# Self-injection Locked Second-Harmonic Generation in Optically Poled Silicon Nitride Microresonators

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**Abstract:** We present a narrow-linewidth second-harmonic source based on a laser diode injection locked to an optically poled silicon nitride microresonator. The device is a compact, highly-coherent dual-wavelength source, with high conversion efficiency up to 280%/W. 

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## 1. Introduction

Silicon nitride (SiN) represents one of the most popular platforms for the manufacturing of integrated nonlinear photonic devices, combining excellent material properties, low losses, and a wide transparency window with the maturity of the CMOS fabrication processes. These key features can be further enriched by hybrid integration, with the heterogeneous combination of passive components and III-V sources on-chip, and, as recently demonstrated, by the self-injection locking (SIL) the latter to microresonators, enabling applications such as the generation of low-noise Kerr microcombs and hertz-level laser stabilization in compact, self-contained devices [1,2].

However, highly efficient frequency conversion is usually ascribed to third-order ($\chi^{(3)}$) nonlinear effects, owing to the centrosymmetric nature of the SiN. One pathway to overcome this limitation is leveraging all-optical poling (AOP), enabled by the coherent photogalvanic effect, to endow the material with a second-order nonlinearity ($\chi^{(2)}$) [3]. Such an approach allows inscribing a waveguide with an inherently quasi-phase-matched $\chi^{(2)}$ grating, capable to support efficient second-harmonic generation (SHG) and sum-frequency generation (SFG), with an observed conversion efficiency CE = $P_{SH}/P_{FH}^2$ exceeding 2,500 %/W in microresonators [4–6].

In this work, we present the self-injection locking (SIL) of a distributed feedback (DFB) laser diode to a state-of-the-art high-Q microresonator where simultaneous efficient narrow line width SHG is obtained through all-optical poling. Such approach, which has recently proven its efficacy in $\chi^{(2)}$ material platforms [7], is here demonstrated in a silicon photonic platform for the first time, using mW-level powers. Our device combines a significantly narrowed laser line, due to the SIL effect, with efficient SHG, enabled by AOP, resulting in a highly coherent source emitting simultaneously in the 1550 nm and 780 nm bands. These results open a pathway for integrated nonlinear frequency conversion beyond the octave range in SiN photonics technology.

## 2. Results and discussion

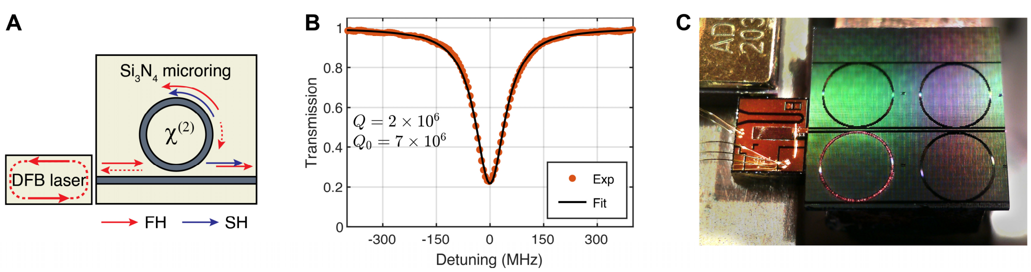


**Figure 1** – **a.** Schematic of the device. Light at FH and SH frequency is represented in red and blue, respectively. **b.** Normalized transmission spectrum of one of the poled resonances. Horizontal axis indicates detuning with respect to the laser frequency. **c.** SHG device in operation.

The device, schematized in Fig. 1a, consists of an electrically pumped DFB laser diode, edge coupled to a SiN chip. The DFB is realized in an InP multi-quantum well, buried waveguide geometry, and it is packaged on a wire-bonded and thermally stabilized stage. The SiN chip is fabricated through the photonic Damascene process [8] and includes microring resonators with a free spectral range of approximately 25 GHz for the fundamental $TE_{00}$ mode at 1550 nm. The azimuthal modes are evanescently coupled to a bus waveguide with a gap of 550 nm. The waveguide cross-section is $2 \times 0.55\ \mu m^2$, and adiabatic mode converters are used for input- and output-coupling. Transmission spectroscopy (Fig. 1b) reveals a set of slightly overcoupled resonances around 1553.6 nm, with an average loaded quality factor of $Q = 2 \times 10^6$ and an estimated intrinsic quality factor of $Q_0 = 7 \times 10^6$.

