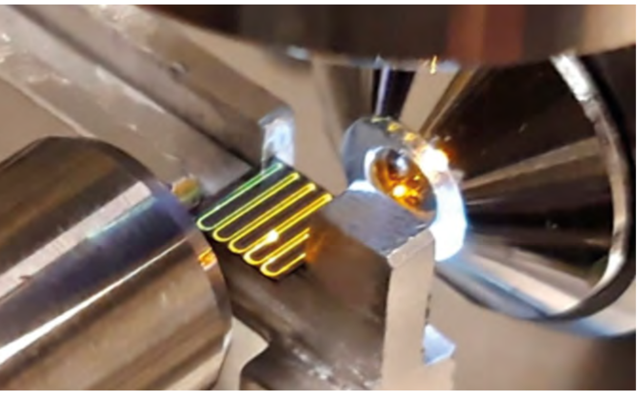
SILICON NITRIDE INTEGRATED NONLINEAR PHOTONICS

Marco CLEMENTI, Christian LAFFORGUE, Camille-Sophie BRÈS*
Photonic Systems Laboratory, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland
***camille.bres@epfl.ch**



Silicon nitride (SiN) has emerged as a key platform for integrated nonlinear photonics by leveraging its excellent optical properties and high fabrication maturity. SiN nonlinear integrated devices can provide efficiency, bandwidth and practicality. Here we show their exceptional performances for Kerr comb generation and frequency conversion. We also show how by inducing the intrinsically lacking 2nd order nonlinearity we can bring new nonlinear functionalities to the platform.

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Integrated photonics is key in many industries including data centers and communication systems, and becoming paramount for upcoming applications such as quantum computing, or mobile devices and sensors. Photonic integrated circuits (PICs), that guide and manipulate light through nanoscale structures, overcome the limited bandwidth and loss experienced by electrons in electronic circuits, while still benefiting from low-cost and high-volume fabrication on semiconductor wafers.

In most cases, the optical response of a material scales linearly with the amplitude of the electric field through the optical susceptibility χ. However, for intense light, the optical response is modified through higher orders of susceptibility with a quadratic $\chi^{(2)}$ or cubic $\chi^{(3)}$ dependence on the electric field. In this regime, the principle of linear superposition does not hold true anymore. The spectral components of the field can interact mediated by matter and can result in the generation of new frequencies, a key features for coherent frequency conversion, ultrafast optical signal processing and quantum optics. As such, the advent of integrated photonics in the last few decades has opened a whole new area of research, namely integrated nonlinear photonics. The ability to confine light at the nanometer scale inside waveguides, significantly boosting light-matter interaction, has contributed to the rapid growth of this field in view of bringing advanced functionalities to PICs.

The search for an ideal integrated nonlinear material is a long ongoing one. Significant work is focused on materials with very high nonlinearity, such as III-Vs or chalcogenide glasses. However, their performance and large-scale implementation remain a challenge. In a slightly surprising alternative, materials with more modest nonlinearities such as thin film lithium niobate and silicon nitride (SiN) have been under the spotlight. The latter, compatible with widely established CMOS fabrication processes, surpasses silicon in its ultra-low loss in sub dB/m, large bandgap close to 5 eV, and wide transparency window from visible to mid-IR, while still offering advanced dispersion engineering capabilities and high fabrication maturity [1] (Fig. 1). This is important as the efficiency of nonlinear processes not only depends on material nonlinearity, but is critically influenced by phase, power handling capabilities and interaction length. In that game, SiN took a significant lead. In this article we discuss the exceptional $\chi^{(3)}$ functionalities of SiN and present opportunities from induced $\chi^{(2)}$.

