TOWARD PHOTONIC QUANTUM COMPUTING WITH LOGICAL QUBITS

Dedalo® Architecture White Paper

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Executive Summary

Quantum computing is entering a new phase, in which the central challenge is no longer only to demonstrate high-performing qubits, but to build systems that can be deployed, scaled, manufactured, and integrated within real computing environments. This white paper presents QuiX Quantum's photonic approach as a practical route toward universal quantum computing, highlighting the architectural advantages of photonics for data-centre readiness, modular scaling, energy efficiency, and compatibility with established telecom and classical-computing infrastructure.

The QuiX Quantum architecture is designed around the system-level strengths of photonic quantum computing. Its foundation in CMOS-compatible silicon nitride photonic integrated circuits supports a path to volume manufacturability, while native optical interconnectivity enables modular expansion. By maximising room-temperature operation and leveraging standard telecom infrastructure, the platform is intended to reduce infrastructure burden and support hybrid quantum-classical deployment in data-centre and HPC environments.

A key theme of the paper is the suitability of measurement-based quantum computing for photonic systems. Because photons cannot be stored easily and two-qubit operations are inherently probabilistic, computation is implemented through measurements on highly entangled resource states, supported by fast feedforward and adaptive photonic control. This model enables probabilistic photonic processes to be organised into effectively deterministic computation, provided that resource states can be generated, selected, and measured with sufficient reliability.

Fault tolerance is another central consideration. In photonic quantum computers, photon loss is the dominant error mechanism; therefore, the architecture must encode quantum information into logical qubits that can tolerate loss. Dedalo® is positioned as a first-generation logical-qubit-based photonic quantum computer designed to demonstrate, within an operating system, the creation, manipulation, entanglement, and measurement of loss-tolerant logical qubits.

Dedalo is structured around three principal system blocks: a pseudo-deterministic photon generator, a primitive state generator, and a universal quantum processor. Together, these subsystems generate synchronous photons, improve photon indistinguishability, create small-entangled states, fuse them into logical qubits, and perform loss-tolerant measurements under fast classical control. The resulting architecture provides a foundation for scalable, fault-tolerant, measurement-based photonic quantum computing.

The outlook identifies the engineering priorities required to scale beyond Dedalo, including reducing component losses below error-correction thresholds, improving phase stability, integrating faster control electronics, reducing system size and cost, and ultimately enabling high-quality magic-state generation for universal fault-tolerant computation. Overall, the paper argues that QuiX Quantum's photonic platform offers a credible and technically coherent path from current demonstrators toward deployable, modular, and commercially relevant quantum computers.

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Building a Quantum Computer that is deployable and useful is key

A universal quantum computer will only achieve broad adoption if it is both scientifically capable and operationally practical. Delivering useful quantum advantage in real-world settings will require far more than isolated demonstrations of qubit performance. The system must be deployable, manufacturable, serviceable, and economically scalable within the infrastructures where future workloads will run.

This is especially important because quantum computing is not expected to replace classical computing, but to operate alongside it. The long-term model is hybrid quantum-classical computing, in which quantum processing units work together with classical IT and HPC systems. As a result, low infrastructure burden, ease of deployment, compatibility with existing environments, and manageable operating overhead become architectural requirements rather than secondary considerations.

To become utility-scale, a quantum computing architecture must deliver a clear set of system properties:

- Energy efficiency to limit infrastructure complexity and operating cost;
- Volume manufacturability to support reliable, repeatable large-scale production;
- Resource efficiency to reduce hardware overhead on the path to useful computation;
- Efficient error correction to enable reliable large-scale operation;
- Modular scalability to grow across systems, sites, and workloads;
- Hybrid deployability to operate effectively alongside classical compute in data-center and HPC environments.

These requirements are tightly linked. A platform that is difficult to manufacture, interconnect, cool, maintain, or scale will struggle to become commercially relevant even if individual technical milestones are strong. The challenge is therefore not only to build a quantum computer that works, but to build one whose architecture supports a credible path from current systems to universal and fault-tolerant operation over time.

Dedalo® is designed against this system-level challenges: it combines a CMOS-compatible silicon nitride photonic platform, room-temperature-maximized system design, low-loss hardware, efficient correction method, and a modular architecture with native optical interconnectivity. This combination is intended to support volume manufacturability, low infrastructure overhead, and scalable hybrid deployment, while preserving a coherent path toward universal and fault-tolerant photonic quantum computing.

The enabling technology stack includes silicon nitride waveguides, optimized photon generation and detection, low-noise optical design, photon distillation, scalable resource-state generation, fast feedforward and modulation, and telecom-grade optical interconnects. Together, these choices position Dedalo not as a laboratory-bound system, but as an architecture designed for practical deployment in real computing environments.

QuiX Quantum Solution: Data-Center Ready Photonic QC

Here are the main features of our solution, enabling disruptive, deployable and energy-efficient photonic quantum computing systems:

Modularity and Rapid Scaling

Practical quantum computers are envisioned as assemblies of multiple modules, typically interconnected via optical fibers. Unlike other quantum computing modalities such as superconducting systems—which require either millikelvin-temperature links between cryostats or complex, noisy conversions of RF signals into optical excitations—photonic quantum computers inherently support modularization. This advantage stems from photonics' compatibility with standard telecom communication systems, enabling straightforward and efficient scalability. In QuiX's photonic architecture, qubits used for computation can also be employed to transfer information between quantum computers without introducing error or decoherence. This architectural feature enhances the viability of datacenter integration.

Volume Manufacturability

The foundation of our photonic quantum computing hardware is built on CMOS-compatible silicon nitride photonic integrated circuits (PICs). This choice is significant because it directly connects our photonic innovation to industrial manufacturability via established semiconductor fabrication ecosystems, circumventing the need for bespoke manufacturing processes. Leveraging the maturity of the semiconductor industry makes scaling up quantum hardware production more practical and reliable.

