Perspective

Integrated Photonics for Quantum Communications and Metrology

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(Received 28 October 2022; revised 24 October 2023; published 12 February 2024)

Over the last two decades, integrated photonics has profoundly revolutionized the domain of quantum technologies. The ongoing second quantum revolution stands as a timely opportunity for a state-of-the-art review and, most important, an exploration of the directions undertaken by integrated quantum photonics. Within this perspective, based on the recent advances, we discuss the current challenges and future trends related to different technological platforms. Key examples will be considered across various subfields, including quantum communication, quantum metrology, and quantum memories. Our discussion encompasses disruptive concepts, progress, and potential limitations. The main objective of this Perspective is to provide the reader with a forward-looking discussion ranging from state-of-the-art developments to open challenges of the field.

DOI: 10.1103/PRXQuantum.5.010101

I. INTRODUCTION

Since antiquity, the fabulous properties of light have attracted the interest of the greatest scientists and shaped the history of science. Thanks to the pioneering works of the founders of quantum physics in the beginning and throughout the 20th century, we have understood that light is inherently quantum.

A. Quantum photonics

The current situation is undergoing a profound change. As J.P. Dowling suggested in 2003, "We are currently in the midst of a second quantum revolution. The first quantum revolution gave us new rules that govern physical reality. The second quantum revolution will take these rules and use them to develop new technologies" [1]. The conceptual and physical foundations of this revolution are quantum superposition and entanglement, which offer new possibilities in computation, communication, and even metrology [2]. Practical advantages of these technologies have already been demonstrated [3].

In this context, photonics will continue to play a major role. Photons serve as ideal two-level systems: they experience minimal noise, support high-speed transmission, and are relatively simple to manipulate and detect. This has significantly contributed to the rapid growth of the fields of photonics and optical communications in the last three decades of the past century, relying predominantly on the nonquantum properties of light, where the field can be described as a classical electromagnetic wave. Thus, it has provided fertile ground for the emergence of quantum photonics.

Quantum photonics is the science dedicated to the coherent manipulation of photons (i.e., the individual quanta of the light field) and its applications. The objective of this Perspective is to review the recent advances made towards developing integrated quantum photonic technologies, as well as the current challenges and future directions, with a specific focus on quantum communications, quantum metrology, and quantum memories. It is worth noting that the computation and simulation aspect of quantum technologies has been extensively discussed elsewhere [4–6].

B. Integrated photonics

Indeed, as it was for classical photonics, microelectronics, and other fields, integration seems to be the key to scalability and, therefore, to many real-world applications.

An introduction to integrated photonics can be helpful in understanding its similarities and differences with traditional electronic circuits. While integrated electronics involves controlling the flow of electrons on a chip, integrated photonics does the same with photons. The high-frequency range of the electromagnetic field of light ($[10^{14}, 10^{15}]$ Hz) significantly increases the bandwidth and

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speed of the circuit without generating significant heat, making photonic integrated circuits much more efficient than their electronic counterparts.

It is worth noting that emerging applications, such as cloud-based storage services, high-definition streaming services, machine-to-machine communication, and 5G radio networks, require large operating bandwidths, reduced fabrication costs, power consumption, footprint, and complexity, which can be met by integrated photonic devices [7–12].

C. Genesis and revolution of integrated quantum photonics

Integrated photonic solutions, which have been the key to modern telecommunications, have similarly acted as "enabling technologies" for the new field of quantum information. They have dramatically boosted experimental quantum photonics to break through laboratory proof of principles, and to evolve from unscalable photon sources, modest efficiency single-photon detectors, and optical circuits constructed from bulk elements bolted to room-sized optical tables, toward practical real-field prototypes. Essentially, the "lever effect" of guided wave optics lies in enhancing the efficiency of optical-optical and electro-optical nonlinear interactions but also the possibility of merging several functions on a single chip, drastically simplifying the realization and use of interferometric quantum (electro-)optical circuits.

From the historical point of view, the first use of guided wave optics as an enabling technology for quantum optics was demonstrated in the seminal experiment of the Geneva group in 1998 [13]. Fiber-based interferometers were used to perform, for the first time, a Bell-inequality violation experiment with detectors located in two villages separated by over 10 kms of optical fiber. In addition a significant hurdle was cleared when the Geneva-Nice collaboration demonstrated the first ultraefficient source of entangled photons pairs in a waveguide [14] paving the way toward "true" integrated photonics, i.e., combining more than a single function onto a device. However, integrated photonics set a game-changing landmark in quantum science when the Bristol group performed an experiment otherwise impossible using a bulk approach in 2010 [15]. In the latter work, a quantum random walk was implemented via a constant splitting of photons into 21 waveguides integrated on a single glass substrate. Experimentally, it amounts to chaining 50:50 beam splitters, but the price to pay is the rapidly growing size of the setup, which up to that point had limited any bulk optics realization to a five-mode system. [16,17].

Over the past 20 years, we have observed an ever-increasing complexity in the demonstrated circuits. However, starting from the first elementary waveguides on lithium niobate (LN) that offered an unprecedented brightness in 2001 [14,18], to the recent highly functionalized devices that combine several high-performance photon sources with interference circuitry [19–23], the most striking feature of quantum photonics is the explosion of materials being investigated [24].

To cite only a few, silicon (Si) photonics [including silicon nitride (SiN), Si and silicon carbide (SiC)], III-V and III-N semiconductors (such as GaAs, InP, AlN, GaN), ferroelectrics (such as LN, KTP, AlN, lithium tantalate), and silica bring their technological assets to the quantum realm based on their independent developments for classical photonic applications. All these platforms share experimental efforts aimed at scalability, low energy cost, high-efficiency entanglement sources, and/or quantum storage and repeater systems, as well as fast and convenient phase modulations for enabling multiple high-fidelity quantum operations on a single chip. More specifically, such features meet the requirements of quantum photonics for producing efficiently multiple pairs of entangled photons to be coherently manipulated using frequency-conversion stages, dynamical routers, and phase shifters, combined with external photons, and eventually detected. At the same time, none of the currently exploited integrated photonic platforms is able to offer by itself all desired functionalities and manufacturability. The exploration of integrated quantum chips has always been strongly influenced by the choice of materials, and it is not surprising that there are strong correlations between the range of feasible circuits and the platform.

In this framework, hybrid quantum photonic chips have emerged in 2014 as a possible solution to the challenges of monolithic integration by combining components, which are optimized for their individual functions [25,26]. Hybridization of different platforms is a promising route to exploiting the advantages of existing technologies [27] thanks to recent progress in material processing. Their levels of technological maturity have led those platforms to compensate their identified weakness through heterogeneous or hybrid integration. For the sake of simplicity, we deliberately gather "hybrid integration" and "heterogeneous integration" under the common denomination "hybrid quantum photonic devices," but we invite the reader to refer to Ref. [28] for clearer discrimination. New hybrid platforms such as lithium niobate on insulator (LNOI), III-V on SiN, SiC on silica, and AlN on SiN, are currently emerging. These platforms require specific materials, designs, and integration strategies to optimize their functionalities for use in photonic quantum technologies.

D. Outline

The ambition of this Perspective is to discuss recent progress toward the development of integrated quantum photonic technologies as well as current challenges and future directions. Accordingly, we provide in Sec. II a nonexhaustive synthesis highlighting strengths and weaknesses of each technological platform. Based on selected monolithic components, we describe state-of-the-art experiments, and highlight the potential of such devices for quantum technologies in communication and metrology applications, in Secs. III and IV, respectively.

While we purposely skipped the computation and simulation axis of quantum technologies since it is exhaustively covered elsewhere [4,5,29], we will rather provide in Sec. V an extensive review of quantum memories, since this key interface between quantum computing *stricto sensu* and quantum communications remains poorly covered in the literature. Finally, Sec. VI proposes several examples of hybrid integration of key physical components that would be required for beyond-state-of-the-art and practical devices.

II. PLATFORMS FOR INTEGRATED PHOTONICS

Several photonic integration platforms, including LN, III-V, or III-N semiconductors, silica and Si, have succeeded worldwide in gathering the necessary building-block functionalities that permit both the creation and manipulation of quantum states of light on a single chip [24]. We provide a short review of the main waveguide platforms currently investigated whose exploitation in quantum technologies will be further explored in subsections dedicated to applications.

By making a short wish list for an ideal integrated quantum platform, we highlight seven criteria with no particular order of importance:

(a) **Quantum light generation:** whether it is based on three-wave, four-wave mixing, or on biexciton de-excitation, this feature is directly related to the entanglement of photons and encompasses generation of discrete photon-pair, vacuum-squeezed states of light, as well as hybrid states relying on different discrete and continuous quantum variables [30].

(b) **Single-photon generation:** such a feature includes the potential for integrating deterministic true single-photon emitters on the contrary to probabilistic single-photon emitters based on the aforementioned photon-pair generation.

(c) **On-chip linear and nonlinear elements:** they offer the ability to passively route and shape light in both spatial and frequency domains [filters, beam splitters, (de)multiplexers] but also to actively manipulate its quantum properties by means of electro-optic modulation.

(d) **Scalability:** it corresponds to the potential for higher integration capacity. It includes material propagation losses, refractive index steps in waveguides, and the effective size of the individual components allowing estimating the integration scaling factor.

(e) **Quantum light detectors:** for some applications, quantum states of light require on-chip detectors with high efficiency, low noise, and low jitter. Such detectors could be single-photon detectors but also high-performance intensity photodiodes for measuring bright nonclassical states of light.

(f) **CMOS compatibility:** it indicates the potential for integration with electronic component layers but also the ability for designing electrically driven devices.

(g) **Memory compatibility:** such a criteria needs further clarification. Within the context of quantum communication, memories can be designed as "in-out" systems, that absorb and store an incoming qubits or as emissive systems that emit on demand a photonic qubit whose state is entangled with an internal degree of freedom of the memory. In the latter scenario, one exploits quantum state teleportation for "storing" the quantum states. Both types of memories find application in different protocols, and each possess specific strengths, that we detail in Sec. V.

In addition, one cannot forget the issue of coupling the devices to beams propagating in optical fibers or free space, that haunted integrated photonics since its birth. We purposely avoid discussing these injection and extraction losses here since the available and proposed solutions are not specifically quantum and lie beyond the scope of this Perspective; yet, we believe, significant efforts should be kept in mind and addressed when designing new devices [31].

In the following, we are briefly introducing the currently developed integrated photonic platforms. For each, we have reviewed their strengths and weaknesses and compared their performance metrics along a spider chart on Fig. 1 for quantum applications.