THIRD ORDER FREQUENCY CONVERSION

$\chi^{(3)}$ nonlinearities are ubiquitous in optical media. At a fundamental level, they can be understood as the interaction among 4 electromagnetic waves, mediated by the electronic response of the propagation medium. Common examples of $\chi^{(3)}$ phenomena are third-harmonic generation, self-phase modulation (SPM) and four-wave mixing (FWM). SiN has shown great success in that domain, particularly for Kerr microcombs, supercontinuum generation and parametric conversion, and stands as one of the only platforms allowing for the exquisite control and high performances of these essential conversion processes.

Kerr microcombs - Optical frequency combs are optical sources characterized by equally spaced spectral lines. They are of fundamental importance in many fields from spectroscopy, metrology, ranging, telecommunications to quantum technologies, and have been very successfully implemented on PICs using microresonators. Microresonators not only provide strong spatial light confinement but also a temporal confinement, as light is forced to re-circulate over the same path. For low-loss platforms such as SiN, this allows for light build-up inside the cavity and significantly lowers the power necessary to trigger nonlinear effects. These frequency combs, often called Kerr microcombs, are generated by injecting a continuous wave (CW) pump inside a microresonator, where parametric gain induces self-sustained oscillations. In the frequency domain, there is a redistribution of energy from the pump laser to the uniformly spaced cavity resonances through FWM. Finally, by tailoring the dispersion properties of the resonator, one can induce a well-defined mode-locked phase relation among all comb lines, corresponding in the time domain to the formation of transform-limited ultrafast pulses: the optical solitons.

Kerr microcombs have been demonstrated in many integrated platforms, but SiN shows some of the best versatility and highest performances. The possibilities in terms of SiN microcombs are numerous: octave spanning, low power threshold, easy access to a wide range of repetition rates from the GHz to the THz, ability to generate and control various families of solitons such as bright/dark pulses, crystals, or multi-soliton molecules [2]. With this wide library of Kerr combs, SiN microresonators find immediate applications in ultra-low noise microwave and terahertz-wave synthesis, optical

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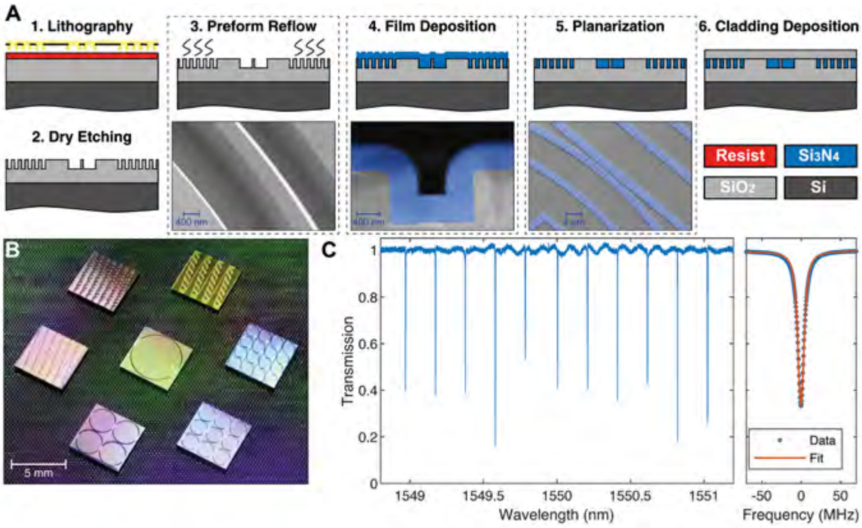


Figure 1. (a) Schematic of SiN PIC fabrication using the additive photonic Damascene process flow, particularly suited for manufacturing thick SiN layers used in nonlinear photonics. Subtractive processes with similar or lower propagation losses have also been developed. (b) SiN photonic chips containing microrings of different radii. (c) Typical transmission spectrum for a ring resonator, displaying equally spaced resonances, and spectrum of a resonance with ultra-high intrinsic quality factor (Q=30,000,000). Adapted from [1].