Compatibility with Telecom Standards

A major strength of photonic quantum computing lies in its intrinsic compatibility with existing telecommunications infrastructure. Operating at wavelengths and using components standard in fiber-optic networks, QuiX's photonic quantum systems can seamlessly integrate with current data center and long-distance communication networks. This alignment allows photonic quantum computers to benefit from the availability, cost-effectiveness, and reliability of commercial telecom hardware. As a result, deploying, scaling, and maintaining large photonic quantum computing systems is more feasible, reinforcing their practicality for real-world distributed quantum applications.

Resource Efficiency

Minimizing the number of hardware components needed to reach quantum advantage is key for practical quantum computation. In photonic quantum computing, reducing component overhead directly supports the development of fault-tolerant systems. Measurement-based quantum computing (MBQC) is foundational for photonic quantum computers, as it allows for constant-depth circuits. Unlike gate-based models—which are inefficient for photons as they lack interaction—MBQC enables computations over many qubits without requiring all qubits to be present at the outset. Instead, qubits are generated as needed during computation. This approach can be likened to constructing a railway track for a train: rather than building the entire track before travel (as in gate-based computation), only the necessary segments are used and extended as the train progresses. This paradigm enhances resource efficiency and scalability within photonic quantum computing layout.

Efficient Error Correction

Reliable computation must be ensured by actively correcting errors within quantum systems. Traditional error correction codes, such as surface codes, assume qubit locality—meaning a qubit can only interact with its immediate neighbors. This restriction limits the efficacy of error correction. In contrast, photonic qubits offer all-to-all connectivity, enabling more efficient error correction and reducing the hardware overhead required for scalability. MBQC also opens the possibility for more effective error correction schemes for in-code errors. By removing locality constraints, overall system size can be reduced while maintaining robust error correction.

Easy Error Detection and Early Correction

In photonics, optical loss is the predominant source of errors, which are simpler to correct than errors such as bit or phase flips. Implementing error correction codes at an early stage is therefore crucial for photonic quantum computing. QuiX Quantum's ultra-low-loss photonic hardware ensures minimal qubit noise, supporting resilient computing operations at the qubit level. Additionally, loss errors are easier to handle if they are heralded, that means, knowing which qubit is lost. Heralding is naturally achieved within measurement-based photonic quantum computing, because qubits are continuously measured and loss is detected. Therefore, loss errors can be detected and corrected efficiently, further improving system reliability.

Photon Distillation and Qubit Identicality

It is often overlooked that optical distinguishability also accounts for a significant portion of the error correction budget in photonic quantum computing. Efficient error-correction schemes, such as photon distillation, address this challenge by ensuring that photonic qubits are as identical as possible. QuiX Quantum has demonstrated, on real hardware, the ability to distill a set of perfect photons from a larger group of imperfect ones, without introducing additional errors. This process is essential for running "perfect" computations—not only must photons be preserved, but they must also be indistinguishable from one another.

Energy Efficiency and Adoptability

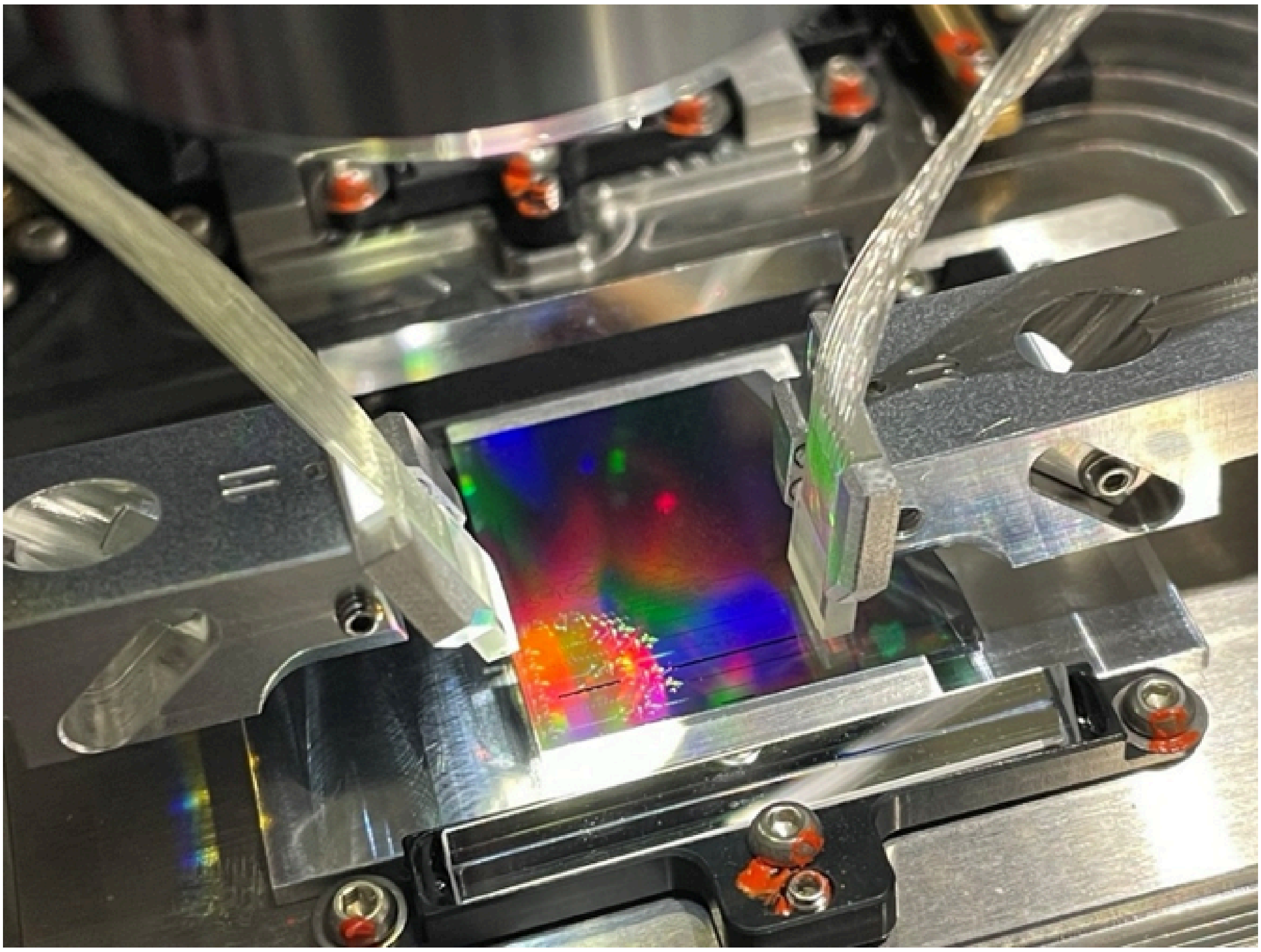
Photonic quantum computers offer significant advantages in energy efficiency due to their ability to operate at room temperature. Unlike superconducting quantum computers that rely on cryogenics operations down to millikelvin temperatures with substantial energy requirements, QuiX's photonic systems require cooling to only a few Kelvin (~4 K) for a minimal part of its hardware. This distinction greatly impacts operational practicality: while dilution fridges reaching millikelvin temperatures are not plug-and-play or compatible with data centers, the cryostats needed for single-photon detection in photonic systems are available as plug-and-play devices with standard 19" rack compatibility. These features make photonic quantum computers well-suited for integration into existing data center environments, reducing both energy consumption and infrastructural complexity.