A. Silicon (Si) and silicon carbide (SiC)

Si photonics has stepped into the quantum world recently: it has emerged as a novel and promising platform, enabling both on-chip generation and manipulation of quantum states of near-infrared light and a full compatibility with CMOS technologies. Technically speaking, Si quantum photonics drew attention for its superior integration density factor, its efficient third-order optical nonlinearities, and highly mature designing and processing knowledge. Passive and active components exhibit sizes typically on the order of approximately 100 μm. Despite its lack of natural electro-optical coefficient leading to slow

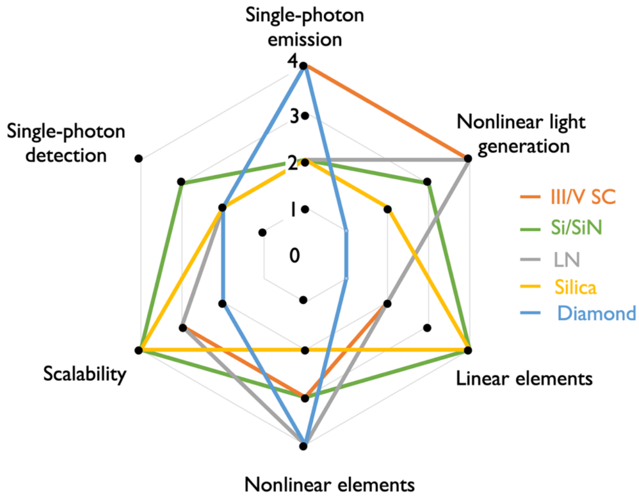

FIG. 1. Overview of the main strength and weaknesses of the main integrated photonic platforms. Their performances (the seven criteria defined earlier) are ranked on a scale from 0 to 4. Such a graph is based on our own expertise and on the current state of the art. It should not be interpreted as permanent or definitive.

optical modulation via local heating, one can also address various further functionalities, such as wavelength add or drop and photon-routing functions [32,33].

Currently, propagation losses and two-photon absorption in Si waveguides are still relatively high and are the main limitation of the platform in terms of scalability. This issue is currently being addressed by SiN, reducing the propagation losses down to ≤ 0.1 dB/cm, extending the transparency range to the visible, and mitigating two-photon absorption allowing high-power handling in order to counterbalance a lower third-order nonlinearity.

In terms of single-photon emission, thanks to continuously refined nanofabrication techniques, nitrogen-vacancy (N-*V*) center in Si [34] and SiC [35], are the most-studied systems among solid-state emitters. In the specific case of SiC, due to wavelength noncompatible with telecom fibers, as well as recent major advances in nuclear magnetic resonance spectroscopy [36], the platform has been oriented mainly towards quantum computation, simulation, and quantum repeater schemes [4].

It can be noted that Si-based components also undergo a significant research effort concerning the interaction of light and sound waves at the quantum level, either in optomechanics (typically, kHz–MHz range) [37] or through stimulated Brillouin scattering (typically, 10 GHz range) [38], which falls beyond the scope of this Perspective.

B. Lithium niobate (LN)

Historically speaking, crystalline LN stands as one of the major technologies for quantum integrated photonics. LN waveguides are known for their superior optical performance from ultraviolet to midinfrared, such as low optical transmission losses, large second-order nonlinear coefficients (optic-optic as well as electro-optic), making it a serious contender for the fabrication of performant integrated photonic devices for both classical and quantum information applications [39]. Compared to spontaneous four-wave mixing in Si ($\chi^{(3)}$ based), quantum states can be generated in LN with unparalleled brightness by spontaneous parametric down-conversion ($\chi^{(2)}$ based), further tailored and modulated by domain engineering simplifying the pump rejection [40,41].

However, the cm-scale typical footprint of conventional (i.e., proton-exchanged waveguide) LN circuits have slowed down the progress of monolithic LN chips in favor of LNOI. Such a technology is currently providing the possibility for the realization of new photonic chips with unprecedented advances in terms of scalability and performance [42], and can reach the size of Si and SiN chips. For instance, electro-optic modulation bandwidth has recently reached up to approximately 100 GHz [43] and the scaling factor becomes comparable to Si photonics even if less mature in terms of fabrication.

The essential feature of LNOI also lies in the possibility of fabricating electro-optically reconfigurable circuits, which can be efficiently operated at cryogenic temperatures. Their integration with superconducting nanowire single-photon detectors (SNSPDs) has been demonstrated by patterning niobium titanium nitride stripes on top of the waveguides [44–46]. Eventually, even at an early stage of development, LN waveguides are also compatible with quantum memory [47] through the use of rare-earth-ion-doped crystal. The LNOI platform is detailed in Sec. VI.

C. III-V and III-N semiconductors

Historically, semiconductor materials have taken advantage of their well-mastered growth and processing techniques, as well as a direct band gap to demonstrate quantum dot (QD) structures for deterministic generation of single photons [48], while the biexciton cascade has been used later for deterministic entanglement generation [49]. By spectrally and spatially coupling the QD emission to microcavity modes, one can drastically increase its spontaneous emission rate and achieve GHz high-purity single-photon emission [50,51]. Beyond the use of a photonic structure to optimize the extraction of single photons to an optical fiber, novel experiments now couple single-photon sources to photonic circuits to perform optical quantum computing tasks [52,53].

At the same time, a promising path comes from GaAs and related compounds. They exhibit a huge potential in terms of integrating since this platform combines a large second-order optical susceptibility enabling the integration of entangled photon sources with SNSPDs. Moreover, they offer the possibility to integrate an active lasing region directly on chip [54], opening the way for electrically driven devices [55].

Similarly, GaN is, behind Si, the second semiconductor worldwide in terms of business share, and one can take full advantage of the technological know how developed so far for solid-state lighting and high-power and high-frequency electronics. Electrical injection as well as photonic building blocks (e.g., air/GaN distributed Bragg reflectors, optical waveguides, in and out couplers, photonic crystals, etc.) already exist in the GaN community worldwide. Aluminum nitride (AlN) is a new material suitable for scalable photonic integrated circuits. Its strong intrinsic second-order nonlinearity ($\chi^{(2)}$) not only shows great potential for realizing on-chip photon-pair sources based on spontaneous parametric down-conversion (SPDC) but also permits integrated low-loss and high-speed electro-optic phase modulators [56]. The high refractive index contrast between AlN waveguides and silica-cladding layers allows for a small device footprint and enables dense integration.

D. Silica

Silica has a weak third-order nonlinear coefficient, lack of an electro-optic coefficient but offers a very versatile and powerful waveguide technology. Benefiting from the lowest intrinsic propagation loss of any material in the IR regions, the femtosecond laser direct-writing (FLDW) technique has attracted interest for the fabrication of complex linear waveguide circuits. Requiring no need for lithographic masks, it allows high-speed device fabrication and offers inherently three-dimensional (3D) routing capabilities. The field of quantum photonics has exploited rapid prototyping of small-scale circuits for previously unfeasible quantum random walks, boson sampling, and for heralded single- and entangled-photon generation experiments [22,25,57–59]. Beyond a laser-written waveguide, a more classical approach has shown high potential for integrated quantum photonics. In 2008, the very first quantum gate was demonstrated on a silica-based planar waveguide on an Si wafer [60] and has grown toward advanced reconfigurable circuits [61] combining up to 15 interferometers.

III. QUANTUM COMMUNICATION

A. Prepare-and-measure QKD

Quantum key distribution (QKD) relies on sharing randomness between two distant users, traditionally named Alice and Bob. Since the first protocol introduced by Bennett and Brassard in 1984 (BB84) and based on a prepare-and-measure scenario [62], a large number of schemes have been developed to simplify the experimental implementation, and improve the performance and the robustness against device attacks. This section provides an overview of recently published works and gives some trends of current thinking in this field, complementing existing reviews [63–65].

QKD was immediately of commercial interest as it addresses the security issue of classical asymmetric key protocols like RSA, which is named after Ron Rivest, Adi Shamir, and Leonard Adleman. Within a short time frame, the objective was to realize compact, stable, and efficient systems in the perspective of creating a new market. This trend has been boosted by the development of integrated photonics for classical communication. As an example, the plug-and-play system developed at the University of Geneva in 1996 employs an integrated phase modulator for preparing the quantum states [66]. Current QKD systems now exploit phase and amplitude modulators and have achieved both speed (5 GHz) [67] and distance (421 km) [68] records. Furthermore, such modulators now serve newly developed approaches, such as measurement-device-independent (MDI) QKD [69] and twin-field (TF) QKD [70]. Moreover, these two techniques offer the possibility to address a large number of degrees of freedom, e.g., polarization [71], time [72,73] or frequency [74].

Another approach consists of developing dedicated integrated devices. In 2004, a pioneering work exploited a planar light-wave circuit on which an unbalanced Mach-Zehnder interferometer is integrated on silica to measure the phase difference between two sequential pulses in a differential-phase-shift (DPS) QKD experiment [75]. The first realization of a QKD system, in 2004, used a planar light-wave circuit unbalanced Mach-Zehnder interferometer integrated on silica to measure the phase difference between two sequential pulses in a differential-phase-shift (DPS) QKD experiment [75]. This way, the authors significantly reduced the size of standard interferometers based on fiber components and improved the phase stability by controlling the temperature within 0.05°C. This work was improved by many research groups to reduce the polarization sensitivity and phase fluctuations [76,77].

The next step lies in integrating a full QKD system, i.e., both the optics and the electronics, to reduce the footprint with respect to that of standard "small form-factor pluggable" systems used in classical communication. A typical realization was the "QKarD," which incorporates a distributed feedback laser and a modulator in a packaging box similar to those of electro-optic modulators [78] [Fig. 2(a)]. The device allows producing polarization states at 1550 nm with three levels of intensity to implement a decoy-state BB84 QKD protocol [79]. The device operates at a frequency of 10 MHz.

The size of the transmitters can be reduced by realizing photonic chips on platforms offering a high integration density. A summary of all the QKD transmitter chips is given in Table I. In 2016, standard Si photonic