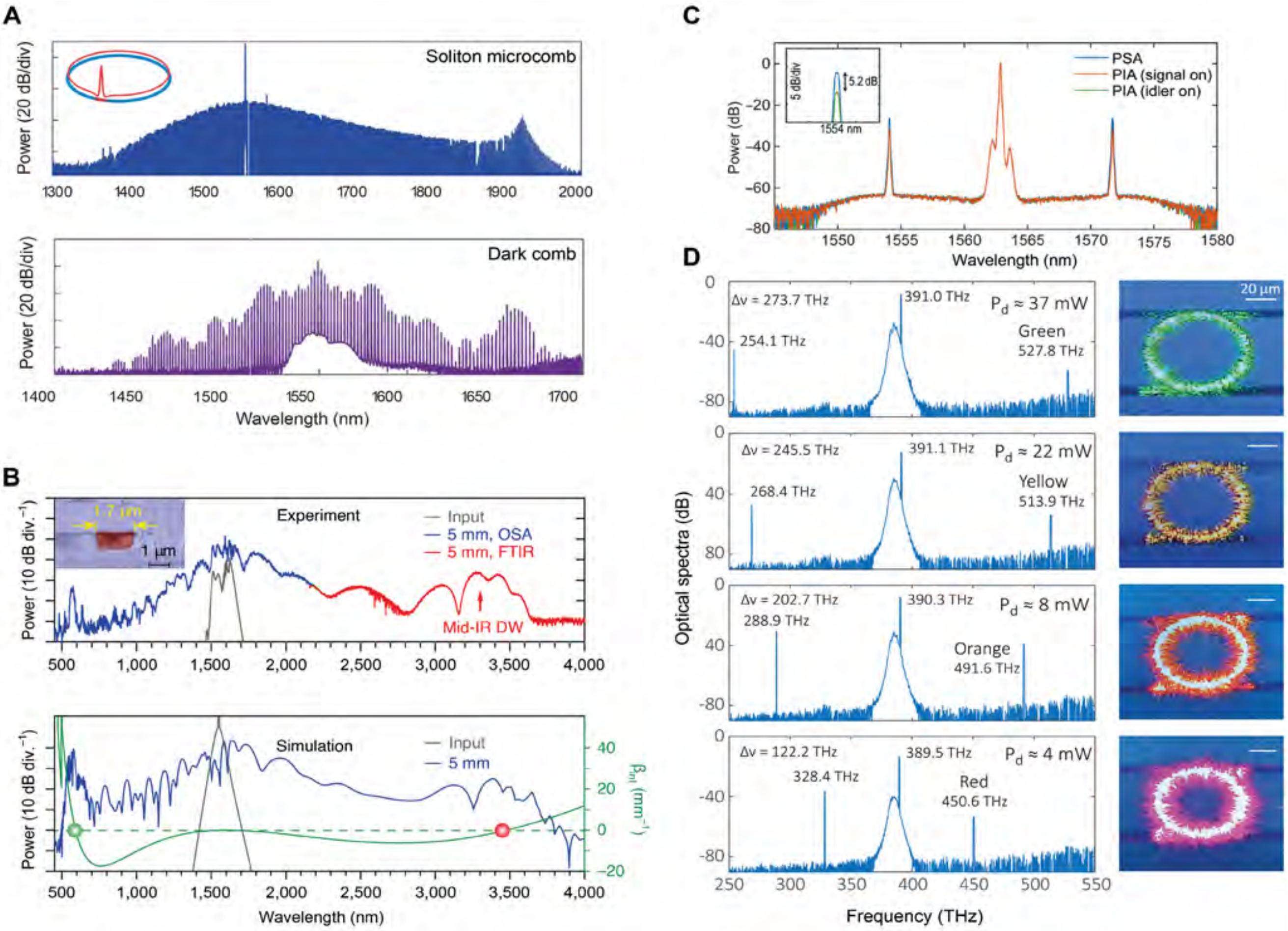
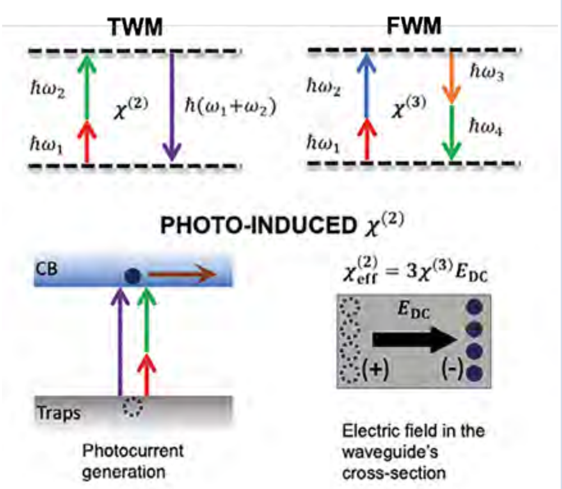