The adoptability of photonic quantum computing is further enhanced by its minimal infrastructural burden and high compatibility with current technology standards. Room-temperature operation simplifies deployment, maintenance, and overall system footprint, resulting in a lower total cost of ownership. At the system level, maximized room-temperature operation for many components—including qubit generation, manipulation, and optimized detection schemes—reduces reliance on cold detection. While the size of optical circuits in photonic systems is larger than other modalities, this is offset by the absence of extensive cryogenic requirements. Unlike quantum computers that need to be segmented into small, cryogenically cooled units, photonic systems allow for greater flexibility in circuit size, making them competitive in terms of practicality and scalability.

Considering the total cost of ownership is increasingly important as quantum computing transitions from laboratory prototypes to real-world deployments. Photonic quantum computers stand out in this regard: their room-temperature operation significantly lowers the need for costly cryogenic equipment, and their compatibility with existing data center standards reduces integration costs. Utilizing widely available photonic components streamlines supply chains and minimizes the need for specialized hardware. Combined with the inherent modularity and scalability provided by fiber optic interconnects, photonic platforms present a cost-effective pathway toward practical, large-scale quantum computing. As the industry progresses, the ability to expand capacity without exponential increases in overhead and costs will be crucial for broad adoption and long-term sustainability.

Universality

Achieving universality in photonic quantum computing hinges on two key technological milestones: fast feedforward and adaptive photonic control. These advancements are essential for realizing measurement-based quantum computing (MBQC). QuiX has demonstrated leadership in adaptive photonic control, establishing itself as a market leader in photonic quantum processors. The development of fast feedforward, recently achieved and soon to be published, marks another critical milestone, representing the world's first implementation of its kind. Together, these innovations enable universal quantum computation, further solidifying the practical potential of photonic quantum systems.



QuiX's solution combines efficient error correction, room-temperature-first design and rapid scaling into a coherent path to fault-tolerance, deployability in hybrid infrastructure and commercial utility.

Main ingredients of QuiX photonic quantum computers

Photonic Qubit

There are several ways of generating a qubit using photons. The basic idea is to find a property of the photon, i.e., a degree of freedom that can mimic a two-level system [a]. The wavefront shape (orbital angular momentum), the polarization (H and V), or the quadrature amplitudes of a mode of the electromagnetic field (also known as continuous variable quantum computing) associated with a photon are some of the methods that have been proposed in recent years.

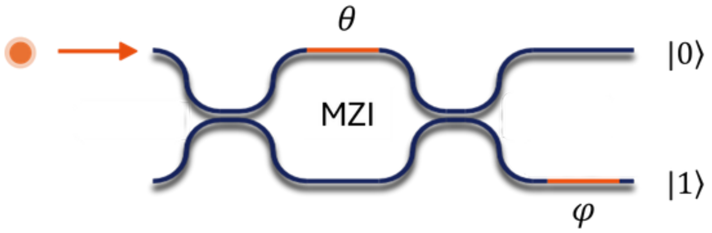


Figure 1 Dual-rail encoding: a single-photon is coupled in a dual-rail unit, i.e., a pair of photonic waveguides (rails) arranged as an on-chip tunable Mach-Zehnder interferometer (MZI). When using classical light, the internal phase of the MZI affects the power distribution at the two outputs, while the external phase affects the relative phase between the output light fields. When using quantum light, i.e., single photons, the internal phase changes the probability amplitudes between the two qubit states $|0\rangle$ *and* $|1\rangle$ *while the external phase add a relative phase between the two qubits states. When* $\theta = \pi/2$ *, the MZI acts like a 50:50 beam splitter, implementing a Hadamard gate in linear optics.*

QuiX Quantum uses dual-rail encoding, where the state of the qubit is encoded based on its position (see Figure 2) in a dual-rail unit [b]. In the case a photon occupies the upper or lower rail (waveguide), we define it as a computational zero $|0\rangle$ or $|1\rangle$, respectively - this approach is also known as Discrete Variable (DV) Quantum Computing. As mentioned above, there are multiple ways of encoding a qubit using a single photon but implementing dual-rail encoding has the benefit of giving us information if a photon was lost – it does not give us information what kind of error occurred, just that an error happened. This leads to a lower footprint in our system, since we can now allow larger loss errors and need less resources to implement quantum error correction codes [c].

