Detailed Scientific contributions of Tobias J. Kippenberg to: Developing next generation photonic integrated circuits

Silicon photonics[1,2] has transitioned from academic research to widespread industrial use over the past two decades. Yet, despite the commercial success of silicon photonics[3], that is used in data centers for transceivers, silicon is not an ideal material for photonics and optics. Silicon has a bandgap of 1 eV therefore cannot be used for visible light generation and processing[4,5]; In addition, silicon cannot withstand high optical powers. Similarly, the loss levels even in the most advanced global foundries silicon photonics commercial production lines, employing billions of dollars of manufacturing equipment are only 1 dB per centimeter. Indeed, ultra-low loss is exceedingly challenging to obtain in chips. The quest for such low loss is not only an academic endeavor: historically, the work of Kao has also laid the foundation to optical fibers with only 1dB/km loss – that resulted in the 2008 Nobel prize in Physics and revolutionized communications[6]. Yet, until recently the progress of low loss integrated photonic circuits has remained stagnant for many decades – at the level of dB/cm. Yet, ultra-low propagation losses on chip are of paramount importance for numerous future applications.

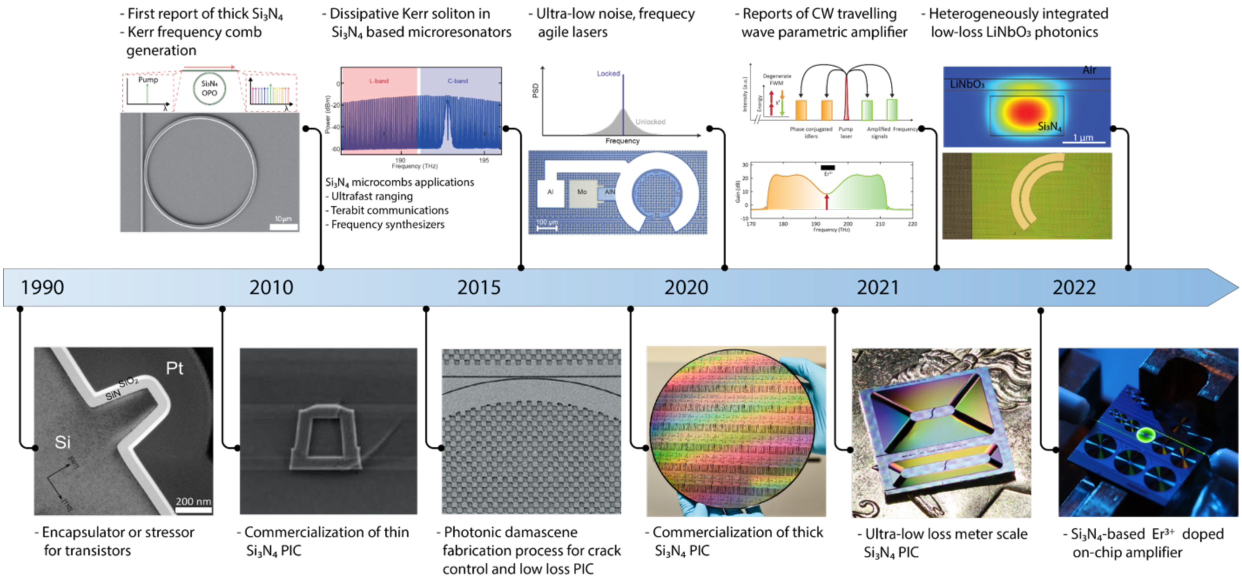

Figure 1: History of silicon nitrde thin films in microelectronics and evolution of the photonic circuit technology based on ultra low loss silicon nitride waveguides as developed by the Kippenberg group at EPFL, and commercialized via LIGENTEC SA.