Figure 2. (a) Examples of soliton microcombs generated in SiN microrings. Top spectrum represents a bright soliton, bottom one a platicon state (dark soliton) [2]. (b) SCG in a 5 mm dispersion engineered SiN waveguide. Widely spaced dispersive waves (DW) are observed near the zero-integrated dispersion points around 600 and 3500 nm, in agreement with simulation [5]. (c) Experimental demonstration of CW parametric amplification from a SiN waveguide [6]. (d) OPO in a SiN microring enabling the coherent generation of visible/near visible light on chip, tunable by adjusting the pump wavelength (around 390 THz) [8].

communications by replacing multiwavelength sources, spectroscopy, LIDAR, microwave photonics or quantum communication [3]. Recently, significant progress has been made towards improving the efficiency of Kerr comb generation. Indeed, a main drawback of this approach is the substantial amount of power that remains in the CW pump. More advanced designs, such as coupled microrings (photonic molecules) now permit additional degrees of control of the systems and have reached 50% conversion efficiency [4].

Supercontinuum generation - An alternative strategy for the generation of broadband frequency combs relies on the propagation of short light pulses through a $\chi^{(3)}$ medium. An optical pulse experiencing SPM and group velocity dispersion (GVD) results in intricate and complex phenomena leading to broadband light generation that can cover multiple octaves. This effect, known as supercontinuum generation (SCG), is particularly studied in SiN waveguides owing to their dispersion engineering capabilities and wide transparency. By playing on the dimensions of the SiN core and the surrounding materials, it is possible to tailor the GVD while maintaining ultra-low loss. When the GVD is positive, meaning that wave packets at longer wavelengths travel faster than shorter wavelengths, smooth and relatively flat spectral broadening occurs. This case usually leads to highly coherent, smooth spectra, but the broadening is generally limited due to the temporal broadening of the optical pulse. When the GVD is negative, SPM counteracts the temporal spreading and pulse propagation is now submitted to soliton dynamics. Higher order solitons travel in the waveguide and split into sub-pulses and dispersive waves. Consequently, extreme spectral broadening happens, at the cost of flatness and sometimes coherence. Integrated SCG is a key technology as it enables spectral broadening towards the mid-IR range using an initial source emitting in common telecom wavelength ranges. Among the applications of SCG, mid-IR spectroscopy is indeed of prime interest integration can bring great benefit to the technology. To that end, SiN platforms are excellent candidates and have shown tremendous results in SCG, with demonstrations covering from the UV to mid-IR ranges in mm-long straight waveguides [5]. Such performances permitted molecular spectroscopy or frequency comb stabilization and control on PICs .