Before performing SIL experiments, the resonator was characterized for AOP using a table-top amplified tunable laser, and 200 mW of pump power was coupled to the bus waveguide. The laser wavelength was then tuned to match the target azimuthal mode of the ring resonator, within the tuning range of the DFB laser. Once efficiently coupled to the resonance, a doubly resonant condition between modes at the FH and SH frequencies was first triggered by frequency tuning as to initiate all-optical poling and then finely adjusted by temperature of the SiN chip with an external actuator, in order to maximize the conversion efficiency. Under such conditions we reached a maximum generated SH power up to 10 mW observed at 776.8 nm, corresponding to a CE = 25%/W.

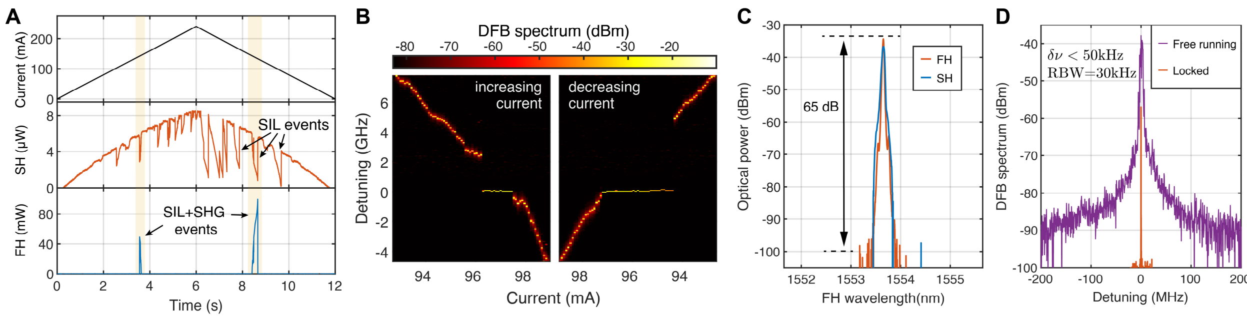


**Figure 2** – **a.** Injection locked SHG under variation of the pump current $I_P$. **b.** Evolution of the DFB spectrum. **c.** Spectrum of the FH and SH signal (resolution: 50 pm). **d.** Optical heterodyne spectrum of the DFB emission, showing significant linewidth narrowing during SIL.

After completion of the AOP testing procedure, we replaced the pump with a DFB diode, edge coupled to the bus waveguide, as shown in Fig. 1c. The device position was controlled with micrometer precision using piezoelectric actuators, reaching a minimum insertion loss (DFB to bus) of 5 dB. The DFB wavelength was controlled by varying the pump current: when this is tuned to one of the ring resonances, the back-reflection associated with Rayleigh backscattering inside the microresonator alters the lasing dynamics, resulting in the locking of the output wavelength to the resonance frequency [9]. This behavior is illustrated in Fig. 2a, where we linearly varied the DFB driving current with a triangular wave pattern while monitoring the output signal at FH and SH. The SIL events are associated with a significant drop in the transmitted power, owing to the wavelength locking of the laser at the minimum point of the transmission dip. By varying the gap between the DFB and the chip, we were able to tune the phase and amplitude of the back-reflected signal, and, therefore, both the probability of a SIL event for a specific resonance, as well as the locking bandwidth, within a range of several GHz (Fig. 2b).

To verify SHG, we tuned the SiN chip temperature to recover the doubly resonant condition previously addressed during AOP testing with the external source. Whenever this condition is fulfilled, any SIL event occurring within the QPM bandwidth yields the observation of a sharp peak in the generated SH power. A maximum generated SH signal of 0.1 mW was estimated inside the bus waveguide (Fig. 2a), corresponding to a conversion efficiency as high as CE = 280%/W. Finally, the spectral properties of the dual-wavelength source were investigated. Fig. 2c shows a comparison of the FH and SH spectra, confirming the second-order nature of the process, and highlighting a signal-to-noise ratio >60 dB, limited by the spectrum analyzer noise floor. An optical heterodyne spectrum at the FH is shown in Fig. 2d. Here, a narrowing from several MHz in the DFB free running regime to the kHz range in the SIL regime was observed, with an estimated short-term linewidth $\delta\nu < 50$ kHz, upper limited by the resolution of the technique.

In conclusion, we presented a compact, dual-wavelength source based on SIL of a laser diode to high-Q, optically poled SiN resonators, which high finesse enables operation at mW-level powers. The simultaneous generation of highly and mutually coherent light in the C-band and 780 nm band opens a promising pathway towards the integration of frequency-stabilized, low-noise laser sources simultaneously spanning widely separated spectral windows.

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