Over the past decade this has fundamentally changed: first used in CMOS electronics as a thin film stressor layer for transistors, stoichiometric silicon nitride (Si_3N_4) has been successfully applied to tightly confining photonic integrated circuits[7–10]. Such circuits employ 800 nm high waveguides to create complex integrated circuits-based devices[11–14]. Today silicon nitride is a next generation integrated photonics platform by itself, that benefits from a visible to mid IR transparency window, high power handling, space compatibility, large Kerr nonlinearity, low Brillouin nonlinearity and ultra-low loss- offering the potential to explore applications that are beyond those accessible with silicon[10,15–18].
This development has been in particular triggered by the advances made by Kippenberg's team, in particular a novel manufacturing process, the photonic damascene process[14], that now allows manufacturing tightly confining waveguides with losses of only 1.4 dB/m to be created – more than 100-folder lower than the best silicon photonic chips. This has enabled an entirely new range of applications, far beyond what silicon could achieve, which has revolutionized numerous areas of science and technology alike, from spectroscopy, photonic computing, frequency metrology to astrophysics or laser technology[19–23]. The Kippenberg laboratory has shown that ultra-low loss Si_3N_4 PICs enable novel

applications such as applications such chip scale frequency combs[10], traveling wave parametric

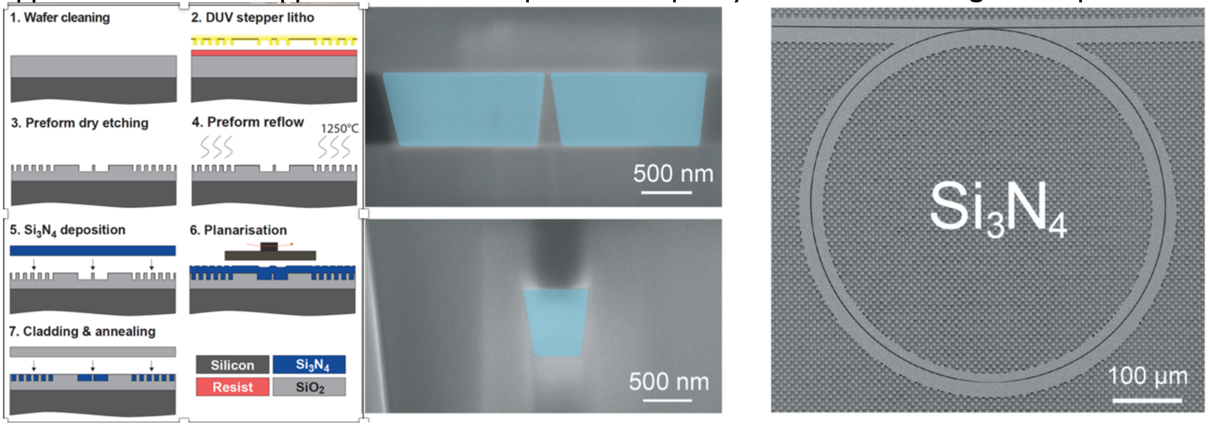

Figure 2: The photonic damascene process as developed by Kippenberg, enables to overcome the large silicon nitride deposition stress, and manufacture ultra low loss integrated photonic circuits based on stoichometric silicon nitride.

amplifiers[24], Erbium amplifiers[25], or narrow linewidth frequency agile lasers[26–28] that exhibit phase noise below state of the art fiber lasers. Silicon nitride PIC technology is also applied in some of the most fundamental experiments, such as astrophysical spectrometer calibration for the searches of exoplanets[20].

Silicon nitride integrated PICs also allow a fundamentally new operational principle: to use the nonlinearity of the waveguides for novel devices. Si_3N_4 PICs arguably the leading platform for "microcombs" – chip-scale versions of laser based optical frequency combs for which Ted Haensch and Hall won the 2005 Nobel Prize in Physics[29,30]. The discovery of microresonator frequency combs[31,32] in 2007 have made it possible to synthesize optical combs in compact devices that can be microfabricated on chip, with unprecedented high repetition rates in the technologically relevant gigahertz regime, and with optical bandwidths that are far beyond what can be achieved with conventional mode locked lasers. The original report[31], published in ***Nature*** in 2007 (>**cited more than 2000 times** in GoS to date), has **opened a new field of research at the intersection of optical metrology and nano- and micro-photonics and nonlinear optics**, and has exploded in the recent years in terms of research activities. The explosion of work has been triggered by Si_3N_4 integrated circuit technology; these circuits have 'democratized access' to microcombs; and more generally to nonlinear optical phenomena. For example, supercontinuum generation, required in the past specialty optical fibers – while in Si_3N_4 octave spanning coherent spectra are generated at nearly 100 times lower pulse energies[33,34]. Similarly, microcombs today can be access with only milli-Watts of laser power.