Parametric amplifiers and oscillators - The redistribution of energy through FWM, provided satisfied energy and momentum conservation, is the principle behind $\chi^{(3)}$ parametric amplifiers (OPA), an important class of active optical devices, which allow to achieve optical gain even in spectral regions where no active media are available. The $\chi^{(3)}$ ● ● ●



Schematic description of nonlinear interactions. $\chi^{(2)}$ interactions cause three-wave mixing (TWM), leading to sum frequency generation, second harmonic generation, difference frequency generation or electro-optic modulation. The figure shows the process of sum frequency generation, where two pump photons are converted to one photon of higher energy, satisfying energy conservation. The black lines represent the energy levels of virtual states. $\chi^{(3)}$ interactions result in four-wave mixing (FWM): two pump photons are converted to two other ones, namely signal and idler, once again with satisfied energy conservation. It is the process responsible of $\chi^{(3)}$ OPA/OPO, SCG and Kerr comb generation. $\chi^{(2)}$ processes can be photo-induced in SiN waveguides: through interference between single and multi-photon absorption processes, an electron in a trap state is transferred to the conduction band (CB) and a directional current is created (represented by the horizontal arrow in the bottom left figure). This photocurrent displaces charges within the cross section of the waveguide's core, creating a DC electric field. The inscribed DC field and the $\chi^{(3)}$ nonlinearity result in an effective second-order susceptibility $\chi^{(2)}_{\text{eff}} = 3\chi^{(3)}E_{\text{DC}}$.

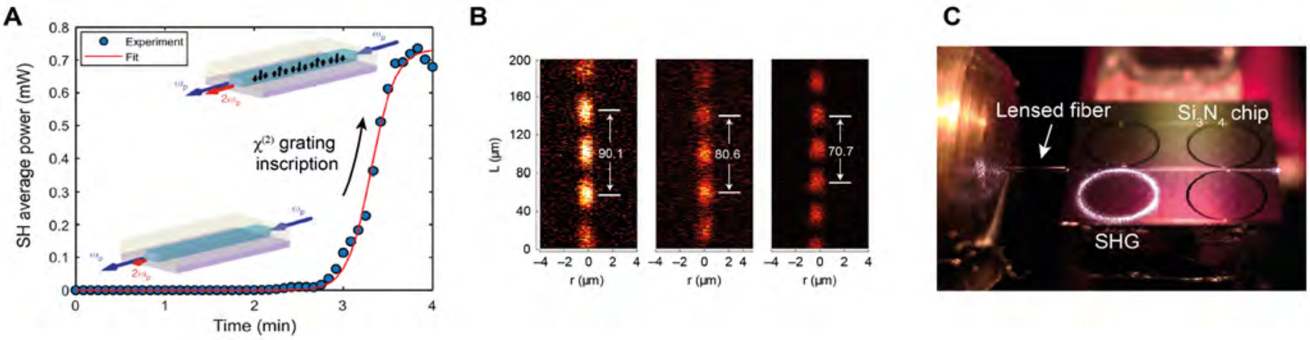


Figure 3. (a) Experimental SH power generated during all-optical poling. The inscription of the grating in a SiN waveguide results in a fast build-up of SH light [9]. (b) Two-photon microscopy images of inscribed gratings in a SiN microring. Depending on the probed resonance, the grating period automatically adapts to guarantee phase matching [10]. (c) Picture of a SiN microring under operation after all-optical poling showing SH light generation.

interaction is exploited to amplify a light field through stimulated FWM, where the energy reservoir is represented by an intense pump. Due to their extremely broad bandwidth, parametric amplifiers can be tuned to cover wide spectral regions by appropriate tuning of the phase-matching conditions, granted transparency of the interaction medium. By introducing an optical feedback mechanism such as a microcavity, one can realize a parametric oscillator (OPO). This class of devices shares straightforward analogies with lasers, but also bears two fundamental consequences: 1) the output always occurs both at the signal and idler wavelengths, which could belong to widely separated spectral regions, and 2) the coherence of the emitted light is bound to that of the pump used.

In the framework of integrated photonics, SiN represents again an ideal platform for the realization of on-chip OPA and OPO, once again leveraging the wide transparency window and low propagation loss. The relatively weak $\chi^{(3)}$ is overcome by using long waveguides [6,7]. As such, SiN is the only integrated platform where traveling CW parametric amplification, with gain higher than 10 dB in the telecom band, has been demonstrated in waveguides exceeding the meter in length. Alternatively, the interaction can be enhanced by resonant structures. These $\chi^{(3)}$ SiN OPO enable the efficient generation of tunable light at widely separated wavelengths [8]. In both cases, the phase-matching conditions play a crucial role in determining respectively the gain and the emission wavelengths, which can be chosen by engineering the dispersion of the waveguide or tuned by acting on parameters such as the pump wavelength or chip temperature.