Quantum interference

The main underlying mechanism of photonic quantum computing is quantum interference that enables the creation of entanglement between photonic qubits (photons).

Photons can interfere both as waves on a classical level, and particles on a quantum level [1]. When two indistinguishable photons, i.e., identical on all their degrees of freedom, interact in a 50/50 beam splitter [d] each from a different input, **quantum interference takes place and an entangled state is created [e].**

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[a] A qubit is generally defined as a two-level subsystem of a physical quantum system with potentially many levels. It thus forms a two-dimensional subspace – the computational space – of the complex valued Hilbert space of the full system. This Hilbert space is spanned by two computational basis vectors that represent the zero and one state, respectively, and are usually realized as the eigenstates of the subsystem's Hamiltonian. This can for example be the spin-up and spin-down states of an electron, the ground and exited states of an atom.

[b] The dual-rail unit is a tunable MZI, formed by two 50:50 directional couplers and equipped with two phase shifters (in orange) to tune both the internal and external phase of the MZI, i.e., the amplitude and phase of the output light fields.

[c] If the photon is lost, there will be no occupation in both waveguides, and therefore this type of encoding detects loss errors per definition.

[d] A 50/50 beam splitter is a linear optical element described by a unitary transformation that maps the input modes *in_top* and *in_bottom* onto the output modes *out_top* and *out_bottom* with equal amplitude for reflection and transmission. Its coherent mixing of modes allows quantum interference between indistinguishable photons.

[e] The reason why an entangled state, like $\frac{1}{\sqrt{2}}(|0\rangle\,|0\rangle - |1\rangle|1\rangle)$ is created is because the probability amplitudes of both photons being reflected or transmitted cancel out due to a π phase shift between the two cases.

This phenomenon was first discovered in 1987 by Hong, Ou and Mandel [2] and it is the benchmark experiment for verifying whether your photons are truly quantum.

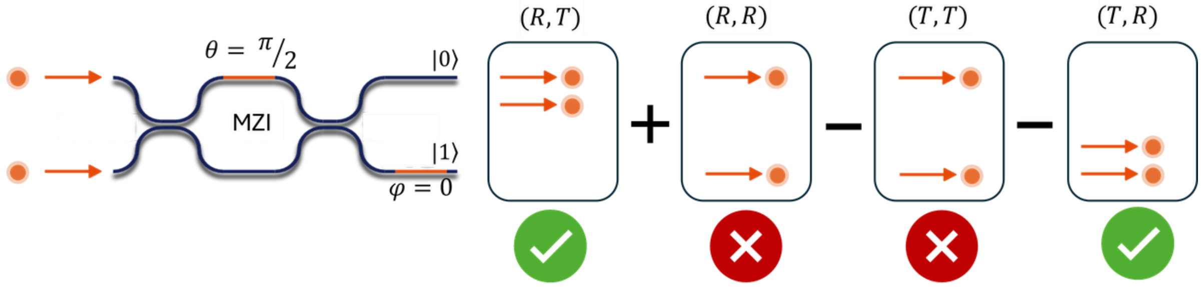

Figure 2 HOM interference: the probability amplitudes of all possible optical paths of each photon are combined, resulting in the events of the two indistinguishable photons always bunching together, i.e., exiting the beam splitter always from the same output, creating an entangled state. The probability of the top and bottom photons being both reflected (R, R) or transmitted (T, T) cancels out.

Photonic architecture

The architecture of a photonic quantum computer differs profoundly from other quantum computer modalities, due to several reasons. For one, entangling gates in dual-rail encoding are probabilistic [3]. This means whenever a two-qubit gate is implemented, it would only succeed sometimes. Second, photons cannot be stored and thus need to be used immediately - used by being measured and thus destroyed. This creates a conundrum, how do you create large entanglement if your gates only succeed probabilistically, and how do you pass on information if the carrier of the information itself gets destroyed.

Measurement-based quantum computation (MBQC) is a paradigm first introduced by Raussendorf and Briegel in 2001 [4] especially for photonic qubits and takes its name from the need to perform only (a specific sequence of) measurements to run a computation. The quantum gates that one would apply on a gate-based quantum computer are here replaced by a sequence of specific measurements (actually, settings of the measurement basis [f] used for measuring the qubits).

The success of MBQC depends on the continuous preparation of a highly entangled resource state. In this approach, all necessary entanglement for computation is established within the resource state, which represents a particular form of graph state [5]—at the outset ensuring that the computation is started only once a "viable" resource state is generated. The generation of entanglement is probabilistic for a photonic quantum computer, but the success rate can be made near-deterministic by performing many attempts in parallel. Rather than utilizing sequential gates to execute algorithms, MBQC employs consecutive single-qubit measurements on the resource state. The outcome of each measurement guides the selection of subsequent measurements in a procedure known as feed-forward.

Measurement-based and gate-based quantum computing are computationally similar; specific compilation algorithms can translate gate-based circuits into MBQC operations and vice versa.

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[f] A measurement basis is a set of orthonormal quantum states that defines the possible outcomes of a measurement. When measured, a qubit's state projects (collapses) onto one of the basis states with a probability determined by the state's amplitude relative to that basis. The most common is the computational basis, $\{|0\rangle, |1\rangle\}$.