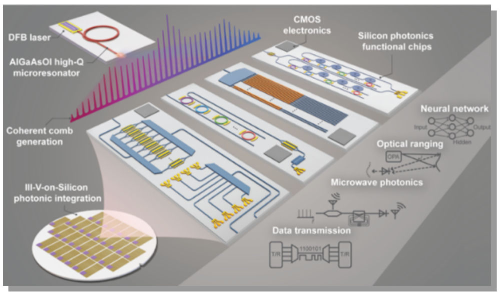

Figure 3: Chipscale frequency combs, are becoming central elements for various photonic applications: future datacom, optical ranging, microwave photonics, and photonic computing. (Bowers, Nature 2022)

Today Si_3N_4 waveguide technology as developed by Kippenberg's lab have been employed in all leading demonstrations of microcombs; including dual soliton comb based distance measurements[35,36], or synthesizing frequencies on chip[37], massivel parallel coherent communications with terabit per second[38], that can counteract the growing demand in energy consumption. They have been used successful in

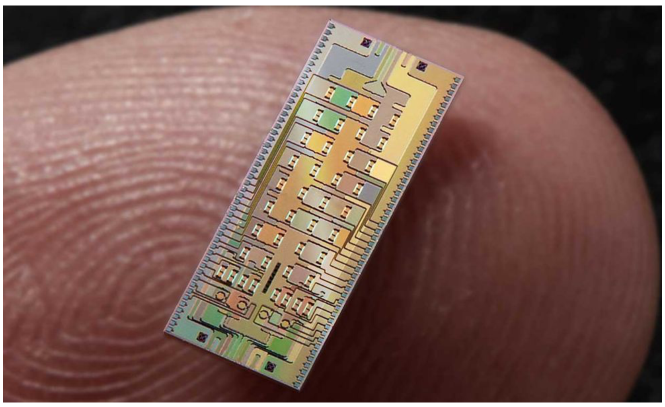

Figure 4: Silicon nitride photonic integrated circuits.

neuromorphic computing[39,40] enabling Teraflops per second computation. Microcombs can also be applied to FCMW LIDAR[41,42]. The integration of microcombs have also advanced significantly: triggered with the observation of self-injection locked soliton microcombs[43] with hybrid III-V integration, **it is possible today to create microcombs on a 4-inch wafer with pump lasers integrated – a single wafer can contain several 1000's of laser soliton microcombs**[44]: more than conventional fiber based femto-second laser combs exist on the planet. They have been integrated moreover with other functionalities, piezo-electrical[45] or soliton photonics[46] based technologies.

Si_3N_4 photonic integrated circuit technology can also be integrated with other materials: Kippenberg's team have been shown that both III-V[27,44,47,48], AlN and PZT for piezoelectrical actuation[27,45] as well as Lithium Niobate[49,50] for ultrafast modulation can be heterogeneously integrated. This has heralded entirely new photonic devices, such as frequency agile integrated lasers that challenge legacy lasers in their phase noise and tuning speed[27]. Such lasers can revolutionize numerous applications where a compact, scalable, and low noise source is required; from LiDAR to fiber sensing, optical communications or next generation of atomic clocks that operate in the visible range. The stellar rise of Si_3N_4 PIC technology has been remarkable; with >500's of papers published each year that use this technology, as well as numerous startups that are relying on Si_3N_4 for their next generation products including NEXUS photonics[51,52], XSCAPE[43,53], to name just two.

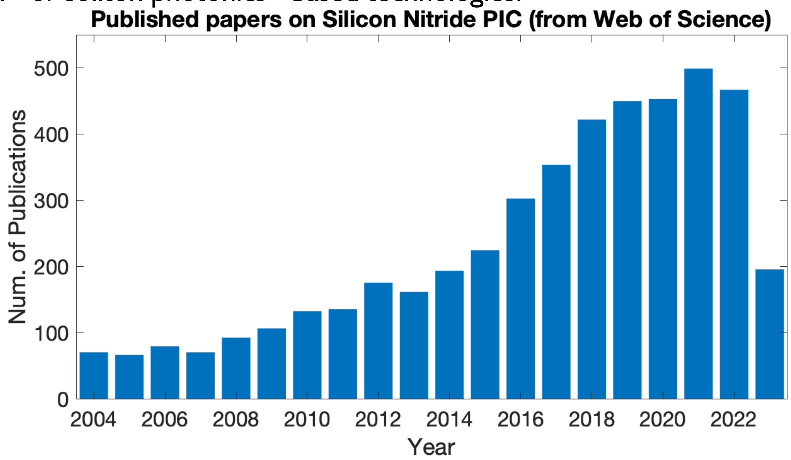

Figure 5: Papers published on "silicon nitride PICs" per year.