INDUCED $\chi^{(2)}$ FUNCTIONALITIES

SiN is an excellent platform of choice for the large-scale integration of $\chi^{(3)}$ nonlinear effects. Its advantages mostly stem from its amorphous nature likewise that of silica optical fibers. However, they similarly share a key disadvantage in the domain of nonlinear optics: the lack of inversion which prohibits any $\chi^{(2)}$ nonlinear processes such as three-wave mixing. Recently, efforts have been focused on the possibility of endowing SiN with a $\chi^{(2)}$ response, and hence to provide a full toolbox of nonlinear effects to the platform. One solution gathering significant momentum is to break the material symmetry through electric fields, similar to what had been done in silica fibers, but with the benefit of integration and substantial reduction of powers. All-optical poling, which results in a photo-induced $\chi^{(2)}$ nonlinearity provides an extremely powerful technique.

All-optical poling is achieved through the coherent photogalvanic effect, the generation of currents originating from single- and multi-photon absorption between three coherently related pump waves. Owing to the coherent absorption mechanism, the current will have a preferential direction reflecting the phase difference between the participating waves. At equilibrium, the resulting charge gradient, and hence static electric field, breaks the inversion symmetry. The displaced charges tend to be long-lived, and the photo-induced $\chi^{(2)}$ stays even in the absence of the external pump. A distinctive feature is that the inscribed nonlinear grating oscillates with a periodicity that always ensures phase-matching of the three-wave mixing process: the grating is self-organized [9]. The self-organization is remarkably also reflected in the transverse direction, as the grating automatically adapts to the modal content of the pump waves.

Despite the relative complexity of the phenomenon, photo-induced nonlinearities are relatively simple from an application standpoint, as all-optical poling does not require additional complex manufacturing steps. The main advantage is reconfigurability: the grating can be written and erased (thermally or optically) at will. This is in contrast with the most established technique of electrical poling, bound to operate around a specific wavelength that must be established *a priori*. After first seminal demonstrations, the photo-induced nonlinearity in SiN has proven its suitability for efficient second harmonic (SH) generation, quickly followed by other important effects such as difference frequency generation, entangled photons generation or $\chi^{(2)}$-assisted comb generation. Its high potential has been exploited in ring resonator structures [10], where the field enhancement effect is used to access all-optical poling even with conventional low-power CW lasers, reaching milliwatt-level generated SH, and net conversion efficiencies comparable to those of $\chi^{(2)}$ materials, despite typical values of $\chi^{(2)}$ in the order of 0.3 pm/V. Most importantly, stringent phase-matching typically imposed by resonant structures is completely bypassed thanks to the self-organization properties. The development of novel integrated devices based on the photo-induced $\chi^{(2)}$ in SiN is still underway in many sectors.

CONCLUSION

The strength of SiN as a nonlinear integrated platform comes from the combination of its linear and nonlinear material properties, along with its extended dispersion engineering capabilities sustained by mature nanofabrication readily available to all through several photonic foundries. We have highlighted some of the exceptional nonlinear effects exploited in SiN waveguides and microrings, such devices constantly pushing bandwidth and performance. To realize the broad potential of these platforms and to bring these devices closer to their full implementation on PICs, efficiencies and practicality still need improvements. We have seen however in recent years great progress in that direction, with more and more devices directly driven by compact low power semiconductor lasers and novel engineering approaches targeted at bringing more control on chip. The continuing development of these essential nonlinear building blocks will endow PICs with more functionalities and bring exciting new opportunities to push performances of classical and quantum systems on chip. ●

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