

Programmable Poling for Electric Field Induced Second Harmonic Generation

CNF Project Number: 2971-21

Principal Investigator(s): Peter McMahon [1, 2]

User(s): Benjamin Ash [1, 3], Ryotatsu Yanagimoto [1, 3], Mandar Sohoni [1]

Affiliation(s): [1] School of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853, USA; [2] Kavli Institute at Cornell for Nanoscale Science, Cornell University, Ithaca, NY 14853, USA; [3] NTT Physics and Informatics Laboratories, NTT Research, Inc., Sunnyvale, CA, USA (6)

Primary Source(s) of Research Funding: National Science Foundation (award CCF-1918549)

Contact: pmcmahon@cornell.edu, ry338@cornell.edu, baa77@cornell.edu, mms477@cornell.edu

Research Group Website: <https://mcmahon.aep.cornell.edu>

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 show mixing of different spectral, spatial, and polarization modes through three-wave mixing. Furthermore, we show that a programmable $\chi^{(2)}$ can adapt to nontrivial underlying waveguide geometries to synergize the linear and nonlinear behavior. 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 quantum light sources, all-optical signal processing, and optical computation.

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. This device relies on a lithium niobate waveguide and photoconductor electrically in series, which allows spatially patterned illumination to induce a refractive index pattern of the same shape. This device has enabled one of the largest purely optical on-chip matrix vector multiplications by

utilizing active optimization [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. This enables lithography-free programmable nonlinear photonics [3].

By engineering $\chi^{(2)}$ quasi-phase matching (QPM) gratings on a channel waveguide, we realized versatile functions on a single device, flexibly controlling nonlinear optical processes in the spectral, spatial, and polarization 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. Specifically, we demonstrated the advantage of real-time optimization by phase-matching nonlinear processes on waveguides that periodically change their width and long, spiral waveguides. These experiments show the scalability, versatility, and highly multi-mode capabilities of programmable nonlinear optics to expand the capabilities of future platforms all while maintaining high device yield.

Continuous-Wave Three-Wave Mixing:

To fabricate the nonlinear programmable slab waveguide, we started with a conductive P-type Si substrate with 1 μm of thermal SiO_2 and 2 μm of PECVD SiNx . We then deposit 1 μm of PECVD SiO_2 as a hard mask and pattern photoresist on top using an ASML stepper. We then etch the SiO_2 hard mask, followed by an etch of the SiNx waveguide. Afterwards, we deposit an additional 1 μm of PECVD SiO_2 , anneal at 1200 $^\circ\text{C}$ for 8 hours, and deposit Si-rich SiN as the photoconductor. The process is finished by sputtering an ITO electrode on the very top and cleaving the waveguide facets open. By applying high voltage to the device stack and selectively

activating the photoconductor with patterned illumination, we can control the electric field distribution (and through the E-FISH effect, the induced $\chi^{(2)}$ nonlinearity) in the SiNx waveguide. Figure 1 shows a diagram of the device's operating principle and potential tasks that a programmable $\chi^{(2)}$ enables.

Figure 2 shows some of the classical nonlinear processes that can all be accomplished on one device. Specifically, we show broadband second harmonic generation, sum frequency generation, difference frequency generation, and polarization mixing through Type-0, Type-I, and Type-II processes. Our experiments show a tunable fundamental harmonic bandwidth of 130 nm, which is limited by the laser implemented in these experiments.

Phase-Matching on Complex Underlying Waveguide Geometries:

While the previous demonstrations were presented on straight waveguide geometries, our approach to programmable $\chi^{(2)}$ can be extended to more complex geometries. As Figure 3 shows, we can use real-time experimental feedback to partition a waveguide structure into many pieces and actively scan the grating period and grating phase on each piece to achieve optimal performance. This technique requires minimal information about the underlying waveguide geometry and can be adapted to a broad bandwidth of pump wavelengths. We then extend this real-time optimization technique to 10.1 cm long spiral waveguides and demonstrate increased nonlinear conversion efficiency over longer phase-matching distances. Furthermore, we show that the phase-matching grating can be adapted to different wavelengths over a 130 nm bandwidth without sacrificing nonlinear performance. This shows that, despite the lower magnitude of the induced $\chi^{(2)}$ compared to existing platforms, real-time optimization shows a path to scale the performance of programmable devices over longer propagation lengths. Moreover, because the $\chi^{(2)}$ pattern can be adapted to waveguides with spatially varying width, linear optical properties can be augmented with complex nonlinear functionalities.

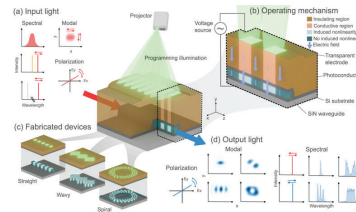


Figure 1: Overview of device operating principle and capabilities. (a) Possible types of fundamental harmonic inputs. (b) Schematic of how programmable illumination induces a programmable $\chi^{(2)}$ nonlinearity. (c) Different waveguide geometries presented in this work. (d) Possible output second-harmonic modes generated in the programmable nonlinear waveguide device.

Figure 2: Continuous-wave experiments. (a) Cartoon diagram of experiment used to show second harmonic generation (SHG), difference frequency generation (DFG), and sum frequency generation (SFG). Experimental results for SHG (b), DFG (c), and SFG (d). (e) Shows the cartoon diagram for polarization mixing experiments, with the results shown in (f).

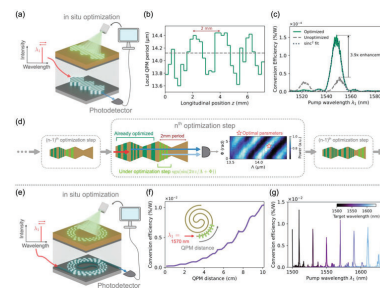
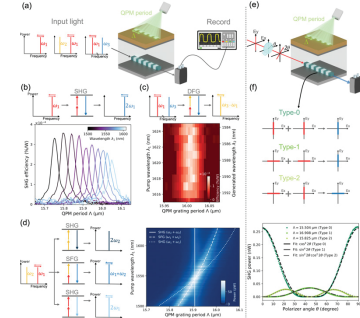


Figure 3: Phase-matching non-straight waveguide geometries. (a) Experimental diagram for phase-matching waveguides with periodically changing width. (b) Optimized phase-matching period at each partition and (c) nonlinear transfer function for optimized and un-optimized phase-matching gratings. (d) Shows the optimization routine that uses real-time experimental feedback to improve nonlinear performance. (e) Experimental diagram for phase-matching long, spiral waveguides. (f) and (g) show the scaling of SHG and broadband tunability capabilities of phase-matching a 10.1 cm long spiral.

Acknowledgements:

PLM gratefully acknowledges financial support from a David and Lucile Packard Foundation Fellowship.

The authors wish to thank NTT Research for their financial and technical support.

We gratefully acknowledge the Air Force Office of Scientific Research for funding under Award Number FA9550-22-1-0378.

This work was performed in part at the Cornell NanoScale Facility, a member of the National Nanotechnology Coordinated Infrastructure (NNCI), which is supported by the National Science Foundation (Grant NNCI-2025233).

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, Arbitrary control over multimode wave propagation for machine learning. Nat. Phys. 22, 164–171 (2026).
- [3] R. Yanagimoto, B.A. Ash, M.M. Sohoni, M.M. Stein, Y. Zhao, F. Presutti, M. Jankowski, L.G. Wright, T. Onodera, P.L. McMahon, Programmable on-chip nonlinear photonics. Nature 649, 330–337 (2026).