These advances have been made possibly by the pioneering work[10] of Kippenberg, that laid the foundation to silicon nitride Photonic integrated circuit manufacturing technology as we know it today, and their commercial adoption. Although stoichiometric silicon nitride is a CMOS certified material, its use for integrated photonics has been a decades long challenges: the material when deposited using high temperature LPCVD tends to form cracks. Although other deposition technique exists, these do not drive out the residual Hydrogen impurities and mandate high temperature anneals that lead to crack formation. Kippenberg and his team demonstrated, for the first time, how to handle the large deposition stress of the films by inventing the photonic damascene process – and special filler patters to handle crack formation[11–13]. This technique uses stressor patterns to relax the stress, and focus crack formation to regions without circuits. The technique has been successfully applied to wafers as large as 200 mm and give Si_3N_4 PICs their unique surface texture. In addition, his team pioneered methods to achieve ultra-low roughness integrated waveguides using this process. Today this breakthrough technique opened a path to manufacturing with high yield integrated photonic circuits. Crucially the technique also enabled to achieve record low losses of 1 dB/meter, which make this platform x100 times lower in loss than silicon. The stress management technique developed by Kippenberg are used widely; both by academic labs but crucially has also been industrialized. The company LIGENTEC SA that Kippenberg co-founded today produces Si_3N_4 integrated photonic circuits using a 200 mm line by the X-Fab in Paris. Chips of LIGENTEC have been used in more than 100 of companies, startups and labs around the world[54], acknowledged so far in more than 65 journal publications (from Web of Science). It is hard to understate the impact that Kippenberg lab at EPFL has had by laying the foundation to this new next generation photonic integrated circuit technology. Overcoming the materials challenges of Si_3N_4 is a defining accomplishment that has been achieved by the Kippenberg group in the domain of photonic integrated circuits. Moreover his team has over the past decade advanced the technology in numerous waves: in addition to inventing novel manufacturing techniques, the contributions range from chips-cale frequency combs[55–58], Erbium-doped amplifiers on chip[25], to frequency agile low noise lasers[27] that can achieve a better performance that the lowest noise legacy lasers based on fibers, as well as novel traveling wave parametric amplifiers[42,59] and mid infrared molecular fingerprinting[22].

Erbium amplifiers are the workhorse of optical communication as their gain medium offers slow dynamics, leading to negligible channel crosstalk. The development of EDWA by Payne[39] and Desurvire[40] has been key to transforming optical fiber communication, as pioneered by Kao (Nobel Prize Physics 2005). Yet, their use in integrated photonics has been compounded by high optical losses and incompatible processing techniques. While numerous attempts have been made both in the 90s at Bell labs[33,34] and over the last decade in integrated photonics, including Erbium-doped Al_2O_3 using RF co-sputtering[35,36] and atomic layer deposition (ALD)[37], the low gain from Erbium due to limitations in doping (ca. 3 dB/cm) and large waveguide losses have prevented efficient EDWA.

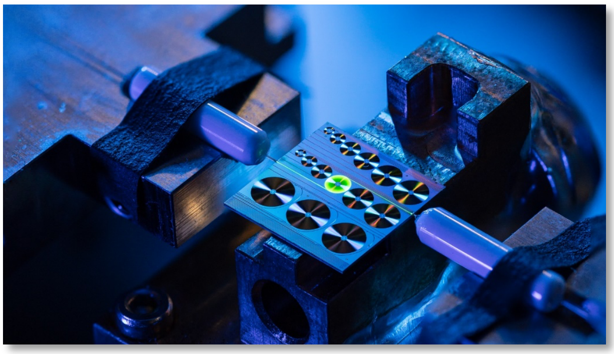

Figure 6: Photonic integrated erbium amplifiers using ultra low loss silicon nitride waveguides

Recent work from the Kippenberg lab has challenged this dogma and demonstrated a high gain (30dB and high power (>100 mW) EDWA[5423] using wafer-scale processing. This work has heralded a new class of integrated photonic components **that use rare-earth gain** and that have **not been demonstrated to date**: this includes **fully integrated multi-lane parallel EDWA implemented using hybrid integration and heterogenous integration**[38], which can amplify **multiple channels on a single chip** and have applications in line cards, but equally in transoceanic cables. In addition, this work opens the path to **demonstrate high power EDWA**– which does not exist in integrated photonics today on any technology basis.