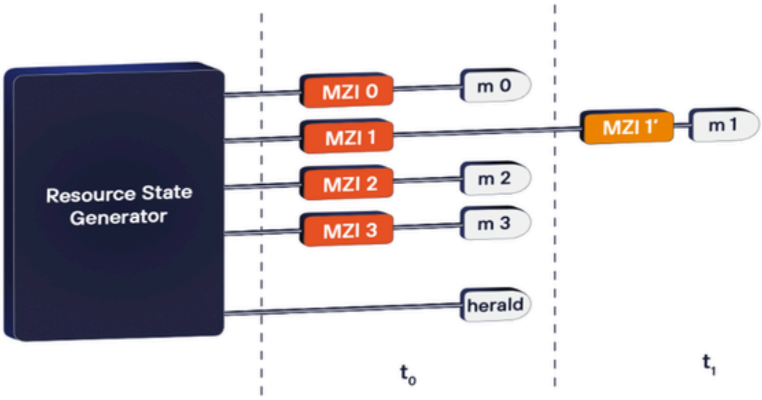


Figure 3 A generic measurement-based quantum computing architecture. MZIs (0,1,2,3) are set to perform specific basis measurement (preparation layer) while MZI 1' is set to a specific value depending on the measurement obtained in the precedent time step, implementing feed-forward. The white boxes are single-photon detectors where the presence of single photons is eventually measured (see Appendix for more details)

Challenges:

In order to create the resource state it is necessary to maintain many individual photons moving until the final resource state is constructed, which requires to lower the losses that they will encounter in the system as much as possible. Creating the resource state is also challenging as the generation of photons is inherently probabilistic. Once this state has been successfully generated, another challenge is to implement fast feed-forward to realize the sequence of interdependent measurements. The issue with feedforward is that it requires very high-speed processing and that the **quantum state of a photon is maintained** for however long it takes to select the measurement to be implemented based on the outcome of the previous one.

Solutions:

Maintaining the relative phases between photons over a long delay **is a technical challenge that QuiX is well poised to solve thanks to its integrated photonic platform that combines low-loss and high circuit density.**

For the resource state generations one should consider that photons can be generated at a very high rate, so although resource state generation is probabilistic, the process can theoretically be repeated many times at **very fast rates**. In practice this requires significant multiplexing, which **QuiX is aiming to be the first to demonstrate**. Additionally, once resource states can be reliably created, the computation only requires implementation of single-qubit measurements. This is contrary to the gate-based model, where the number of qubits involved in a computation is defined by the algorithm that is performed. The feedforward can be solved by tailored engineering of a high-speed digital signal processing module which QuiX aims to be the first to demonstrate.

MBQC is the only viable option for photonics, because it provides a way to address the probabilistic nature of quantum computations with photons, by realizing a deterministic quantum computation.

Towards Fault-Tolerance

Quantum computations are affected by errors. Quantum error correction therefore is an integral part of any quantum-computing architecture. In this section we explain the errors relevant for photonic quantum computing and provide an overview of corresponding error-correction strategies.

Photon loss

The dominant error in photonic quantum computing is photon loss. This contrasts with other platforms, where usually Pauli errors (bit and/or phase flip) are more relevant. It is therefore necessary to adjust the error-handling strategies to the specific platform one is considering. To be more specific, in photonics the loss of a photon is known only when the corresponding qubit is being measured. This type of error sits between the standard erasure channel (for which the location of the lost qubit is known before measurement) and a completely unheralded loss (which cannot be detected during measurement). The computational model of a photonic quantum computer has to be able to handle this specific type of error.

Logical qubits

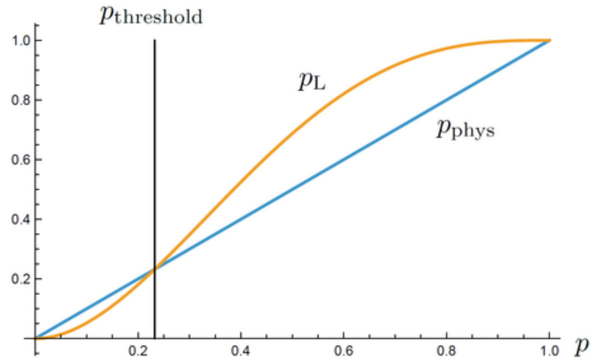
To tolerate the loss of photons in a quantum computation, a suitable approach is to encode information in a redundant way (see e.g. [6, 7]). For instance, the information can be distributed over several physical qubits such that losing some photons, i.e., physical qubits, does not destroy the information.

Therefore, a logical qubit corresponds to several entangled physical qubits that encode one unit of quantum information. More concretely, a logical qubit can be realized as a [[n, k, d]] quantum code [g] which consists of n physical qubits, which encodes the logical information of k qubits, and which can tolerate the loss of d – 1 photons.

Loss thresholds

Although a logical qubit can tolerate photon loss, the probability of losing the logical information is typically too high for practical applications. A common strategy is then to concatenate [8, 9] logical qubits several times, such that the logical qubit in layer l+1 is build out of logical qubits in layer l (where the first layer is a logical qubit that is represented by several physical qubits.)

Provided that the physical loss probability p is below some loss threshold p_threshold, that is p < p_threshold, the logical loss probability p_L of a concatenated logical qubit can be made sufficiently small by increasing the number of layers. In this case a useful computation can be performed, while in case p > p_threshold, the loss in the logical information is even greater than the loss of my physical qubits and no useful computation is possible.



The main source of error for a photonic quantum computer is photon loss. This error can be tolerated by encoding quantum information in logical qubits, which correspond to quantum codes with a good tolerance of losses (threshold).

Photonic based quantum computing has yet to demonstrate the creation, entanglement and measurement of photonic logical qubits in an operating system. QuiX's Dedalo architecture is poised to achieve this milestone by demonstrating for the first time photonic quantum computing based on error-corrected logical qubits, i.e., protected against photon loss.

Dedalo – Photonic Quantum Computing with Logical Qubits

Dedalo is the world's first logical-qubit-based photonic quantum computer to be delivered as first-generation system, where logical qubits will be demonstrated by overcoming long-standing challenges in photonic quantum computing such as resource-state generation, feed-forward and loss-error detection and correction. It is a pivotal step towards fault-tolerant universal quantum computing as it allows a practical path towards scalable photonic quantum computers.

