superconducting nanowires (superconducting nanowire single-photon detectors, SNSPDs) have generally developed as the most powerful single-photon detectors. They combine ultra-fast response behavior with very high detection efficiency and low dark counts in a wide spectral range up to telecom wavelengths at 1.3 μm and 1.55 μm. Corresponding developments also include the on-chip integration of superconducting single-photon detectors in heterogeneous IQPC architectures. In fact, detectors of this type are predestined for applications in integrated quantum nanophotonics as they have a comparatively small size footprint and can be combined with the common IQPC material platforms using common deposition and lithography processes. In addition, their geometry can be flexibly adapted to the respective circumstances so that the superconducting elements are structured directly on the waveguide, for example, in order to achieve high coupling and detection efficiency. Another important parameter of single-photon detectors is the timing jitter, and state-of-the-art SNSPDs nowadays reach values on the order of 10 ps, while maintaining a high detection efficiency of >75%. Similar performance will be required for on-chip SNSPDs in order to reliably detect single-photon pulses emitted by Purcell-enhanced quantum emitters. Interestingly, high temporal resolution in conjunction with low detector dark counts can improve the entanglement fidelity of photon pair generation by QDs under resonant excitation.

Examples of heterogeneous waveguide circuits with integrated quantum emitters and superconducting single-photon detectors include QD-WGs in the GaAs material system with an NbN SNSPD. Moreover, on-chip Hanbury Brown and Twiss configurations including quantum emitters, directional couplers, and superconducting detectors were demonstrated in Refs. 140 and 141 using electrically driven carbon-nanotube-based quantum emitters coupled to Si-WGs and optically pumped InGaAs QDs coupled to GaAs WGs, respectively. In this context, it is interesting to note that efficient stray-light suppression is an important aspect to limit the dark counts of on-chip single-photon detectors. In Ref. 141, simple Al covers were used for this purpose, but the authors mention that further optimization is required to improve the signal-to-noise ratio.

With respect to upscaling, 10 single SNSPDs were bonded onto a Si-based photonic circuit for parallel operation and a traveling-wave configuration can even further enhance the performance of SNSPDs. Another class of single-photon detectors with additional benefits comprises photon-number resolving (PNR) detectors. An external transition-edge-sensor (TES) based system was shown to have a number-resolving capability in the range of 1 to 25 photons, and a waveguide-based on-chip TES was realized for single-photon detection in the telecom O-band. It will be interesting to develop also integrated PNR detectors to analyze, for instance, higher photon number Fock states directly on chip.

Compared to Si avalanche detectors, cooling to a few Kelvin is required for SNSPDs in order to ensure operation in the superconducting phase. However, the same temperature requirements also apply to many quantum emitters to reduce dephasing and other adverse temperature effects that reduce the photon indistinguishability so that cooling the detectors does not require any additional effort and the necessary cryogenics can be used synergistically for emitters and detectors. Moreover, cryogenic temperature can also be beneficial for the required low-noise read-out electronics of the detectors. In this context, the development of compact stand-alone cooling units will play a very important role in the future.

CONNECTING TO THE WORLD—ON-CHIP FIBER COUPLERS AND INTERCONNECTS

Homogeneously or heterogeneously integrated on-chip structures may be operated stand-alone in the case of boson sampling or photonic quantum computing. However, when it comes to secure quantum communication and distributed quantum computing via quantum nodes in large-scale quantum networks, it is essential to provide suitable interfaces for efficient fiber coupling. An example for such nodes might be on-chip assemblies of quantum emitters or circuits with polarization control and integrated detectors for Bell-state measurements to enable entanglement swapping in long-distance quantum networks based on the quantum repeater concept. For the conservation of the photons' properties such as spatial modes and polarization, polarization maintaining single-mode fibers are required. These fibers have a rather small core diameter of 5 μm – 7 μm, which complicates their alignment to grating in- and out-couplers or to laterally oriented tapered photonic waveguides. Moreover, using efficient fiber coupling, the IQPC could be interfaced to atomic systems acting as off-chip quantum memories.

