

Programmable Poling for Electric Field Induced Second Harmonic Generation

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Primary CNF Tools Used: Oxford PECVD, Oxford 100 ICP Dielectric, ASML DUV Stepper

Abstract:

Nonlinear photonics uses coherent interactions between optical waves to engineer functionality that is not possible with purely linear optics. Traditionally, the function of a nonlinear-optical device is determined during design and fixed during fabrication, which limits the scope and flexibility of its use. Here, we present a photonic device with an arbitrarily reconfigurable distribution of $\chi^{(2)}$ nonlinearity. To showcase the versatility of our device, we demonstrated spectral, spatial, and spatio-spectral engineering of second-harmonic generation by tailoring the quasi-phase-matching (QPM) grating structures in a two dimensional slab waveguide. Moreover, we have demonstrated record-breaking on-chip poling lengths by optimizing our poling pattern to a spiral waveguide geometry. Our work shows that we can transcend the conventional one-device-one-function paradigm, expanding the potential applications of nonlinear optics in situations where fast device reconfigurability is not merely practically convenient but essential—such as in programmable optical quantum gates and quantum light sources, all-optical signal processing, optical computation, and adaptive structured light for sensing.

Summary of Research:

Lithography-free photonics has attracted considerable attention in the field of programmable photonics because the large number of programmable parameters allows the device to move beyond the one-device-one-function paradigm. This means lithography-free devices can perform a large range of tasks and compensate for fabrication error [1]. Recent advances in lithography-free technology have enabled a device with real index

of refraction modulation on-chip. In this device, a photoconductor and waveguiding layer with high native $\chi^{(2)}$ nonlinearity are stacked in series and placed under high voltage, allowing the two layers act as a voltage divider. Because the index of refraction of the waveguiding layer depends on the electric bias, the index of refraction can be spatially controlled by shining different patterns of light onto the photoconductor [2]. Using the same device concept, the core material can be replaced with silicon nitride, which possesses a large induced $\chi^{(2)}$ during an electric-field induced second harmonic (E-Fish) process.

By engineering $\chi^{(2)}$ quasi-phase matching (QPM) gratings on a two-dimensional slab waveguide, we realized versatile functions on a single device, flexibly controlling nonlinear-optical processes in the spectral, spatial, and spatio-spectral domains. The programmability of the device further enabled in-situ inverse designs and optimizations based on real-time experimental feedback, robustly achieving complex functions that are challenging on conventional non-programmable devices [3]. This approach can be extended to one-dimensional channel waveguide, where the loss of orthogonal spatial programmability is compensated by lower propagation loss, broader band operation, and longer interaction length. Preliminary studies show super-linear scaling of the nonlinear conversion efficiency with increased interaction length, paving a way for programmable nonlinear photonics on silicon nitride to one day rival lithium niobate.

Spatio-Spectral Engineering on Programmable Slab Waveguide:

To fabricate the nonlinear programmable slab waveguide, we started with a conductive P-type doped Si substrate

with 1 μm of thermal SiO_2 and 2 μm of PECVD SiN_x provided by Silicon Valley Microelectronics. We then deposit 1 μm of PECVD SiO_2 followed by 12 μm of PECVD silicon-rich nitride (SRN), which acts as the photoconductive layer in the device.

Lastly, we sputter 30 nm of indium tin oxide (ITO) as our top electrode. After cleaving and polishing the waveguide facet, we couple an ELMO-HP pulsed laser from Menlo systems into the waveguide, apply high voltage to the stack, and project an image (generated by a spatial light modulator) onto device. The photoconductor and waveguide layers act as a voltage divider, so whenever the photoconductor becomes more conductive upon illumination, more voltage drops in the waveguiding layer, inducing a larger $\chi^{(2)}$ nonlinearity in the illuminated region. This process is shown in figure 1. The output of the waveguide is then imaged out to a grating, which separates the spectral components of each spatial position.

By sculpting the spatial $\chi^{(2)}(x, z)$ pattern, we can programmably phase match different processes at once. As figure 1 shows, we can engineer the output second harmonic wavefront in both the spatial and spectral domain by reprogramming the $\chi^{(2)}(x, z)$ pattern. Furthermore, because we can alter the nonlinearity distribution with no memory of the previous pattern, we can optimize the poling pattern to produce non-trivial spectral outputs. Figure 2 shows this concept, where we can use analytic poling patterns to produce easy spectral outputs, but more complicated outputs rely upon real-time feedback and optimization.