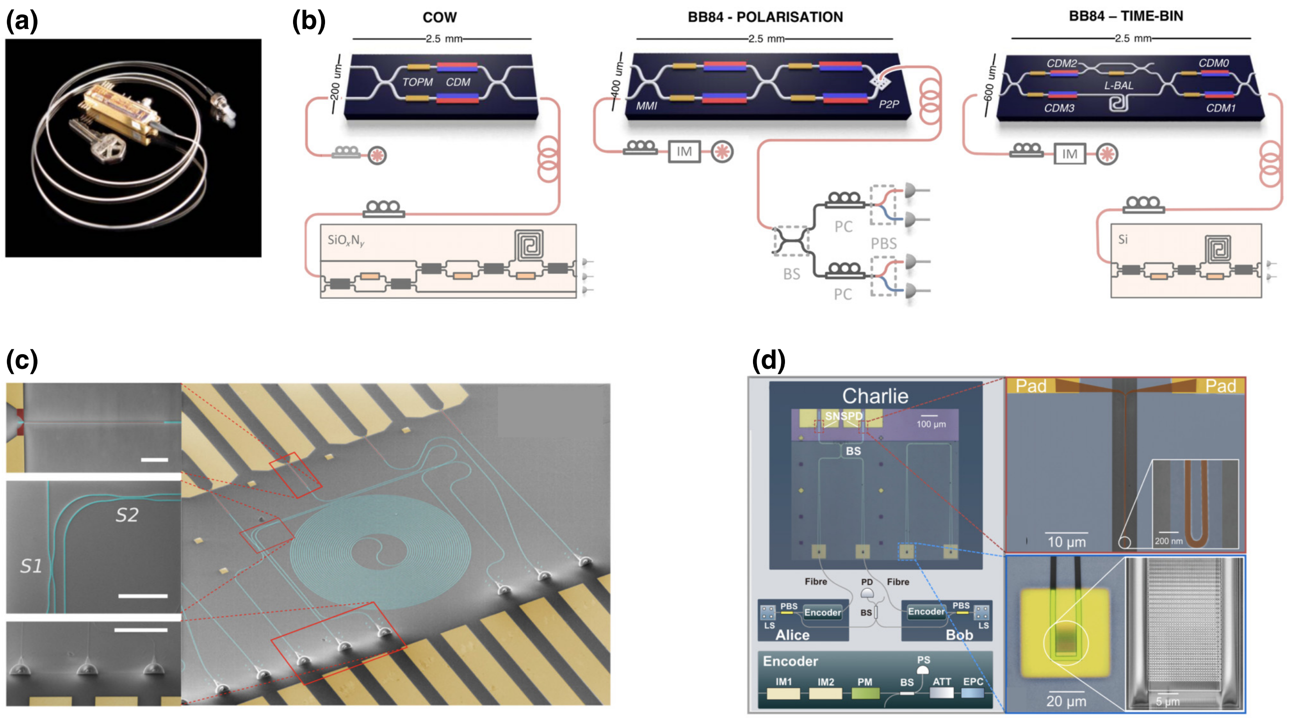

FIG. 2. Integration of various devices for prepare-and-measure protocols. (a) First generation of QKarD, from Ref. [78]. A photo of Los Alamos National Laboratory's QKarD (Quantum Smart Card.). (b) Integrated silicon photonic devices for QKD: COW, BB84 polarization and BB84 time bin, from Ref. [80] (c) SEM image of receiver chip integrating superconducting nanowire single-photon detectors (red) on top of the waveguide (cyan). Splitters (S1 and S2), Mach-Zenhder and vertically couplers allow a time-bin protocol with one decoy state, from Ref. [81] (d) Heterogeneously integrated, superconducting Si photonic platform for MDI QKD, from Ref. [82].

foundry processes were exploited to realize a QKD transmitter containing two ring modulators, four variable optical attenuators, and a polarization modulator [84]. A QKD link based on the polarization-encoded BB84 protocol was demonstrated at a rate of 10 MHz. Shortly after, three transmitters in Si has been developed to prepare states for coherent one-way (COW), polarization-encoded BB84, and time-bin-encoded BB84 QKD protocols [80] [Fig. 2(b)], respectively. Correspondingly, quantum state analysis was ensured using silicon oxynitride (SiO_xN_y) photonic receiver circuits with off-chip single-photon detectors.

All these implementations require an external laser to generate the photons that carry the quantum states. The first fully integrated QKD link was achieved with the transmitter and the receiver made on InP and SiO_xN_y, respectively [85]. The transmitter chip includes a continuous tunable laser diode, an amplitude and a phase modulator, and a variable optical attenuator. Such a QKD link allowed realizing all time-coded based QKD protocols, i.e., COW, BB84, and DPS at repetition rates of 560 MHz, 860 MHz, and 1.76 GHz, respectively, thus confirming the flexibility of the approach.

Photonic platforms for MDI QKD protocols have also been developed. The transmitters are similar to those used for BB84 protocols, but Hong-Ou-Mandel interference needs to be observed between the states emitted by two independent transmitters. To comply with this step, it is mandatory to realize two transmitters that emit coherent states that are perfectly indistinguishable over all degrees of freedom, except the one used to encode the states. Three experiments have demonstrated the feasibility of this approach, one based on InP transmitters [91] [Fig. 2(c)] and two on Si [92,93].

Considering the very productive developments in integrated optics for QKD in the past few years, packaging such systems into commercial devices tends to become the current challenge. As an example, current technologies enable quantum state generation within a "small form-factor pluggable" module [96]. Today's main challenge lies in integrating single-photon detectors on a single photonic chip. Recent developments (mainly based on SNSPD) offer the possibility to detect single photons directly on a photonic circuit [97]. Notably, Ref. [81] reports on a Si photonic circuit including integrated SNSPDs to analyze time-bin qubits. A superconducting Si photonic platform has also been developed to perform the Bell-state measurement for MDI QKD links [82].

In addition to QKD schemes that exploit quantum optical states at the single-photon level, an increasing

TABLE I. List of QKD experiment realized with integrated transmitter. DPS, differential phase shift; COW, coherent one way; CV, continuous variable; FLWG, femtosecond-laser-written waveguides.

Reference	Year	Material	Protocol	Observable	Laser source	Receiver	Clock
[83]	2015	FLWG	BB84	Polarization	External	Integrated	100 MHz
[84]	2016	Si	BB84	Polarization	External	Fibered	10 MHz
[85]	2017	InP	BB84, DPS, COW	Time bin/Polarization	On chip	Integrated	1.76 GHz
[80]	2017	Si	BB84, COW	Time bin/Polarization	External	Integrated	1 GHz
[86]	2017	Si	High-dimension	Path	External	Integrated	5 kHz
[87]	2018	Si	BB84	Polarization	External	Integrated	625 MHz
[88]	2019	Si	BB84	Time bin	External	On chip	100 MHz
[89]	2019	Si	CV Gaussian-modulated	quadrature	External	Integrated	10 MHz
[90]	2019	InP	BB84, DPS	Time bin	On chip	Integrated	1 GHz
[91]	2020	InP	BB84 MDI	Time bin	On chip	Fibered	250 MHz
[92]	2020	Si	BB84 MDI	Polarization	External	Integrated	0.5 MHz
[93]	2020	Si	BB84 MDI	Polarization	External	Fibered	1.25 GHz
[94]	2021	Si	BB84	Polarization	External	Fibered	50 MHz
[95]	2022	FLWG	BB84	Polarization	External	Integrated	100 MHz

number of demonstrations are focusing on continuous-variable (CV) QKD. Here, quantum information is encoded on the amplitude and phase quadratures of the electromagnetic field, which are continuous spectrum observables. Most protocols rely on Gaussian modulation of a coherent state and on the homodyne detection of its quadratures at the receiver side [98]. In 2019, elements for both information encoding and detection, including modulation and multiplexing stages as well as the homodyne detection, respectively, have been integrated on two Si photonic chips. These components allowed a secret key rate of 0.14 kbit/s (under collective attack) over a simulated distance of 100 km in optical fiber [89].

Finally, while QKD based on bipartite entanglement stands at the heart of many important realizations, most of the reported schemes exploit only integrated photonics as a resource to generate the entangled state in compact configurations. Since multiple research articles and reviews have already been published on this topic [39,98], we chose not to detail it here, and to focus instead on the trendier topic of QKD based on high-dimension entanglement, as it offers a promising path towards new and enhanced realizations. High-dimension QKD exploits states in N-dimensional Hilbert spaces, allowing for an increase in the number of secret bits per trial compared to two-dimensional schemes. This approach is a serious candidate for distributing information in an unconditionally secure way, but also opens new horizons when considering entanglement between different partners. Besides the aforementioned QKarD [78], some realizations have already started exploiting this approach. Among others, Ref. [86] proposes an integrated transmitter and receiver on Si chips to realize QKD links based on path observable. The two devices are able to prepare and analyze single-photon states delocalized over four spatial modes transmitted in four single-mode cores of a multicore fiber. Other approaches to multimode entanglement are discussed in the following subsection.

B. Multimode quantum photonics

Multipartite states find relevant applications in many ambitious quantum information protocols in both discrete-variable (DV) and CV regimes. Multimode optical entanglement lies at the heart of quantum metrology [99], advanced quantum simulation [5], large alphabet quantum communication [100], and, as previously discussed, multipartner secure quantum networks [86,101]. Remarkably, cluster states, a special class of multipartite entangled states, are essential to on-the-fly optical quantum computing exploiting measurement-based protocols [102]: this approach originally developed in the context of DV quantum information encoding (see Ref. [102] for a review) has been progressively extended also to CV regime [103–105]. At the same time, in many situations, the quantum advantage relies on the possibility of having access to a high number of modes that can be individually manipulated and measured, and whose entanglement features can be as finely controlled as possible [106]. Depending on the choice of entangled observables and modes, increasing the number of parties can quickly become a great challenge for the traditional bulk optics approach. Integrated photonics naturally offers the possibility of developing compact and highly scalable devices, that can be (re)configured to satisfy the criteria of controllable quantum features in compact and flexible implementations.

One of the first degrees of freedom to be exploited and manipulated for the generation of multimode quantum systems has been the spatial mode, also referred to as the path observable [100]. Demonstrations cover both DV and CV regimes. At low dimension, in CV regimes, two-mode path entanglement can be obtained on chip by mixing two single-mode squeezed states on a tunable waveguide coupler where their relative phase is electro-optically adjusted [23].

High-dimension path-entangled states can also be obtained in structures using networks of optical couplers [107]. Implementations of this concept are straightforwardly compatible with integrated photonic on different platforms. Applications range from fundamental quantum physics, such as for the demonstration of photonic Anderson localization in a network of laser-written waveguides [108] or the generation and verification of single-photon W states involving up to 16 spatial modes [109] to quantum walk schemes whose study is essential in the context of topological physics as well as in quantum computation [5]. Among others, planar architectures involving a cascade of multiple splitter and couplers are particularly compatible with small footprint integration platforms, such as Si or SiN. In these platforms, a high number of optical couplers and phase controllers can be integrated on a single optical chip [110], exploiting a technology that finds applications in QKD as in Ref. [78], but also in quantum simulation [111] or boson sampling [112].

As represented in Fig. 3(a), integrated optics on Si has allowed the realization of a programmable large-scale quantum circuit, integrating, on a single chip, more than 550 photonic components, including 16 identical photon-pair sources based on spontaneous four-wave mixing (SFWM) [113]. In this scheme, a photon pair is generated by SFWM in superposition across 16 optical modes, producing a tunable multidimensional bipartite entangled state. Signal and idler are separated by an array of asymmetric Mach-Zehnder interferometers (MZIs) and routed by a network of crossers, allowing the local manipulation of the state by linear-optical circuits. By uniformly pumping the sources, maximally entangled states can be obtained.

It is relevant to note that complex quantum optical circuitry similar to the one just described plays an essential role also in the context of quantum computing and quantum simulation due to the possibility of applying an external control to reconfigure the photonic circuits as demanded to implement different quantum algorithms. The demonstrations of such reconfigurable devices are multiple [110]. In the DV regime, this concept has been explored since at least 2015, when a cascade of 15 Mach-Zehnder interferometers with 30 thermo-optic phase shifters was integrated on a silicon on silica photonic chip [114]. By electrically setting all phase shifters the chip could be reconfigured so as to implement heralded quantum logic and entangling gates, boson sampling with verification tests, and six-dimensional complex Hadamards [114]. In the CV regime, an important advance has been obtained in 2021 with the realization of a reconfigurable SiN photonic chip, integrating four squeezers based on microring resonators and a network of beam splitters and phase shifters, implementing a user-programmable gate sequence. Proof-of-principle demonstrations of the Gaussian boson sampling, molecular vibronic spectra, and graph similarity quantum algorithms have been performed with the device [6].