Kippenbergs research team also laid the foundation to commercializing Lithum Niobate and Lithium Tantalate ferroelectrical integrated photonic circuits. Within the last years, there has been a meteoric rise of research on *ferroelectrics* based integrated photonics platforms, chief among them **Lithium Niobate**[12]. Lithium niobate is the workhorse of optical modulator technology[3] due to its high Pockels (i.e. electro-optical) coefficient[4]. Following the commercial availability of thin-film lithium niobate on insulator "LNOI" (first commercialized by NanoLN in China), it has become possible to create ferro-electric - i.e. electro-optical - integrated photonic devices. These devices offer ultra-fast, linear, and efficient optical modulation with applications ranging from electro-optic frequency combs on chip[5], CMOS-compatible modulators operating at volt levels[6], as well as novel devices that utilize electro-optic modulation, as, e.g., required to create synthetic frequency dimension lattices using optical modulation[7]. Equally, the large Pockels effect is the basis for for microwave to optical quantum signal transduction[8]. Beyond the Pockels effect, the non-centrosymmetric crystal supports a second order nonlinearity, which is central for realizing chip based squeezers based on OPO[9], which have been used to demonstrate bulk-optics based quantum optical computational advantage using photons[10]. As such, electro-optic integrated photonic based circuits, can significantly enhance the performance of existing, and expand the application domain to new areas, ranging from quantum transduction, quantum and neuromorphic computing to LiDAR.

Yet, despite the impressive advances, the original challenges of Lithium Niobate have not been solved: it is difficult to etch due to its inertness and chemical resistance to commonly used etching techniques. To date, **all Lithium Niobate integrated photonics** has been **limited to ridge waveguides**, i.e. waveguides that only exhibit a shallow etching. The latter is a direct consequence of the hardness of Lithium Niobate (or other ferroelectrics such as BTO), which suffer from mask erosion. Ridge waveguides, however, have a number of significant disadvantages: they exhibit larger bend losses, limiting integration density, exhibit mode mixing in bend waveguides, and make input coupling challenging with low loss. In fact, the **lack of truly nanophotonic waveguides**, i.e. fully confining Lithium Niobate waveguides, that are routine in silicon photonics, is **not merely an academic problem** but **critical to transitioning** the technology from academic research to industrial – and foundry – use.

Hence a platform featuring ultra-low loss fully etched strip waveguides, already well established and successfully commercially employed for silicon (Global foundry, etc.) and silicon nitride (LIGENTEC, etc.) would be highly desirable.

Kippenbergs research overcome this challenge and demonstrated a low loss, tightly confining Lithium Niobate integrated photonic circuit (PIC) platform and demonstrated the platform to realize for the first time an ultrafast – Petahertz per second – tunable integrated Pockels laser. The approach is based on the realization that **diamond like carbon (DLC)**. Diamond like Carbon (DLC)[11] was discovered accidentally by methane discharge in the 1960s. The films exhibit primarily diamond type sp^3 bonds and, as a result, exhibits properties similar to diamond in terms of hardness, chemical inertness, and bulk elastic modulus. Yet it is amorphous and can be deposited as thin films and conformal coatings. Its use today is pervasive, ranging from protective coatings for magnetic read heads, razor blade coatings, and medical devices to automotive components and MEMS sensors. It can also be deposited on wafers using Methane decomposition using standard micro-electronic deposition tools. While the material's promise as a hard mask for micro-electronic manufacturing was early on recognized and demonstrated already in the 1990', its use in micro-electronics remained scarce.