The fiber-coupling issue is made more difficult by the fact that quantum emitters often only show sufficiently high luminescence at cryogenic temperatures, while the optical fiber alignment can only be carried out at room temperature. In order to solve this problem, scanning processes were developed in which the position of the QD structure is determined optically via the photoluminescence of the surrounding semiconductor matrix or via interference measurements and the glass fiber is then precisely aligned with the target structure via piezo-positions. In the simplest case, a permanent fiber-to-chip coupling is then achieved through a glue connection. Further concepts are based on on-chip fiber holders with integrated micro-optics, which can be aligned precisely with sub-micrometer accuracy to the nanophotonic structure, such as grat-
ing outcouplers, using two-photon lithography, and then simply be connected to single-mode glass fibers.\textsuperscript{31,132} Approaches of this kind are already established for fiber-coupled single-photon detectors and have recently been successfully further developed for the implementation of fiber-coupled stand-alone single-photon sources.

In the future, it will be important to further develop or adapt the fiber coupling concepts developed for detectors and single-photon sources for IQPCs as well. This usually results in the further challenge that even in the smallest of spaces, many output signals may have to be coupled into fibers, for example, in the case of boson sampling circuits with fiber-coupled external detectors. Multi-core glass fibers with corresponding on-chip holders could be used for this purpose. In addition to the pure mechanical coupling, the photonic coupling efficiency must also be maximized. To this end, it can be useful to numerically optimize the entire system, including waveguides, grating outcouplers, possibly micro-optics, and glass fibers, in order to ensure mode matching between the on-chip elements and the fibers for optimum performance of modular IQPCs.

**SUMMARY AND OUTLOOK**

The previous depiction of materials, components, and fabrication techniques allows us to draw a route toward the realization of fully functional modular IQPCs. Such quantum devices have great potential to revolutionize information processing and data communication by using quantum effects in the single emitter and single-photon regime of the second quantum revolution. Their conception not only requires a profound understanding of quantum physics and photonics but also a high level of knowledge in material engineering and peripheral areas such as low-temperature electronics. The development of the IQPCs continues to place the highest demands on the manufacturing technology, for example, to integrate multi-quantum emitters into the quantum circuits in a scalable manner. Overall, this offers an extremely interesting research environment that benefits from innovative solutions and advanced technological approaches in the field of quantum engineering.

Based on the successes already achieved in integrated quantum nanophotonics, it will be particularly interesting in the next few years to implement individual components such as quantum emitters; branched, reconfigurable waveguide systems; and single-photon detectors in a scalable manner and in modular fiber-coupled units. The realization of such complex systems will stay out-of-reach when utilizing a simple homogeneous material assembly, traditional fabrication techniques, and standard operation configurations. To reach these high aims, we will have to realize heterogeneous material assemblies while using deterministic fabrication techniques such as pick-and-place techniques or in situ EBL in combination with spectral fine-tuning knobs. Furthermore, efficient solutions are required for the on-chip resonant excitation of the emitters, for example, via integrated micro- and nanolasers, which, compared to currently applied schemes using external lasers, will be decisive for the compact design of the quantum circuits.

It is also becoming apparent that future fully functional IQPCs will have to be operated at low temperatures. This is already due to the low transition temperatures of the integrated superconducting single-photon detectors in the few Kelvin range. Although heralded single-photon sources based on SPDC exist that operate at room temperature, the low-temperature operation of the detectors, which is necessary anyway, facilitates the decision to use quantum emitters as on-demand single-photon sources with high single-photon flux and high photon indistinguishability. In this context, it is necessary to develop inexpensive and compact stand-alone cooling units that go beyond the existing Stirling cryocoolers with base temperatures of only 40 K or still rather bulky pulse-tube cryocoolers for the operation of IQPCs.

In summary, the development of IQPCs forms an extremely attractive and interdisciplinary topic of modern quantum technology with many exciting facets in the areas of material engineering, nanophotonics, quantum optics, and quantum information technology. In the near future, it will be very interesting and important to accelerate the further development of IQPCs toward scalable and fully functional modular units for use in large-scale quantum networks.

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**DATA AVAILABILITY**

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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