It utilizes technologies that are required for fault-tolerant quantum computing at larger scale such as, for example, integrated photon generators that operate at room temperature, high-speed electro-optical switches, integrated spatial/temporal demultiplexer, resource state generation and feedforward mechanisms.

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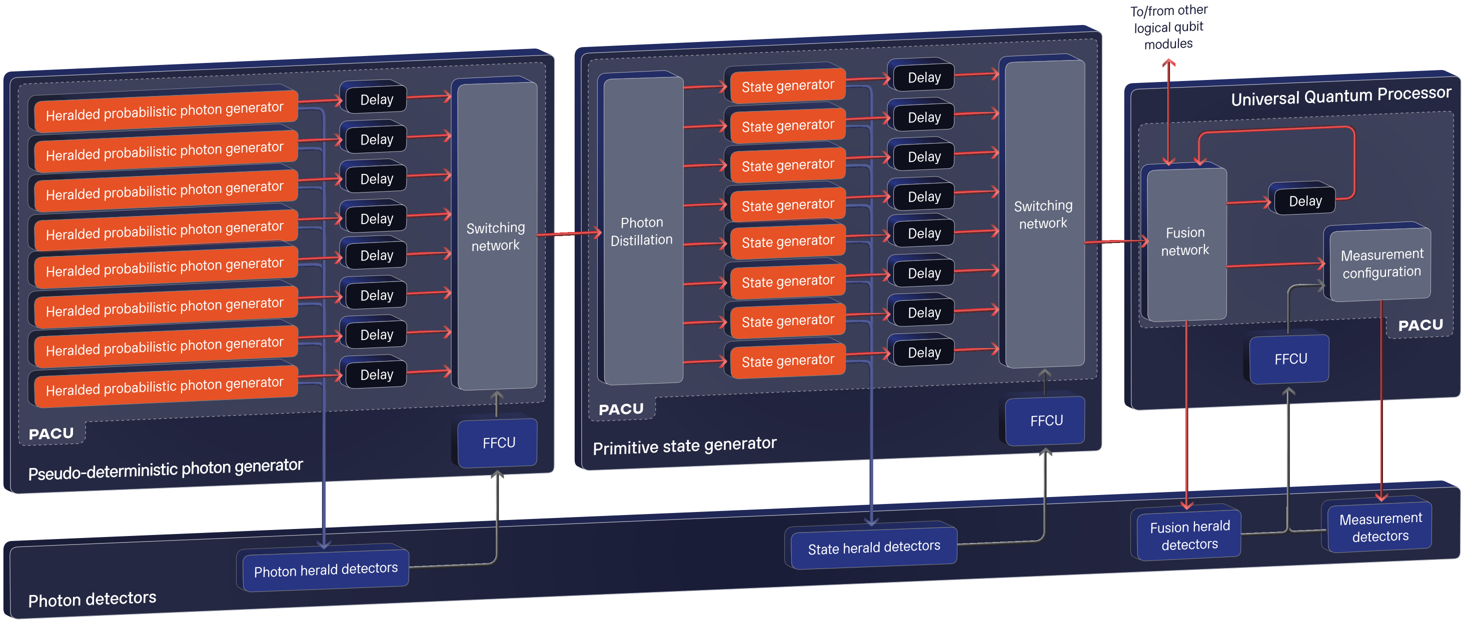
[g] A quantum code can be pictured either as a graph state or a 2D or 3D lattice.

In the figure below, we present a blueprint of Dedalo's system architecture showing the creation, manipulation, and loss-tolerant measurement of logical qubits. The architecture consists of three main blocks: a pseudo-deterministic photon generator, a primitive state generator and a universal quantum processor.



System Architecture

Pseudo-Deterministic Photon Generator

By having multiple heralded probabilistic photon generators working in parallel we ensure a pseudo-deterministic generation of n synchronous photons. The heralded probabilistic photon generator is an on-chip micro-ring resonator that generates a signal and idler photon pair probabilistically by spontaneous four-wave mixing (SFWM), and by detecting the idler of each pair one can herald on the creation of the signal single photon. The photon pairs are split into signal and idler photons by wavelength division multiplexing and the idler photons are immediately detected by the herald detectors, informing the feed-forward control unit (FFCU) which of the n photon generators has generated photons at which time-steps. The FFCU process the herald detections and set the switching network accordingly ensuring that the n signal photons are injected into the primitive state generator at the same time.

Primitive State Generator

The n signal photons enter the primitive state generator: first the n photons are distilled into m photons with higher indistinguishability, where m < n and then are fed into state generators returning small, entangled states such as, e.g., 3-GHZ and Bell quantum states.

The state generators are probabilistic and generate a specific heralding pattern when they successfully generate their primitive (3-GHZ and Bell state). The heralding pattern is fed into the FFCU that provides the detection results to the switching network that follows.

The purpose of the latter switching network is to select the primitives that were successfully generated, based on the click patterns detected by the herald detectors, and to ensure their transmission onto the universal quantum processor.

Universal Quantum Processor

The universal quantum processor unit can fuse primitive states to form a logical qubit, can entangle them with logical qubits on other modules, and can measure the logical qubit in different bases. More concretely, the fusion network of the universal quantum processing unit combines smaller primitives like 3-GHZ states into a larger resource state through type-I or type-II fusion operations [10]. This process might require delaying some photons, which is accomplished through delay lines. The resulting resource state is the logical qubit, and its properties can be adjusted by combining the primitives in different ways. Through fiber connections to other modules, different logical qubits can be logically entangled with each other through fusion operations. Finally, the measurement of the logical qubit performs the quantum computation. This requires setting measurement bases such as Pauli-X or Pauli-Z eigenbases for the physical qubits, depending on the computational step. These processes are controlled by the FFCU.