A different approach relies on the use of continuous-time quantum walks implemented with arrays of N evanescently coupled laser-written waveguides tailored to produce a lattice Hamiltonian [5] and often organized in three-dimensional arrays [5,117,118]. In particular, on LN, this concept has been fruitfully associated with the material nonlinear properties, leading to the possibility of working with arrays of nonlinear waveguides in which entangled photons generated via SPDC in a given waveguide diffuse over the entire array by means of the coupling between adjacent channels [119]. In a seminal experiment, photon-pair states with a controllable degree of entanglement in multiple discrete spatial modes have been produced through quantum interference of photon pairs generated by SPDC in an array of four periodically poled waveguides [119]. Later on, many theoretical papers have discussed how tuning the properties of the pump beam or changing the sample structure allows generating different types of path entanglement states. The central point of these analyses conceptually lies in the identification of the system propagation eigenmodes that are shape-invariant along propagation. This has been performed for the single-photon DV regime [120] as well as in the CV regime, where large spatial entangled states are predicted by exploiting phase matching of a propagation eigenmode [121].

Despite their interest, demonstration of multipartite entanglement among spatial modes requires fabricating multiple copies of the same structure on the same photonic chip. Increasing the number of modes thus requires the integration of a rapidly growing number of functions. A particularly promising approach to high-dimension entangled states relies on exploiting correlations among frequency and time modes that are produced around target wavelengths via SPDC or SFWM in nonlinear optical waveguides [106]. This strategy overcomes scalability issues linked to the use of spatial degrees of freedom as all entangled frequency and time modes are generated in a single spatial mode. Downstream of the generation stage, individual entangled modes can be spatially separated and independently manipulated by making use of standard time or frequency multiplexing stages [122], fully compatible with integrated circuit realizations [23,123] and fiber optical components. Remarkably, most of the available nonlinear processes employed in quantum optics naturally generate multimode frequency and time quantum correlations [124]. Multipartite quantum states have been generated in resonant and single-pass configurations on different optical platforms. Broadband biphoton frequency states with controlled symmetry have been generated by SPDC in a AlGaAs waveguide, based on the interplay of relative

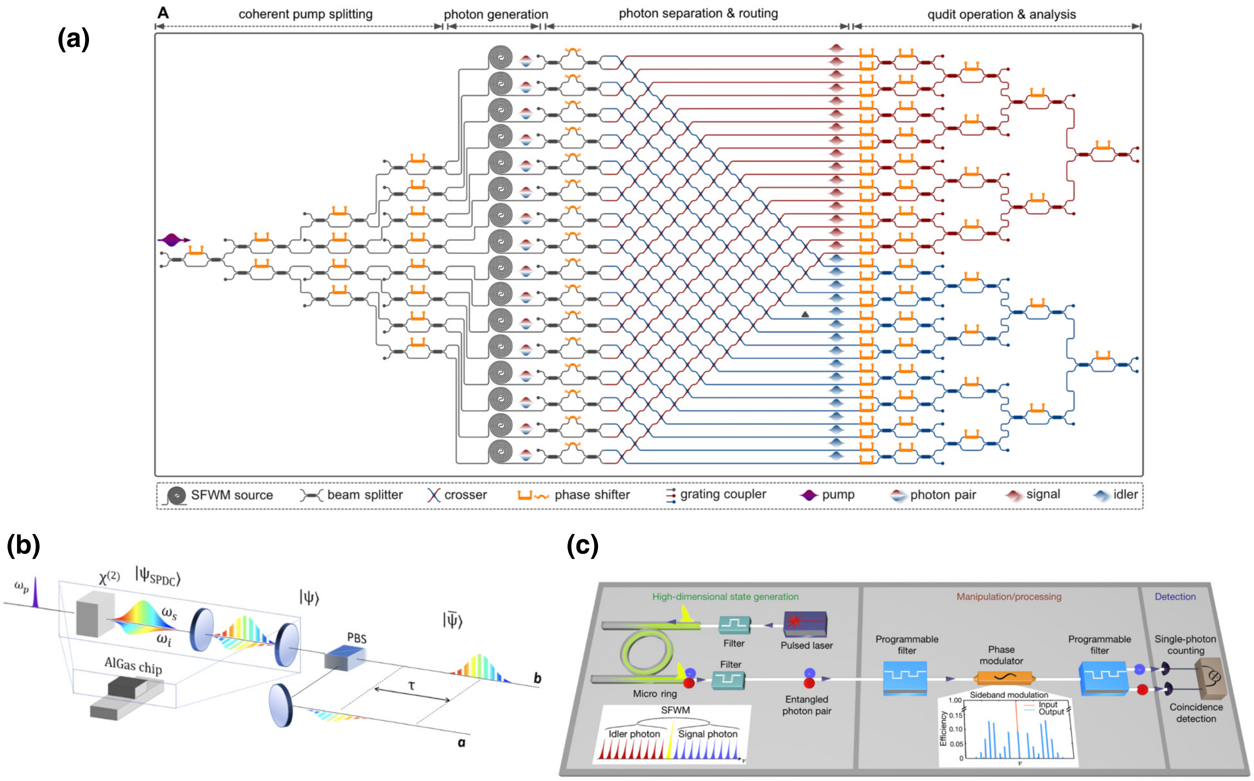

FIG. 3. On-chip generation of multipartite states. (a) An architecture for generating high-path entangled state: a large-scale integrated quantum photonic circuit in Si based, from Ref. [113]. (b),(c) rely on exploiting correlations among frequency and time modes, from Ref. [115] and Ref. [116], respectively. (b) Schematic of the experimental setup for the generation and manipulation of biphoton frequency comb. (c) Experimental setup for high-dimensional quantum state generation and control. The quantum state is formed by two entangled qudits with $d = 10$.

temporal delay between the two photons of each pair and cavity effects due to Fresnel reflections at the waveguide facets [see Fig. 3(b)] [115]. Frequency-entangled qudits have been obtained via SFWM in an integrated nonlinear microring resonator fabricated in high-refractive-index silica glass (Hydex) and continuously pumped. This configuration allows generating multiple two-photon frequency-entangled states with high purity that are subsequently exploited to experimentally prove qudits of dimension up to $D = 4$ [see Fig. 3(c)] [116,125]. Continuing to expand the Hilbert dimension spaces, an experiment involving entangled frequency qudits sourced from silicon nitride (SiN) conducted full tomographic analysis on entangled pairs of qudits with a dimensionality of $D = 8$ [126]. Very recently, second-order photon correlations have been used to investigate the quantum dynamics of soliton microcombs in an integrated SiC microresonator. Experiments relying on DV measurements have shown that a stable temporal lattice of solitons can isolate a multimode below-threshold Gaussian state from any mixture of coherent light [127]. In the CV regime, there has been a progressive increase in the number of frequency and time modes carrying nonclassical information. A first CV realization demonstrated two-partite intensity correlation in an above-threshold SiN microresonator [128]. Later on, quadrature squeezing among light in two distinct frequency modes has been demonstrated [129,130]. These seminal works opened the way to the demonstration of 20 simultaneous two-mode squeezed pairs observed at the output of a quantum microcomb generated from a silica microresonator on a Si chip. The detected 40 CV quantum modes span an optical bandwidth of 1 THz at telecommunication wavelengths [131].

To conclude this section, it is worth noting that in recent years, there has been increasing interest in engineering nonlinear optical processes as a strategy to customize multimode time and frequency entanglement [106]. These techniques rely on manipulating the interaction joint spectral amplitude (JSA) by acting on the spectral properties of the pump [132,133] or on (quasi) phase matching [134,135], including via electro-optical control of the nonlinear material [136]. This approach is worth mentioning as a more pioneering and potentially disruptive path towards future photonic circuits that integrate versatile sources of high-dimensional entanglement. Experimental works have demonstrated the pertinence of these ideas in bulk single-pass systems exploiting second-order optical nonlinearity and operating, mostly in the DV regime [135,137–139]. These promising realizations, however, have not yet reached the full maturity required to be implemented in complex integrated circuits. Alternative strategies propose to purify [140] or tailor entanglement by coupling or cascading third-order nonlinear optical processes in microresonators [141–143]: integrated optics becomes an essential ingredient to the practical implementations of these complex architectures. In particular, dense integration and scalability offered by silicon-based platforms made their experimental validation possible in the DV regime with the generation and manipulation of programmed frequency-bin qudit entanglement [144–146].

IV. PHOTONIC QUANTUM SENSORS

If, on one hand, quantum states' fragility is at the origin of many challenges in practical quantum technologies (see Secs. III A, III B), on the other hand, their sensitivity to their environment can be conveniently exploited for measuring environment-dependent physical parameters. This subfield is nowadays referred to as quantum metrology. Manipulating quantum light for developing novel quantum sensors is an appealing opportunity offering high-accuracy measurements of physical values, such as pressure, temperature, position, time, velocity, acceleration, electrical and magnetic fields, and gravity [147,148]. The huge potential has mainly been assessed using large-scale (bulk) optical elements. At the same time, the physical size and inherent instability of such an approach hinders the development of more complex quantum optical schemes and currently prevents the realization of fully scalable quantum optical devices [149]. From the technological perspective, the development of quantum photonic sensors is facilitated by integrated photonic platforms enabling selective and real-time analysis.

The on-chip generation and manipulation of quantum photonic states has pushed forward the scientific research (Sec. IV A) and has initiated use cases (Sec. IV B). We discuss in the following how integrated photonics is used to boost optical quantum sensors. We will focus on photonic quantum sensors dedicated to the qualification of the properties of optical materials and biochemical species.

A. Integrated circuits for optical quantum sensors

A primary requirement for optical quantum sensors based on DV is the generation of entangled photon pairs via SPDC over a broadband spectrum, namely a quantum white-light source, enabling quantum optical coherence tomography (QOCT) [150], and enhanced two-photon absorption (TPA) [151]. As already discussed in the context of multimode entanglement, the smart engineering of the quasi-phase-matching in optical waveguides allows one to shape both spatial and temporal properties of entangled photon pairs [139] and the SPDC spectrum (and associated JSA), finding repercussions in QOCT [152]. Combining several types of quasi-phase-matching conditions has been investigated as a solution to increase the photon-pair generation efficiency [153]. However, combining both an increased flux to a broad emission bandwidth still remains challenging. Recent works have enabled both features using periodically poled stoichiometric lithium tantalate ridge waveguides, based on chirped quasi-phase-matching type-0 SPDC [154]. By implementing a chirped structure in a nonlinear waveguide, the authors show a MHz photon-pair flux over a spectral bandwidth approximately 300 nm. This source of photon pairs could replace bulk sources favorably in QOCT experiments as demanded to prevent any stability issues, as discussed in Refs [155, 156]. Notably, with this technique, Lyons *et al.* achieved path length resolutions on the nm scale with the perspective of reaching pm scales by further exploiting two-photon NOON states [155].