Super-linear Conversion Efficiency Scaling on Programmable Channel Waveguide:

Using the same principle as the slab waveguide, we fabricated a programmable channel waveguide using SiN_x . To fabricate this device, we start with a conductive P-type doped Si substrate with 1 μm of thermal SiO_2 . We then deposit 2 μm of PECVD SiN_x and etch it using a $\text{CHF}_3/\text{O}_2/\text{N}_2$ chemistry and SiO_2 hard mask. We deposit an additional 1 μm of conformal PECVD SiO_2 followed by a 4 hour 1200 $^\circ\text{C}$ anneal to drive N-H bonds out of the film. We then follow the same process as the slab waveguide, depositing 12 μm of PECVD (SRN), sputtering, 30 nm of ITO, and cleaving the facets open.

With a finished device, we couple a Santec TSL-570 continuous-wave laser into a spiral structure and pole along the outer Archimedes spiral waveguide. By utilizing interference between different subdivisions of the spiral, the phase and poling period of each section can be optimized to achieve superliner scaling. Figure 3 shows the scaling of SHG signal measured with increasing poling distance (measured on a

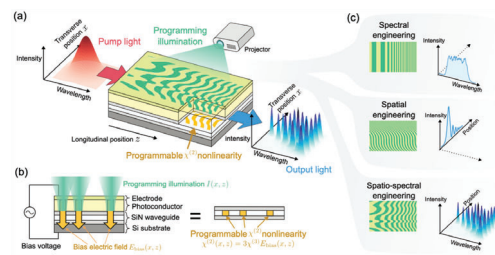


Figure 1: Overview of spatio-spectral engineering. a) Device operational overview. b) Schematic of how programmable illumination induces a programmable $\chi^{(2)}$ nonlinearity. c) Experimental data showing how different programmed poling periods yield different beam outputs in the spatial and spectral domain,

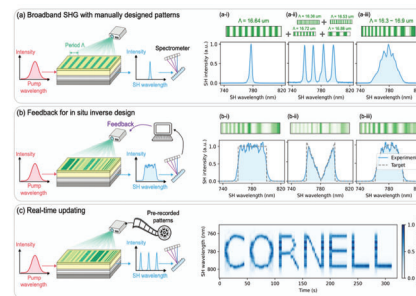


Figure 2: Real-time optimization of poling pattern. a) Output spectra from a single poling period, multiple poling periods added, and a chirped poling period. b) Different output spectra achieved through real-time optimization of the poling period. c) Output spectra changing in time to print the word "CORNELL".

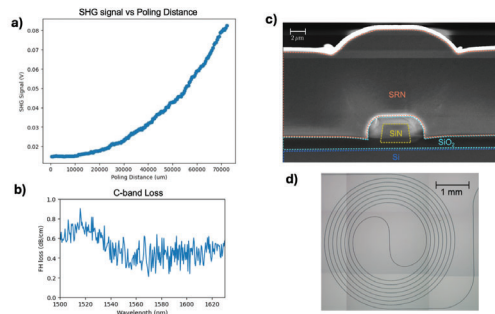


Figure 3: Early results on programmable channel waveguides. a) Super linear scaling of the second harmonic signal, as measured on a photomultiplier tube. The signal scaled with poling distance to the power of 2.5 and poling was done over a total of 7 cm. b) Loss measurement on device using cut-back method. c) SEM image of device cross-section with each material layer labeled. d) Microscope image of a device with a 7 cm spiral.

photomultiplier tube) and the loss of the device over the C-band, which shows the broadband potential of this device to be reprogrammed for efficient conversion.

References:

- [1] P. L. McMahon, Nature Reviews Physics 5, 717 (2023).
- [2] T. Onodera, M. M. Stein, B. A. Ash, M. M. Sohoni, M. Bosch, R. Yanagimoto, M. Jankowski, T. P. McKenna, T. Wang, G. Shvets, M. R. Shcherbakov, L. G. Wright, and P. L. McMahon, Scaling on-chip photonic neural processors using arbitrarily programmable wave propagation (2024), arXiv:2402.17750
- [3] Ryotatsu Yanagimoto, Benjamin A Ash, Mandar M Sohoni, Martin M Stein, Yiqi Zhao, Federico Presutti, Marc Jankowski, Logan G Wright, Tatsuhiro Onodera, Peter L McMahon, Programmable on-chip nonlinear photonics (2025), arXiv:2503.19861