Outlook

All photonic components have losses, which means that some photons simply disappear. A commercially viable UQC will require quantum error correction to compensate for losses and other errors, and this is what Dedalo demonstrates on small scale. However, quantum error correction techniques require that the uncorrected losses fall below a certain error threshold before they are effective. Overall, photonic components such as fast modulators, facets, and delay lines need to be optimized to bring the overall system loss below the threshold required for error correction, including low-dispersion waveguides for efficient SFWM sources, heterogeneous integration of EO materials for fast switching networks, ultra-low-loss SiN waveguides for on-chip delay lines and integrated and non-cryogenic single-photon detectors. In addition, optimized facet designs are being co-developed to minimize chip-to-fiber insertion loss. Together, these platform developments form the basis for reaching the loss and performance targets required for fully-error corrected scalable photonic quantum computers and QuiX is collaborating with leading foundries in Europe to develop a customized proprietary process stack tailored to achieve this goal.

Maintaining phase coherence in delay lines presents notable challenges in current systems. In the short term, we are mitigating these issues using thermally controlled enclosures and active stabilization techniques. Our long-term strategy involves implementing a permanent solution: the PACU has been developed to support the potential integration of an ASIC, which would sufficiently reduce the latency of photon demultiplexing to enable on-chip delays as replacements for fiber-optic lines. This advancement is expected to enhance reliability and significantly lower both manufacturing costs and the overall system size.

Dedalo is designed to demonstrate loss-error tolerance in a photonic quantum computer. To achieve universal quantum computation within the framework of fault-tolerant measurement-based quantum computing, two capabilities are required. First, one must be able to generate entanglement between logical qubits; second, one must be able to perform measurements of logical qubits both in the logical X, Y, and Z basis as well as in a non-Clifford basis. Dedalo will demonstrate up to the generation, manipulation and entanglement of logical qubits and their measurements in the logical basis.

For logical qubits encoded in a quantum error-correcting code such as in Dedalo, the non-Clifford measurements are generally not available in a fault-tolerant manner: the standard approach is to use magic states. These are special ancillary states that are consumed during the computation by entangling them with the logical resource state, effectively promoting the available Clifford operations to a universal gate set. Magic states are typically generated through distillation protocols (not to be confused with the photon distillation needed to improve the indistinguishability of the photons), which take multiple noisy instances of a candidate state and produce a higher-fidelity version. These protocols can be executed offline and in parallel, decoupled from the main computation, and the resulting high-fidelity magic states can be injected when required. The remaining step toward universal fault-tolerant quantum computation in our architecture is therefore the realization of high-quality magic states, which is planned after Dedalo.

Conclusion

Amongst the various quantum computing modalities, QuiX's photonic quantum computing solution offers fascinating advantages such as native interconnectivity, that allows modularity and rapid scaling, low hardware overhead, thanks to favorable error correction schemes, and data-center readiness, allowed by room temperature and telecom operation.

Photonics quantum computing, however, has yet to demonstrate error-correction in an operating system and QuiX aims at achieving this milestone with Dedalo, showing the creation, measurement and entanglement of logical qubits corrected for loss-errors. Dedalo will therefore be a **pivotal step towards fault-tolerant measurement-based quantum computing.**

For more information, contact: sales@quixquantum.com

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FAQ

How is universality demonstrated?

A quantum computer is said to be universal if it can implement a gate set that allows to perform arbitrary unitary operations on its qubits. In other words, a universal quantum computer can approximate any quantum state within an n-qubit Hilbert space to arbitrary precision through operations of its gate set. To achieve this, a quantum computer needs a gate set that can create arbitrary superpositions of qubits and their entanglement. One gate set that can do this is the (Clifford + T) set: (Clifford + T) = {H, S, CNOT, T}, where H, S and CNOT are called Clifford gates.

The Gottesman-Knill theorem [11] states that any circuit that consists solely of Clifford gates can be simulated efficiently on a classical computer. The non-Clifford gate T can be implemented by a magic state.

[11] Gottesman, Daniel, "The Heisenberg Representation of Quantum Computers", arXiv:quant-ph/9807006 (1998).

How is Measurement-Based QC different than Gate-Based QC?

In gate-based quantum computing (GBQC), the computation starts from a register of qubits and proceeds through a sequence of quantum gates, much like a circuit. Measurements are typically performed at the end to read out the result, so the model is naturally described in terms of gates, circuits, and the evolution of an initial quantum state.

Measurement-based quantum computing (MBQC) takes a different and particularly attractive route for photonics. Instead of driving the computation through sequential two-qubit gates, the computation is embedded in an entangled resource state. The algorithm is then executed by measuring individual qubits in a defined sequence, with each measurement progressively consuming the resource state and advancing the computation.

This makes MBQC well aligned with photonic hardware. Photons are excellent carriers of quantum information and are naturally suited to being generated, routed, interfered, measured, and connected optically. In MBQC, the resource state does not necessarily need to be prepared all at once: new layers can be generated and added as the computation progresses, while earlier layers are measured. This creates a streaming model of computation that matches the travelling nature of photons.

Another key feature of MBQC is feed-forward: measurement outcomes are used to determine the basis of later measurements. Rather than being a limitation, this adaptivity is what turns probabilistic measurement outcomes into a controlled computational process. With fast classical control and photonic switching, MBQC provides a clear route to reliable and programmable photonic quantum computation.

Computationally, MBQC and GBQC are equivalent: gate-based circuits can be translated into MBQC measurement patterns and vice versa. The difference is architectural. GBQC is built around applying gates directly to stored qubits, while MBQC is built around preparing entanglement first and then driving the computation through measurements. For photonics, this is a strong advantage because it shifts the demanding part of the computation into resource-state generation, which can be parallelized, multiplexed, and optimized using integrated photonic hardware.

Is photonic quantum computing deterministic or probabilistic?