Integrated photonics naturally offers solutions to alleviate instability and allowing an accurate control of the path length through the implementation of reconfigurable quantum circuits [157]. Reconfigurability allows for performing integrated quantum metrology experiments in which NOON states can be generated and manipulated on chip [Fig. 4(a)] [59,158,159]. Monolithic platforms as LN have now reached such levels of maturity that single chips showing high levels of integration become possible [59,158,159]. Reported solutions generally rely on the generation and the deterministic separation of two nondegenerate photon pairs in a heralded single-photon configuration. Switching from a two-photon separable state to a NOON is demonstrated through resistive or electro-optic component reconfiguration. Obtained visibilities of two-photon interference, typically higher than 90% in the raw data, are promising in the race to beat, using chip devices, the standard quantum limit.

Another branch of optical sensors has very recently emerged. It deals with the exploitation of two-photon entangled states serving as quantum probes for the qualification of optical materials' properties with higher precision and sensitivity [160]. In this framework, two proof-of-concept experiments have been reported to date using quantum white-light interferometry. In Ref. [160], the authors qualify the dispersion of standard optical fibers, with a 2.4 improvement factor in the obtained value compared to classical white-light interferometry methods.

Remarkably, the quantum approach brings several further advantages besides a higher precision, such as flexibility and a reduction of systematic errors. In Ref. [161], the authors aim at measuring precisely the refractive-index differences between the core and the cladding of a fiber. By exploiting a quantum optical method based on low-coherence Hong-Ou-Mandel interferometry, the authors

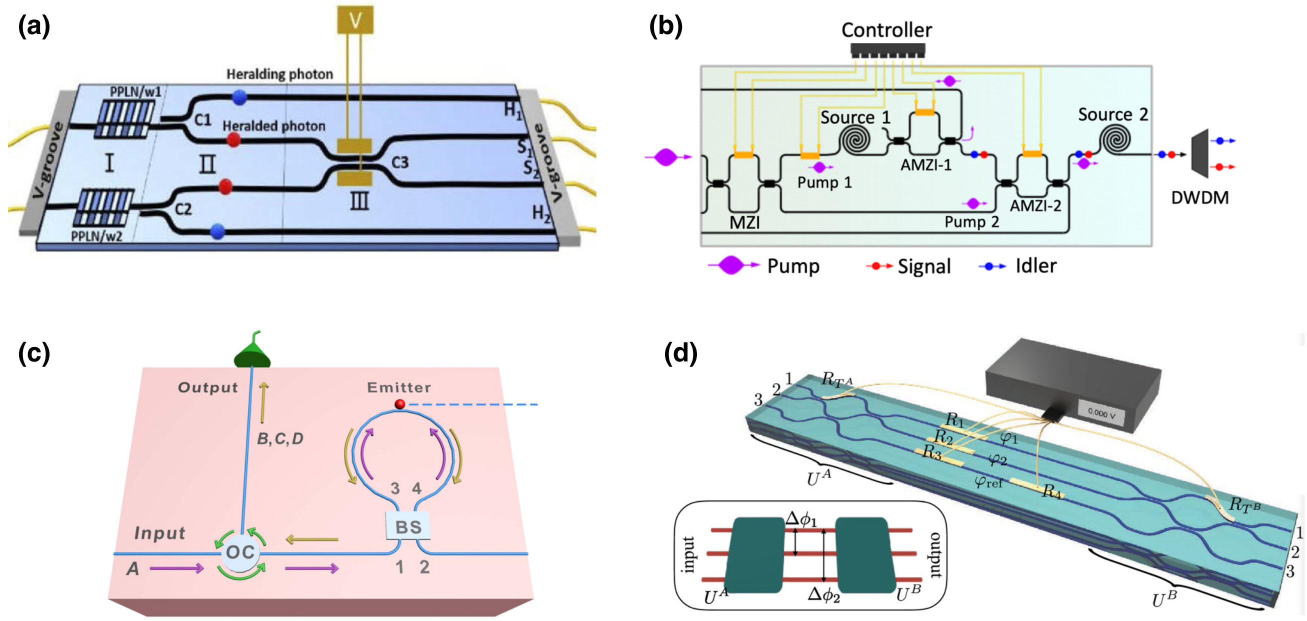

FIG. 4. Overview of various photonic circuits for optical quantum sensors. (a) Configurable heralded two-photon Fock states on a chip, from Ref. [159] (b) Nonlinear interferometer: generation of signal and idler photons occurs in the first spiraled waveguide source (source 1) and is enhanced or suppressed in the second one (source 2) on an Si photonic chip, from Ref. [166] (c) Schematic of an integrable high-efficiency generator of three-photon entangled states in a Sagnac loop, from Ref. [173] (d) Schematic of a multiphase estimation experiment on a chip, from Ref. [175].

show in the classical regime an improvement by an order of magnitude of the precision compared to already reported classical methods, and, in the quantum regime, an additional factor of 4 on the precision enhancement. Both techniques are particularly well suited to be integrated directly on chip by adding an interferometer and access to the sample under test. In addition, these works show the quantum photonic metrology to be powerful characterization tools that enable characterization of integrated photonic circuits that are the focus of this Perspective, which is currently not possible by classical methods, due to their very short length, while maintaining high accuracy.

B. Use cases: nonlinear interferometry

Recent years have seen a growing body of work in the area of quantum sensing using nonlinear interferometry [162–164]. The main motivation comes from inferring biochemical properties within the mid-IR range thanks to photon detection at visible wavelengths. Such an original concept (referred to as “induced coherence”) introduced by Mandel and co-workers [165], recently drew attention in the context of practical applications, such as imaging, spectroscopy, optical coherence tomography, and polarimetry [163]. Up to now, reported demonstrations have exploited this configuration using mainly bulk optics [163]. Recent progress in integrated photonics allows a transposition of this type of technology onto photonic chips. This miniaturization stands as a preliminary and essential step before considering industrial prototyping. On Si chips, Ono *et al.* have recently shown the first integrated version of a nonlinear interferometer, demonstrating high-interference visibility above 96% [Fig. 4(b)] [166]. Remarkably, the Si platform is of particular interest as its 2–4 μm transparency windows enables small-footprint optical quantum sensors for gas traces and biomolecule detection. Beside demonstrating the feasibility of nonlinear interferometry on chip, this pioneering work highlights new challenges, as the need for exploring other spectral ranges for one of the two entangled photons (say, the idler), at least in the mid-IR, while keeping the other (say, the signal) in the visible range, as already shown in bulk optics [167].

C. Noise resilience

Entangled states offer precision measurements unachievable with classical light resources, but they are also very sensitive to noise. An increase in sensitivity balances the robustness and the resilience of the quantum state: the more informative these resources are, the more fragile they are [168]. The promised quantum advantage is then easily spoiled by uncontrolled or spurious coupling with the environment, as shown, for instance, in the case of interferometry [169,170]. Keeping such quantum advantage in a realistic scenario is of major importance for ensuring the deployment of on-chip quantum sensors. As for quantum communication, multimode entanglement has been investigated as a solution to improve quantum metrology performances. Recently, Shettel *et al.* have shown that a specific variety of graph states maintain a quantum advantage after being subjected to dephasing or erasures [171]. Ye *et al.* numerically investigated the use of entangled triphoton states (also known as photon triplets) to prove a sensitivity enhancement in two-photon absorption with respect to results obtained with bipartite states [172]. This numerical work has been recently endorsed by the recent generation of three-photon entangled states on a photonic chip [Fig. 4(c)] [173], thus proving that integrated photonics not only plays a key role in the miniaturization of functionalities but also enables turning concepts into actual demonstrators.

Until now, related works in this section treat so far the assessment of a single parameter, e.g., the absorbance of a material probed by a signal. On the other hand, achieving the simultaneous estimation of multiple parameters is demanded by the dynamics of the overall sensing process. Few experiments have been realized so far, investigating multiparameter scenarios, due to the challenge of producing multiphoton states, which requires long acquisition times at the expense of the stability of the measurement setup. Quantum integrated photonics offers viable solutions with the possibility of realizing complex, however stable, interferometers [174]. Polino *et al.* reported for the first time an experimental proof of concept for determining simultaneously two-optical phases based on a reconfigurable integrated multimode interferometer written on silica [Fig. 4(d)] [175]. By using two-photon input states, the authors show a quantum enhancement performance in a postselected measurement scenario. In addition, by exploiting additional phase shifters to increase the number of control parameters, this device stands as a versatile platform for testing the multiparameter estimation scenario thanks its high reconfigurability.

D. Towards quantum lab-on-a-chip

Over the last two decades, efforts have led to the emergence of integrated, fully functionalized, biochemical photonic sensors, commonly named “lab-on-a-chip” systems. These devices integrate all required classical devices, such as lasers, transducers, and detectors, on a single chip [176]. From a global perspective, developing on-chip quantum sensors (notably for quantum imaging, quantum spectroscopy, and QOCT) represents a typical challenge in quantum integrated photonics as it faces limitations occurring also in the context of other quantum technologies.

From the material perspective, on-chip biosensing remains dominated by Si-based realizations, which benefit from mature fabrication know how in semiconductor microelectronics and photonics, and from the compatibility of silica-based microfluidic chips with flow cells [177]. A typical scenario is offered by two-photon interferometry. In Ref. [178], a two-photon NOON state, generated using bulk optics in a nonlinear bismuth borate BiB_3O_6 (BiBO) crystal, is sent to a Mach-Zehnder interferometer integrated on a silica substrate with a microfluidic channel passing through one arm. The measurement of the refractive index of a solution within the microfluidic device is then used to determine the solution protein concentration. Due to the high interference visibility, beyond the threshold required for supersensitivity, this work constitutes the most favorable proof-of-principle demonstration of an on-chip quantum biosensor. At the same time, the detrimental effect of chip losses and the nondeterministic photon pairs’ splitting strongly limits the rate of measured photon pairs, thus leading to a measurement precision lower than the standard quantum limit. Substantially increased fluxes would be required for measurements of this kind to compete, in terms of absolute precision, with conventional measurement techniques, showing therefore the need for fully integrated solutions.

We provide a glimpse of a photonic chip, which is, from our point of view, representative of future on-chip quantum labs. A sustained and multidisciplinary research effort is required to implement advanced optical measurement techniques on an operational photonic chip, while performing quantum metrology protocols [179].

One of the major challenges remains surpassing the standard quantum or interferometric limit in realistic, i.e., lossy sensors [2]. Optimal quantum states for lossy phase estimation are, not surprisingly, dependent on the exact value of the losses in the interferometer [170]. Consequently, no universal scheme for their preparation has emerged to date. As an example, NOON states are optimal in the absence of loss. On the other hand, squeezed states have been used to improve the signal-to-noise ratio in interferometric sensors [180–183]. Hence, a versatile platform should be able, depending on the situation, to generate either squeezed or entangled states. A possible solution comes from an Si-based quantum state generator enabling generation of both low and high-dimension states, as well as in both in DV [127,173] and CV [131] regimes.