In Kippenberg's work it was demonstrated that by using DLC as a hard mask, we can unlock the full potential of Lithium Niobate integrated photonic circuits, and more generally other ferro-electrical platforms such as BTO. The exceptional hardness of DLC and ability to precisely etch the material using Oxygen plasma make it an ideal hard-mask for Lithium Niobate specifically and for any ferro-electric in general. Using DLC, we demonstrate the fabrication of deeply etched, tightly confining, low-loss Lithium Niobate photonic integrated circuits – an achievement not demonstrated by any group before. The ability to create tightly confining waveguides benefits from a more than one order of magnitude higher area integration density while maintaining efficient electro-optical modulation, low loss, and offering a route for efficient optical fiber interfaces, via widely used inverse tapers developed in silicon photonics. Moreover, the improved lithographic precision will enable the development of building blocks and mark a critical step for foundry adoption. This enables ultra-low roughness waveguides that can be fully etched. The Kippenberg group achieved **record-low optical losses as low as 3 dB/m,** while retaining excellent lithographic precision. The process was also show to work for Lithium Tantalate, and is commercialized via the startup LUXTELLIGENCE SA.

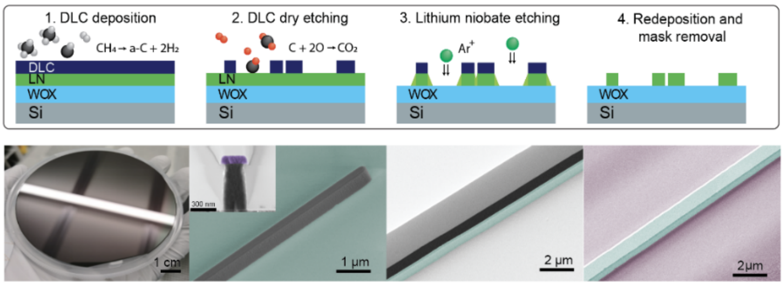

Figure 7: Process flow for high density LNOI waveguide fabrication with DLC hard mask.

In summary photonic integrated circuits beyond silicon, based on silicon nitride, as pioneered by the manufacturing techniques of Kippenberg and numerous novel application demonstrations, as well as more recently the manufacturing of ultra-low loss high density Lithium Niobate and Lithium Tantalate integrated photonic circuits, have had enormous impact and are laying the foundation for a new generation of photonic integrated devices that harness ultra-low loss and which can find applications in optical communications, sensing, LiDAR, quantum technologies or photonic computing, and can contribute to energy efficient communication, computing as well as interconnects or quantum photonic computing. Academically, the work has been published in more than 15 publications in *Nature* and *Science* and gathered substantial citations and recognition. Yet, most crucially Si_3N_4 photonic integrated circuits are today – a widely accepted platform – firmly established next to Silicon and Indium Phosphide and have transitioned to industry and Kippenberg has not only scientifically contributed but also contributed via technology transfer and cofounded LIGENTEC SA and LUXTELLIGENCE SA that has democratized access to next generation integrated photonic circuits based on silicon nitride and ferro-electrics.