Photonic quantum computing is inherently probabilistic, but in practice the success probability of a computational step can be made very close to one. At a basic level, operations on single qubits can be performed deterministically, while interactions between two qubits succeed only with a certain probability. In a traditional gate-based approach, one can try to improve the success rate of these two-qubit operations by using additional photons and more elaborate setups. However, this quickly becomes difficult to manage as the size of the computation grows.

A more suitable approach is measurement-based quantum computing. In this framework, the computation is carried out by measuring qubits of a large, highly entangled resource state. While the outcomes of these measurements are random, their overall effect on the computation is predictable and can be corrected using classical feedforward. In MBQC, the probabilistic aspect is shifted to the preparation of the resource state. Importantly, this preparation can be performed ahead of time and in parallel, allowing repeated attempts until the desired state is successfully created. Once such a state is available and verified, it can be used to run the computation in a reliable way.

As a result, even though the underlying processes in photonic quantum computing are probabilistic, the overall computation can be made effectively near-deterministic by preparing the necessary resources in advance.

Appendix

Here is a more detailed description of each subsystem of the measurement-based quantum computer in Fig.3 of the main text.

Resource state generator:

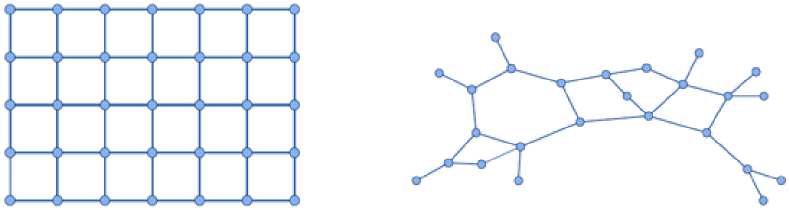

Figure 5 Examples for entangled resource states: regular lattices (left) are often implemented in superconducting QCs. In photonics more general resource states can be realized (right), with less restrictions on the qubit connectivity.

The resource state generator generates probabilistically a highly entangled quantum state (resource state) (Fig. 5) that forms the starting point of computations in MBQC as described above. A resource state is a particular type of graph state where nodes (dots) are connected to their nearest neighbors via edges (lines). The wave function of a resource state can be expressed as the product of qubit states in the X-basis (where $|+\rangle$ and $|-\rangle$ are the two basis vectors) pairwise coupled via a Cz gate. The major cost of computing is in this step.

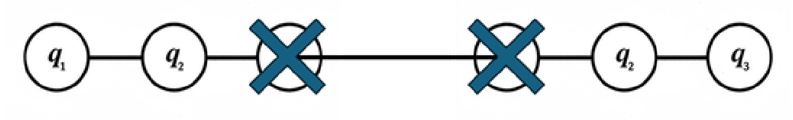

Figure 6 Fusion operation: two 3-qubits GHZ states are fused together forming a 4-qubits GHZ state

The resource state is created usually by first generating small, entangled states [h] which are then fused together (Fig. 6) [12] to generate the large resource state. Resource states can be either regular two- or three-dimensional lattices (see Fig. 5 (left)), or not regular lattices (see Figure 5 (right)). The latter approach has the advantage that the resource state can be tailored to the particular computation one wants to perform, thereby reducing resource requirements (see e.g. [13]).

In MBQC the computation is realized by measuring qubits of an entangled resource state. For a universal quantum computation one has to be able to measure qubits in the eigenbasis of the Pauli Z operator and in the eigenbasis of $M(\theta) = \cos\theta X + \sin\theta Y$, where $\theta \in [0, 2\pi)$ [1]. However, for universality it is actually sufficient to realize measurements of $M(\theta)$ for angles θ being multiples of $\pi/4$. The outcome of a measurement of a qubit in the eigenbasis of Z or $M(\theta)$ is probabilistic. But given this outcome, one can correct the next step of the computation through a classical feed-forward/adaptive measurement. Therefore, the quantum computation can be considered as deterministic.

Preparation layer:

In the preparation layer, the measurement basis is chosen. In MBQC, a quantum algorithm is not described anymore by a sequence of gates but is translated into a sequence of measurements to be performed on the resource state. For each measurement one should specify the angle α of the X-basis [i]: the X-basis is the measurement basis of choice, native for MBQC using dual-rail encoding.

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[h] A Greenberger–Horne–Zeilinger (GHZ) state is a maximally entangled quantum state of three or more qubits where all qubits are correlated in an all-0 or all-1 superposition. As a result, measuring any qubit (in the computational basis) instantly determines the state of all the others.

[i] An X-basis measurement is a quantum measurement in the basis of the Pauli-X operator. The angle α corresponds to the phase setting of the MZI, given by the combination of θ and φ phases (see Fig. 2)

Gate	**Measurement basis**	**α value**
Hadamard	X-basis	0
Phase (S = Rz(π/2))	rotated X-basis	π/2
T gate (Rz(π/4))	rotated X-basis	π/4
General Z rotation (Rz(θ))	rotated X-basis	θ
X gate (up to H conversions)	sequence with α = π, 0	-

Measurement:

The single-qubit measurements that are defined by the algorithm are executed. Single photon detectors as used to detect the presence or not of the qubit at each output. The measurements at each time step (except for measurements at t=0) depend on the measurement results of the previous time step.

Feedforward:

The feedforward evaluates the measurements on the qubits and then generates the next set of measurements (angles of the measurement basis) according to the outcomes of the current set of measurements. The evaluation and adaptation of the angles of the measurement basis needs to happen very fast, requiring ultra-fast classical control systems: it is a crucial step to ensure universality, and it has yet to be proven.

[12] Raussendorf, Robert, et al. “Measurement-based quantum computation on cluster states.” Phys. Rev. A 68, 022312 (2003).
[13] Feynman, R.P. Simulating physics with computers. Int J Theor Phys 21, 467–488 (1982).