A challenge in quantum imaging, QOCT, and spectroscopy, lies in producing frequency nondegenerate entangled photon pairs over different detection ranges, especially in the visible and mid-IR. As discussed above, $\chi^{(2)}$ materials represent a valid strategy to achieve such SPDC phase-matching condition. Beside the aforementioned hybrid solutions, artificially creating $\chi^{(2)}$ on a $\chi^{(3)}$-based platform appears as a trade-off combining the best of both worlds. However, the transposition into the quantum regime still remains ambitious [184]. Optically reconfigurable quasi-phase-matching in SiN (transparent from 0.4 to 5 μm) would be disruptive for quantum biosensors, quantum spectroscopy, and quantum imaging, paving the way for the use of possible frequency combs across visible and mid-IR spectral regions [185]. The intermediate regime between classical and quantum would help replace single-photon detection by standard photodiodes, thus mitigating the level of integration [186,187]. Rich libraries of design kits based on silicon-on-insulator waveguides will be useful for the realization of integrated components in the mid-IR range, which is so far unexplored, including wavelength-division multiplexer, grating, and directional couplers. Such quantum grade components have not yet reached maturity and must be optimized to work at different wavelengths. A second group of photonic chips tackles the manipulation stage of quantum states, and more specifically their interaction with chemical species or biological tissues. A moderate index refraction value combined with a high degree of flexibility stands as the premium criterion for a sensitive biosensor. Laser-written waveguides on silica show low losses, and offer 3D routing capabilities [57,188]. In this regard, note that the SiN platform, often used for photonic quantum state generation, is fully compliant with functionalized manipulation blocks (silica-on-silicon), thus ensuring low-loss interconnection. In addition, the silica platform allows machining at will the surface for the fabrication of microfluidic channels or hollow chambers directly connected to the surface. Dynamic operation and reconfiguration of multiport interferometers are typically achieved by externally controllable phase elements [188]. While electronic integrated circuits are by themselves a mature technology, merging electronic and photonic function onto single integrated devices remains a challenge requiring the realization of physical interfaces and adequate control circuits, which is tightly linked to the development of overlaid quantum protocols, including Bayesian and machine learning algorithms [189,190].

V. INTEGRATED QUANTUM MEMORIES

Photonic quantum memories (QM) play a central role in quantum information protocols, thanks to their synchronizing ability. In particular, they enable the implementation of quantum repeaters, which allow for extending the maximum distance over which quantum information can be shared [191]. As briefly mentioned in Sec. II, they can be divided into two main categories: the so-called “emissive” memories, where a photon heralds the creation of a local excitation, and the “in-out” memories, for which an incoming photon can be stored and released after a certain time. Emissive memories mostly find applications in quantum network developments, where synchronization is required between local “nodes.” The versatility of “in-out” QMs, on the other hand, allows them to be applied to a wide variety of fields, ranging from quantum communication, quantum state engineering, and quantum computing. Their performances are mainly characterized by their efficiency (i.e., the probability to retrieve the excitation), their fidelity (i.e., how similar the input and output quantum states are) and their storage time. The ability to store excitation at the single-photon level (low added noise), the bandwidth, and the wavelength of the input photons as well as multiplexing capabilities, must also be taken into account to comply with specific quantum network applications. Eventually, the spatial mode size should also be considered as a benchmark for scalability towards integrated photonic devices.

A large variety of systems and protocols have allowed the implementation of such QMs, but the focus of this section, like the rest of this Perspective, will be made on realizations that have allowed integration on waveguide platforms. In this context, two main groups of systems display a clear advance: color centers and rare-earth ion-doped crystals. Their solid-state nature makes them particularly suitable for integration. Integration of color centers has been extensively documented over the last years [192,193]. We will, therefore, focus only on the latest realizations of these systems, and on the integration strategies that are developed on rare-earth ion-doped systems. Strategies to integrate active centers for QM applications mainly follow three paths, that will be detailed in the following paragraphs.

A. First strategy: embedding active systems in waveguides

One approach is to take advantage of an already existing high-performance guiding technology in a given material and dope it with active elements. The main difficulty lies in the preservation of the performance of the active centers when embedded in the guiding host material.

An integration platform that has retained attention for storing photonic excitations is LN, both in its bulk and thin-film forms, by implanting active centers in it. Thulium has notably been chosen thanks to its easily accessible resonance wavelength (approximately 795 nm) and the possibility to implement storage protocols with it. Photon-echo memories have been demonstrated in titanium (Ti) in-diffused LN waveguides doped with thulium [194,195]. A sketch of the developed waveguides is shown in Fig. 5(a). Long-coherence lifetimes were reached (up to 110 μs) by decreasing the sample temperature down to 800 mK, leading to a reduction of phonon-induced decoherence mechanisms [195]. The same platform has been used to implement multiple kinds of information processing schemes. These include the atomic frequency comb (AFC) protocol implemented by performing optical pumping, and showing the possibility of storing entangled photons [47], as well as light manipulation in the spectrotemporal domain [199].

Erbium is also suitable for integration in LN, and proton-exchanged waveguides doped with this rare earth have been studied to implement the controlled reversible

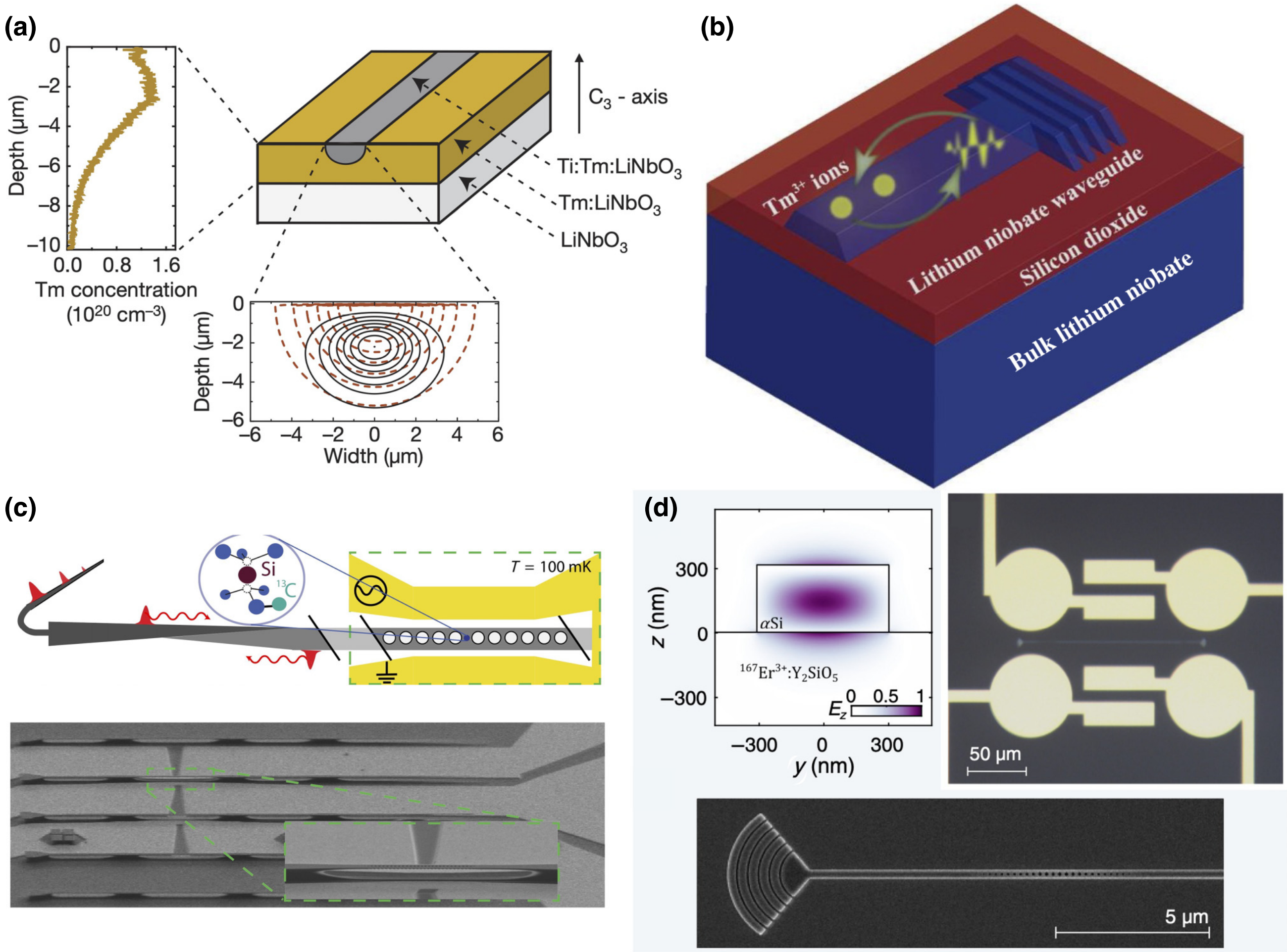

FIG. 5. Implanted and evanescently coupled QMs. (a) Waveguide built by Ti in-diffusion in a thulium-doped crystal, from Ref. [47] (b) Thulium-doped LNOI architecture, from Ref [196]. (c) Diamond nanoresonator coupled to a single Si-*V* center, from Ref. [197]. (d) Amorphous Si waveguide on Er:YSO with bias field control, from Ref. [198].

inhomogeneous broadening (CRIB) protocol by using the Stark effect [200]. Erbium was then doped into Ti in-diffused waveguides to implement two-pulse echoes with partially readout ensembles to demonstrate coherent storage in the telecom band [201,202]. However, until recently, it was impossible to perform storage and re-emission of telecom photons in this material, due to the difficulty to perform efficient population polarization due to relaxation processes. Fortunately, a combination of high magnetic fields ($\gtrsim 1$ T) and low temperatures ($\lesssim 1$ mK) allows performing efficient optical pumping and reaching long-coherence times [203]. Following this study, an AFC could be shaped in Er^{3+}:Ti^{4+}:LN, and storage of heralded single photons [204] over large bandwidths [205] could be performed.

Thin-film thulium-doped LN has also been developed, under the form of ridge waveguides on silica [196], as shown in Fig. 5(b). By performing optical pumping, the AFC protocol could be implemented for a storage of up to 250 ns [45]. Due to the very tight confinement, a threefold improvement in optical Rabi frequency compared to ion-diffused waveguides [195] could be achieved. Perspectives to extend this integration technique to erbium ions has also been investigated [206].

Parasitic effects in these materials, such as excitation-induced spin flips and frequency shifting due to two-level systems or nonequilibrium phonons, limit the performance, and further studies in material development need to be conducted in order to improve the purity of crystal growth. Note however that the coherence times remain mostly unaffected by the waveguide fabrication itself.