References

1. Soref, R. The Past, Present, and Future of Silicon Photonics. *IEEE J. Sel. Top. Quantum Electron.* **12**, 1678–1687 (2006).
2. Thomson, D. *et al.* Roadmap on silicon photonics. *J. Opt.* **18**, 073003 (2016).
3. Rickman, A. The commercialization of silicon photonics. *Nat. Photonics* **8**, 579–582 (2014).
4. Foster, M. A. *et al.* Broad-band optical parametric gain on a silicon photonic chip. *Nature* **441**, 960–963 (2006).
5. Foster, M. A. *et al.* Silicon-chip-based ultrafast optical oscilloscope. *Nature* **456**, 81–84 (2008).
6. Kao, K. C. & Hockham, G. A. Dielectric-fibre surface waveguides for optical frequencies. in *Proceedings of the Institution of Electrical Engineers* vol. 113 1151–1158 (IET, 1966).
7. Ikeda, K., Saperstein, R. E., Alic, N. & Fainman, Y. Thermal and Kerr nonlinear properties of plasma-deposited silicon nitride/silicon dioxide waveguides. *Opt. Express* **16**, 12987–12994 (2008).
8. Moss, D. J., Morandotti, R., Gaeta, A. L. & Lipson, M. New CMOS-compatible platforms based on silicon nitride and Hydex for nonlinear optics. *Nat. Photonics* **7**, 597–607 (2013).
9. Levy, J. S. *et al.* CMOS-compatible multiple-wavelength oscillator for on-chip optical interconnects. *Nat. Photonics* **4**, 37–40 (2010).
10. Kippenberg, T. J., Gaeta, A. L., Lipson, M. & Gorodetsky, M. L. Dissipative Kerr solitons in optical microresonators. *Science* **361**, eaan8083 (2018).
11. Pfeiffer, M. H. P. *et al.* Photonic Damascene process for integrated high-Q microresonator based nonlinear photonics. *Optica* **3**, 20–25 (2016).
12. Pfeiffer, M. H. P. *et al.* Ultra-smooth silicon nitride waveguides based on the Damascene reflow process: fabrication and loss origins. *Optica* **5**, 884–892 (2018).
13. Pfeiffer, M. H. P. *et al.* Photonic Damascene Process for Low-Loss, High-Confinement Silicon Nitride Waveguides. *IEEE J. Sel. Top. Quantum Electron.* **24**, 1–11 (2018).
14. Liu, J. *et al.* High-yield, wafer-scale fabrication of ultralow-loss, dispersion-engineered silicon nitride photonic circuits. *Nat. Commun.* **12**, 2236 (2021).
15. Gaeta, A. L., Lipson, M. & Kippenberg, T. J. Photonic-chip-based frequency combs. *Nat. Photonics* **13**, 158–169 (2019).
16. Ji, X., Roberts, S., Corato-Zanarella, M. & Lipson, M. Methods to achieve ultra-high quality factor silicon nitride resonators. *APL Photonics* **6**, 071101 (2021).
17. Blumenthal, D. J., Heideman, R., Geuzebroek, D., Leinse, A. & Roeloffzen, C. Silicon Nitride in Silicon Photonics. *Proc. IEEE* **106**, 2209–2231 (2018).
18. Raja, A. S. *et al.* Ultrafast optical circuit switching for data centers using integrated soliton microcombs. *Nat. Commun.* **12**, 5867 (2021).
19. Marin-Palomo, P. *et al.* Microresonator-based solitons for massively parallel coherent optical communications. *Nature* **546**, 274–279 (2017).
20. Obrzud, E. *et al.* A microphotonic astrocomb. *Nat. Photonics* **13**, 31–35 (2019).
21. Riemensberger, J. *et al.* Massively parallel coherent laser ranging using soliton microcombs. *ArXiv191211374 Phys.* (2019).
22. Guo, H. *et al.* Nanophotonic supercontinuum-based mid-infrared dual-comb spectroscopy. *Optica* **7**, 1181 (2020).
23. Feldmann, J. *et al.* Parallel convolutional processing using an integrated photonic tensor core. *Nature* **589**, 52–58 (2021).
24. Riemensberger, J. *et al.* A photonic integrated continuous-travelling-wave parametric amplifier. *Nature* **612**, 56–61 (2022).
25. Liu, Y. *et al.* A photonic integrated circuit–based erbium-doped amplifier. *Science* **376**, 1309–1313 (2022).
26. Jin, W. *et al.* Hertz-linewidth semiconductor lasers using CMOS-ready ultra-high-Q microresonators. *Nat. Photonics* **15**, 346–353 (2021).
27. Lihachev, G. *et al.* Low-noise frequency-agile photonic integrated lasers for coherent ranging. *Nat. Commun.* **13**, 3522 (2022).
28. Bohan, L. *et al.* Reaching fiber-laser coherence in integrated photonics. *Opt. Lett.* (2021) doi:10.1364/OL.439720.
29. Hall, J. L. Nobel Lecture: Defining and measuring optical frequencies. *Rev. Mod. Phys.* **78**, 1279–1295 (2006).
30. Hänsch, T. W. Nobel Lecture: Passion for precision. *Rev. Mod. Phys.* **78**, 1297–1309 (2006).