Implanted silicon vacancies (Si-*V*) in diamond have also been used in nanophotonic Si waveguides in order to implement "emissive" memories, with long-coherence times (approximately 1 ms) [197] [see Fig. 5(c)]. Here, the photonic state is teleported to the spin state upon photon detection. This architecture has further been used

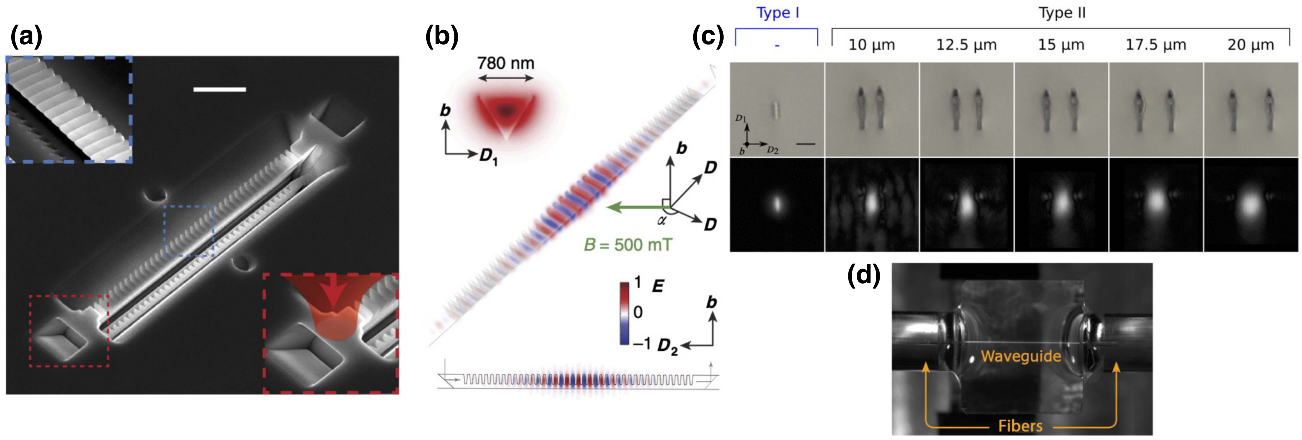

FIG. 6. Examples of QMs crafted directly in the material. (a) Nanophotonic photonic crystal resonator. Light is coupled in and out by total internal reflection in the red dashed region of the guide, from Ref. [213]. (b) Simulated electric field in the structure in (a). (c) Femtosecond laser direct-written waveguides of types I and II in Pr:YSO of various dimensions, from Ref. [216]. (d) Picture of a fiber-pigtailed waveguide on Pr:YSO, from Ref. [217].

to demonstrate an advantage in quantum communication protocols [207].

B. Second strategy: evanescent coupling

Another way of guiding light through photonic QMs consists in using nanophotonic guiding structures, which evanescently couple to the active systems, which can be bulk material. In this approach, light guiding is ensured by the step of index between the guiding material and the substrate. The challenge is to reach sufficiently high light-matter coupling in order to perform good quality manipulation.

Developments of such a strategy for QMs were first conducted by depositing a thin film of TeO_2 on Pr^{3+} [208]. This led to high-quality samples, whose coherence lifetimes were, however, 1.6 times shorter than in bulk configurations. The evanescent coupling with the active centers also led to weak coupling, which can ultimately be circumvented by using resonant circuits to enhance light-matter interaction. Silicon photonic circuits were used in different realizations to address single erbium ions [209] and Er- and Yb-implanted LN [210]. More recently, storage, frequency, and bandwidth control of input photonic states have been performed on a Si photonic resonator coupled to Er:YSO, proving the viability of this technology for QM implementations [198]. In this realization, the authors also took advantage of specific magnetic conditions [203] in order to perform efficient pumping, and implement the AFC protocol with delay control thanks to Stark shift [211]. The device used is shown on Fig. 5(d).

Despite the high integration capability of the aforementioned techniques, the performances of the QM protocols in these setups are still below state-of-the-art bulk realizations. Indeed, even if bulk-doped substrates are used, the guiding device could have an effect on the coherence properties [208], and memory efficiencies are to date well below free-space realizations (e.g., $\eta = 0.03$ % at 250 ns in Ref. [45] versus $\eta = 15$ % at 500 ns in Ref. [212] for thulium).

C. Third strategy: crafting high-performance bulk crystals

As pointed out in previous realizations, the coherence properties of QMs are often degraded by the integration process. Therefore, an intuitive way of circumventing this issue is to start from a well-identified high-performance bulk material for implementing QMs and embed a waveguide in it with a technique that is as minimally invasive as possible. The procedural difficulty lies in keeping as best as possible the performance of the system even after the waveguide fabrication process.

In rare-earth ion-doped crystals, this concept was first applied to neodymium-doped Y_2SiO_5 (Nd:YSO) crystals, where nanophotonic suspended cavities were shaped thanks to a focused ion-beam milling technique [213]. The resulting structure is depicted in Fig. 6(a), showing the grooves on top of the waveguide used to form the cavity. Due to strong light confinement, high light-matter coupling could be achieved and a Purcell factor of 42 could be measured. Importantly, the coherence time (approximately 3 μs) was very similar to bulk values. The same fabrication technique was then applied to Nd : YVO_4, in which on-demand storage and retrieval of optical pulses was performed thanks to the AFC protocol combined with ac Stark pulses [214]. At high magnetic fields and in a dilution refrigerator, the same nanostructures allowed storing light at telecom wavelengths at the single-photon level in Er:YSO with the AFC protocol [203,215]. Retrieval

TABLE II. Summing up of basic performances of state-of-the art waveguide in-out QM.

	Mode diameter	Element	On demand	Efficiency[a]	Storage time	Qubit fidelity[a]
Diffusion in LN	∼ 1 μm	Tm	No	∼ 0.2% [47]	∼ 1.5 μs [199]	∼ 95% [47]
		Er	No	∼ 0.01% [204,205]	∼ 50 ns [204]	
LNOI	∼ 300 nm	Tm	No	∼ 0.14% [45]	90 ns [45]	
Amorphous Si on YSO	∼ 500 nm	Er	Yes (dc Stark)	0.4% [198]	200 ns [198]	
Suspended resonator	∼ 700 nm	Nd:YVO	Yes (ac Stark)	∼ 2.5% [214]	75 ns [214]	∼ 95% [214]
		Er:YSO	No	∼ 0.2% [215]	165 ns [215]	∼ 90% [215]
FLDW	∼ 10 μm	Pr:YSO	Yes (Spin wave) [218]	0.4% [218]	3 μs [218]	∼ 90%[217]
		Eu:YSO	Yes (dc Stark)	6 % [222]	1 μs [222]	∼ 99%[222]
		Er:YSO	Yes (dc Stark)	2.5 % [224]	∼ 200 ns [224]	∼ 98%[224]

[a]Efficiency and qubit fidelity are expressed as in-out (external) values. Notice that all storages reported here were realized at the single-photon level, except for Refs. [45,218]. Tm, thulium; Er, erbium.

efficiencies with this platform are still low (approximately 0.2%), but increasing the quality factor of the resonators should allow reaching higher efficiencies.

A second technique to shape a waveguide directly in the bulk material consists of relying on FLDW (see Sec. II). Different types of waveguides can be fabricated with this technique, and are classified as type I to IV, see Fig. 6 for types I and II on YSO. Photon echoes and AFC storage were first realized with type-II waveguides in Pr:YSO [218], followed by the storage of heralded single photons with type-I waveguides [216,219]. The strength of this type of waveguide is that the spatial profile already matches that of single-mode fibers well, allowing direct fiber-pigtailing of the waveguide, as demonstrated in a subsequent realization for the storage of entangled photons [217]. A picture of such a system is shown in Fig. 6(d). Similar systems were built in Eu:YSO for the storage of classical pulses with the revival of silenced echo (ROSE) and the AFC spin-wave protocols on type-II inscribed waveguides [220], further followed by coherent storage [221], and time-bin qubits encoded on weak coherent pulses [222] on type-IV inscribed waveguides and polarization qubits on type-III inscribed waveguides [223]. Eventually, on-demand storage of time-bin qubits was realized on Er:YSO type-III inscribed waveguides, thanks to the AFC Stark protocol [224].

D. Challenges

Table II summarizes the performances of previously mentioned in-out QMs, and shows variations of more than 3 orders of magnitude from one platform to another, in terms of efficiency and storage time. Moreover, the best values reported here are still far below state-of-the-art bulk implementations (e.g., 56% efficiency [225] and 1-h storage time [226] in Eu:YSO). The main challenge added by waveguide structures is the inevitable losses experienced at the in- and out-coupling end facets, and caused by the guiding itself. Fortunately, impedance-matched cavities can be used to push the efficiencies to much higher levels [227]. Following this line, some of the reviewed technologies already embed cavities, and therefore only need parameter adjustments in order to reach this regime [215]. However, the step in efficiency to overcome is higher than with other technologies such as FLDW, in which the implementation of a cavity remains to be accomplished [216]. This efficiency is also dependent on the ability to manipulate the spin population accurately and efficiently, for realizing spin rephasing [228] or dynamical decoupling sequences [229]. Given the resonance frequency of the ions involved, this implies that circuits capable of generating radiofrequency or microwave signals should be integrated into the devices. Geometries like coils around the crystals cannot be used in this configuration; therefore, field inhomogeneity should be considered, which could play a detrimental role. Moreover, integration also implies the proximity of the electrodes to the ions, so heating should also be taken into account to enable efficient manipulation without decreasing the coherence lifetime.

A second question concerns the integration capabilities of the fabricated devices. Implementing a QM in waveguides is indeed the cornerstone towards this goal, but is not sufficient to guarantee a gain in the architecture scalability. Devices containing multiple functionalities on the same chip, where light is guided from one function to the other (lab-on-a-chip as discussed in Sec. IV D) yet remain to be developed for QMs. There again, the chosen technological platform imposes constraints that can be limiting to reach this goal. To push this reasoning even further, current quantum memory apparatus requires the generation and manipulation of external laser beams, which usually involves electro- or acousto-optic modulators and spatial mode shaping. Downstream from the memory, filtering stages are usually required to remove residual noise sources for manipulating photonic states in the single-photon regime. Therefore, even if the quantum memory device itself can be considered as integrated, it is usually not the case for the whole setup. The route towards full integration will most probably rely on the simultaneous use of different integration technologies, such as the ones described previously in this Perspective. Light generation with laser diodes could be hybridized with LN circuitry for light preparation and modulation thanks to electro-optic modulators. Light filtering can be performed with similar devices as for the memory, by employing spectral hole burning in integrated devices [213]. Also, it should be noted that most of the aforementioned quantum memory platforms require working at cryogenic temperatures, a regime that could be unfavorable for the other devices. Blocks of functional devices working in different temperature regimes should therefore be interfaced together, through optical fiber buses, for instance [217].

Finally, we have seen that the coherence properties of the active ions strongly depend on their local environment. Therefore, continuous investigations in material science in order to identify a suitable host crystal and active ion agreement are necessary. Such research can be done by relying on well-established host materials [230] or by developing new methods for efficiently implanting ions in a large variety of substrates [209,231–233]. Notably, regarding color centers, new candidates for high-performance and long-duration storage such as SiC is currently being investigated in nanoresonators [36].