31. Del'Haye, P. *et al.* Optical frequency comb generation from a monolithic microresonator. *Nature* **450**, 1214–1217 (2007).
32. Kippenberg, T. J., Holzwarth, R. & Diddams, S. A. Microresonator-Based Optical Frequency Combs. *Science* **332**, 555–559 (2011).
33. Johnson, A. R. *et al.* Octave-spanning coherent supercontinuum generation in a silicon nitride waveguide. *Opt. Lett.* **40**, 5117 (2015).
34. Porcel, M. A. G. *et al.* Two-octave spanning supercontinuum generation in stoichiometric silicon nitride waveguides pumped at telecom wavelengths. *Opt Express* **25**, 1542–1554 (2017).
35. Suh, M.-G. & Vahala, K. Soliton Microcomb Range Measurement. *ArXiv170506697 Phys.* (2017).
36. Trocha, P. *et al.* Ultrafast optical ranging using microresonator soliton frequency combs. *ArXiv170705969 Phys.* (2017).
37. Spencer, D. T. *et al.* An Integrated-Photonics Optical-Frequency Synthesizer. *ArXiv170805228 Phys.* (2017).
38. Shu, H. *et al.* Microcomb-driven silicon photonic systems. *Nature* **605**, 457–463 (2022).
39. Xu, X. *et al.* 11 TOPS photonic convolutional accelerator for optical neural networks. *Nature* **589**, 44–51 (2021).
40. Feldmann, J. *et al.* Parallel convolutional processing using an integrated photonic tensor core. *Nature* **589**, 52–58 (2021).
41. Riemensberger, J. *et al.* Massively parallel coherent laser ranging using soliton microcombs. *arXiv:1912.11374* **accepted by Nature**,.
42. Lukashchuk, A., Riemensberger, J., Karpov, M., Liu, J. & Kippenberg, T. J. Dual chirped microcomb based parallel ranging at megapixel-line rates. *Nat. Commun.* **13**, 3280 (2022).
43. Stern, B., Ji, X., Okawachi, Y., Gaeta, A. L. & Lipson, M. Battery-operated integrated frequency comb generator. *Nature* **562**, 401–405 (2018).
44. Xiang, C. *et al.* Laser soliton microcombs heterogeneously integrated on silicon. *Science* **373**, 99–103 (2021).
45. Liu, J. *et al.* Monolithic piezoelectric control of soliton microcombs. *Nature* **583**, 385–390 (2020).
46. Shu, H. *et al.* Microcomb-driven silicon photonic systems. *Nature* **605**, 457–463 (2022).
47. Raja, A. S. *et al.* Electrically pumped photonic integrated soliton microcomb. *Nat. Commun.* **10**, 680 (2019).
48. Voloshin, A. S. *et al.* Dynamics of soliton self-injection locking in optical microresonators. *Nat. Commun.* **12**, 235 (2021).
49. Snigirev, V. *et al.* Ultrafast tunable lasers using lithium niobate integrated photonics. *Nature* **615**, 411–417 (2023).
50. Churaev, M. *et al.* A heterogeneously integrated lithium niobate-on-silicon nitride photonic platform. *Nat. Commun.* **14**, 3499 (2023).
51. Extending the spectrum of fully integrated photonics to submicrometre wavelengths | Nature. https://www.nature.com/articles/s41586-022-05119-9.
52. Park, H., Zhang, C., Tran, M. A. & Komljenovic, T. Heterogeneous silicon nitride photonics. *Optica* **7**, 336 (2020).
53. Corato-Zanarella, M. *et al.* Widely tunable and narrow-linewidth chip-scale lasers from near-ultraviolet to near-infrared wavelengths. *Nat. Photonics* **17**, 157–164 (2023).
54. Arrazola, J. M. *et al.* Quantum circuits with many photons on a programmable nanophotonic chip. *Nature* **591**, 54–60 (2021).
55. Liu, J. *et al.* Photonic microwave generation in the X- and K-band using integrated soliton microcombs. *Nat. Photonics* (2020) doi:10.1038/s41566-020-0617-x.
56. Brasch, V. *et al.* Photonic chip–based optical frequency comb using soliton Cherenkov radiation. *Science* aad4811 (2015) doi:10.1126/science.aad4811.
57. Karpov, M. *et al.* Dynamics of soliton crystals in optical microresonators. *Nat. Phys.* **15**, 1071–1077 (2019).
58. Guo, H. *et al.* Mid-infrared frequency comb via coherent dispersive wave generation in silicon nitride nanophotonic waveguides. *Nat. Photonics* **12**, 330–335 (2018).
59. Riemensberger, J. *et al.* Massively parallel coherent laser ranging using a soliton microcomb. *Nature* **581**, 164–170 (2020).