VI. GOING FURTHER

In order to create efficient quantum technology systems, it is crucial for photonic circuits to be capable of seamlessly integrating all key operations. While the specific features and number of elementary blocks required will vary depending on the application, there are some key characteristics that stand out. For instance, in the realm of quantum computing and simulation, platforms must be equipped to handle a large number of sources or exhibit impressive multiplexing capabilities. With the right photonic circuitry, the scope for quantum technology is huge.

One of the critical aspects of integrated optics, especially in the context of single photons, photon pairs, or continuous variable states, is the amount of loss in the circuit. However, recent progress in this area is quite promising, with linear waveguides exhibiting propagation losses around 0.2 dB/cm [43], and ring resonators achieving losses as low as 0.0034 dB/cm (estimated after taking the ring quality factor into account) [234]. The amount of insertion losses may vary depending on the coupling strategy employed (e.g., butt coupling, gratings, tapers, pig-tailed fibers) and the presence of antireflecting coatings. The best performance reported so far is 0.6 dB using a complex taper architecture [235], while typical losses range from 1 to 2 dB in the microlens edge-coupling strategy [236]. Finally, in the context of hybridization, minimizing the interface losses between two different materials is a major challenge. It is currently quite difficult to estimate losses in LNOI hybrid circuits, and adiabatic couplers between layers (similar to those used in semiconductor photonic circuits) may be required [237].

Integrated electrically pumped-laser sources followed by efficient nonlinear optical stages would allow plug-and-play quantum state generation [54]. This nonlinear conversion strategy, enabled by precise control of the quasi-phase-matching condition, allows for the generation of identical photons from different sources [159]. Ideally, a complex, reconfigurable circuit, based on tunable interferometers could be used for a broad range of protocols [113]. This requires the development of optical couplers and wavelength multiplexers with steep bending to reach denser integration, as well as lower losses to preserve the properties of quantum states. Such circuitry elements should be controlled at high speed, via the electro-optical effect, for fast switching between configurations or light modulation at high frequency [98]. For general quantum photonic technology purposes, efficient and fast single-photon detectors as well as high-bandwidth shot-noise-limited CV detectors [238] are essential for on-chip light detection. Although available quantum photonic platforms often offer more of these functions, so far, none has emerged as a universal integration platform, capable of efficiently combining all discussed abilities. To overcome this issue, it is essential to guarantee low coupling losses so as to allow efficient interface between different platforms but also with existing optical fiber networks.

A promising platform, offering high optical and electro-optical nonlinearities, a large integration density and the possibility of integrating both photon sources (single or entangled pairs) and detection stages, is LNOI. As emphasized in Sec. II B, conventional LN platform substrates with several 100 micrometers thickness are already widely used in quantum integrated photonics. However, due to guiding technologies on these thick substrates (metal in-diffusion or proton exchange), which so far allow only weakly confined modes ($\Delta n \leq 0.1$), its integration density remains limited. During the last decade, the LNOI platform has permitted a real breakthrough in integration, and it is now considered as a very promising candidate for on-chip quantum applications [239].

Remarkably, nanoscale circuitry building blocks on LNOI have already been demonstrated successfully in the classical regime and are now under investigation in the quantum regime [240,241]. First realizations of photon-pair sources or heralded single-photon sources demonstrate count rates comparable to optimized Si photonic sources [242]. Very recently, a pulse-driven optical parametric oscillator has been integrated in an LNOI opto-electronic circuit by using a tunable on-chip femtosecond pulse generator [243]: this device, although validated so far only in classical regime, opens to the possibility of generating tailored multimode entangled states in CV [106]. A low-noise frequency-conversion process on the LNOI nanophotonic platform has also recently been demonstrated in quantum regime, providing an interface between telecom and near-visible bands [244]. The LNOI high integration density offers the possibility of gathering, on a single chip, a large number of multiplexed sources that could be useful to overcome the probabilistic emission via the SPDC process [245]. Another way to prevail against probabilistic emission would be the inclusion of QD, or the doping of LN thin films with rare earth to emulate color centers as sources [196,206,233,240,246–251]. However these uses of deterministic sources raise the challenge of lower indistinguishability and fidelity.

As mentioned in Sec. V, rare-earth doping has been performed for classical uses and will undoubtedly lead to the study of on-chip QM. The set of individual components is completed with filtering devices, such as Bragg reflectors, resonators, and interferometric filters, that have also been used to separate the pump from the on-chip generated photons [252,253]. In addition, the LNOI platform exhibits high-performance components, including directional couplers, y splitters, and tunable interferometers, which likely makes it a major, fully functional, quantum photonic platform [254–257].

Moreover, novel components have been developed making it possible to exploit multiple degrees of freedom such as the polarization with polarization beam splitters [258], or time bin with delay lines up to 15 cm (delay of 2 ns) over only a few-cm device [259]. Active manipulation of these components through the electro-optic effect is also possible, leading to active optical switches, tunable filters (bandwidth or central wavelength), phase or/and amplitude modulators, and tunable-duration delay lines. Using electro-optic manipulation as well, ring resonators can also be used to store photons for some nanoseconds [260].

All members of the community predict a bright and exciting future for the LNOI platform, which is based on an elegant and comprehensive photonic toolbox and promises major advancements in the quantum regime. The main challenge for this platform is to provide high-density circuits, and most importantly, to have the ability to scale up dramatically.

In parallel to the technological advances of LNOI standalone circuitry, significant efforts are directed towards hybridizing its resulting components with more mature integrated photonic platforms. Here, the objective is to merge the remarkable nonlinear performance of LNOI structures with high-integration densities as well as mass-production capacities of silicon-based circuits. Despite the considerable appeal of LNOI, some functionalities (e.g., on-demand quantum light sources or on-chip detectors) might not be achievable in the near future. Hybridization would therefore make it possible to benefit from already proven devices manufactured using better-known substrates. As a result and more generally speaking, we really believe in pushing research and development in hybrid photonic integration to achieve quantum circuits showing unprecedented levels of integration, capabilities, and functionalities [237,261].

Indeed, a dream photonic quantum circuit that combines different platforms could take advantage of their specific benefits. On-demand single photon or photon pairs would be emitted by QD [262], defects in crystal [263], or defects in 2D materials [264,265], the photons would then be addressed to the following building blocks using ultralow loss guiding structures, such as silica [32] or SiN [266] waveguides, which are both quite compatible with fiber optics communication networks. Signal processing requiring a huge number of individual components can be made in silicon-on-insulator circuits, since they are naturally CMOS compatible, provided the signal is within the range of the infrared wavelength band [32,267]. Nonlinear operations would be performed in LNOI chips, as mentioned above, electro-optic modulation could be achieved using both LNOI or aluminum nitride [268] stages. Finally, Si photodetectors or niobium-titanium nitride superconducting nanowires have already been used on LNOI to allow on-chip detection of quantum light. The latter (on-chip SNSPD) have been proven to detect single photons [44,46,269], while Si photodetectors could lead to the fabrication of on-chip avalanche photodiodes [270].

Despite its appealing characteristics, however, realizing such a dream photonic quantum circuit is still very challenging since some of the key-feature materials or fabrication techniques are not all compatible. So far, the best integration strategies are as follows: heteroepitaxial growth of semiconductor layers [271] and likely in the near future of LN [272], wafer molecular direct bonding [273,274], component transfer using pick-and-place devices, like transparent stamp microprinting [275,276] or microprobe transportation [277,278].

Finally, a new paradigm in quantum photonic circuits opens with these hybridization technologies, the emerging architecture will mostly depend on the aimed applications, operating conditions (cryogenic or room temperature), the need to be interfaced with existing optical networks, and the ability for the manufacturer to easily deliver out-of-the-lab chips at low cost.

VII. CONCLUSION

Looking ahead, the field of quantum integrated photonics presents many exciting challenges that still need to be addressed. These include self-consistent “prepare and measure QKD” systems with on-chip single-photon detection, scalable quantum applications for generating and manipulating high-dimensional photonic states, and integrated QM—all of which offer incredible potential for advancing the field. To achieve these goals, we need to continue pushing the boundaries of fundamental research and technological innovation not just in quantum photonics, but also in classical photonics. To pursue novel directions in the field of quantum integrated photonics, rigorous theoretical studies are essential. These theoretical investigations, exclusively focused on quantum photonic systems, serve as critical components in unlocking new possibilities. Linking these conceptual disruptions with advancements in computer science, notably those of artificial intelligence (AI) and advanced machine learning techniques, will undoubtedly play a key role in driving a paradigm shift. The interplay between AI and integrated photonics, with a specific focus on quantum circuits, promises a symbiotic relationship where AI assists in the design and optimization of the circuits, while (quantum) integrated photonics provides a platform for developing more powerful and efficient AI systems. Such an association has the potential to drive significant advances in both fields, enabling the realization of quantum enhanced AI and pushing the boundaries of (quantum) information processing and computation [279,280].

ACKNOWLEDGMENTS

This work has been conducted within the framework of the project OPTIMAL granted by the European Union by means of the Fond Européen de développement régional (FEDER). The authors also acknowledge financial support from the Agence Nationale de la Recherche (ANR) through the projects METROPOLIS (ANR-19-CE47-0008), SPHIFA (ANR-20-CE47-0012), SoLuQS (ANR-20-ASTQ-0003-01), Hy-Light (ANR-17-CE30-0006-01), Waquam (ANR-21-CE47-0001-01), QAFEINE (21-ASTR-0007-DA), PARADIS (ANR-22-ASTR-0027-01), INQURE [QuantERA Call 2021 - Applied Quantum Science (AQS)], ADEQUADE (European Defense Fund, 2023), the Région Provence Alpe Côte d'Azur through the project SIPS and the French government through its Investments for the Future programme under the Université Côte d'Azur UCA-JEDI project (Quantum@UCA) managed by the ANR (ANR-15-IDEX-01). V.D.A. thanks the Institut Universitaire de France for the support.

We would like to warmly thank Daniel B. Ostrowsky for all his valuable advice and guidelines, as well as for his numerous insightful reviews. We would also like to thank reviewer A during the review process, who has significantly contributed to the quality of the Perspective and has dedicated a considerable amount of time to enhancing this work, which would not have been as remarkable without their contribution. Also, we would like to extend our warm thanks to several former collaborators who each contributed to a part of the work reported in this Perspective, Djeylan Aktas, Lutfi-Arif Bin Ngah, Bruno Fedrici, Florian Kaiser, Dorian Oser, and Panagiotis Vergyris.

Eventually, we would like to make a dedication to our late friend and colleague, Marc P. de Micheli, who departed unexpectedly 5 years ago. Marc devoted his entire research career to advancing integrated photonics. He was a mentor to all the authors of this review article, and his influence, warm smile, and perpetually positive mindset will be remembered in our hearts forever.

All the authors contributed equally to the entire process, from the first draft to the final version of the Perspective before submission. We all read, discussed, and contributed to the writing, reviewing, and editing. S.T. coordinated and managed the project, ensuring its successful completion.

The authors declare no competing interests.

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