Rewritable Photonic Integrated Circuit Canvas Based on Low-Loss Phase Change Material and Nanosecond Pulsed Lasers

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ABSTRACT: Programmable photonic integrated circuits (PICs) are an increasingly important platform in optical science and engineering. However, current programmable PICs are mostly formed through subtractive fabrication techniques, which limits the reconfigurability of the device and makes prototyping costly and time-consuming. A rewritable PIC architecture can circumvent these drawbacks, where PICs are repeatedly written and erased on a single PIC canvas. We demonstrate such a rewritable PIC platform by selective laser writing a layer of wide-band-gap phase change material (PCM) Sb$_2$S$_3$ with a low-cost benchtop setup. We show arbitrary patterning with resolution up to 300 nm and write dielectric assisted waveguides with a low optical loss of 0.0172 dB/μm. We envision that using this inexpensive benchtop platform thousands of PIC designs can be written, tested, and erased on the same chip without the need for lithography/etching tools or a nanofabrication facility, thus reducing manufacturing cost and increasing accessibility.

KEYWORDS: rewritable photonic integrated circuits, phase-change materials, low loss, laser writing
insulator. However, these devices are still conventional programmable PICs with programmability limited by the immutable PIC architecture.

Here, we experimentally demonstrate a low-loss and rewritable PIC platform using laser-written Sb$_3$S$_3$. A dielectric-assisted waveguide structure$^{9,23}$ is used to lower the optical propagation loss while enhancing the endurance and reliability of PCMs. We first demonstrate arbitrary patterning on the PCM canvas with a fine resolution of 600 nm line pitch, to demonstrate the rewritable capability of our platform, then write laser-written waveguides between pairs of predefined grating couplers. This is achieved by amorphizing the c-Sb$_3$S$_3$ using an inexpensive nanosecond pulsed laser to form low index a-Sb$_3$S$_3$ cladding around the high index c-Sb$_3$S$_3$ core. The propagation loss was then measured via a cutback measurement as 0.01722 dB/μm, comparable to the 0.010 dB/μm loss in simulation. While this loss is ∼1000 times larger than current commercial silicon photonic waveguides,$^{37}$ this loss is acceptable to create waveguides of submm length. Our rewritable and low-cost platform shows a promising path to democratizing PIC prototyping for designers without access to a nanofabrication facility, which will enhance PIC education and accelerate rapid PIC prototyping.

Figure 1a shows the schematic of our rewritable PIC setup, where an Sb$_3$S$_3$-based rewritable PIC canvas was written with a nanosecond pulsed laser (write laser) and a three-axis motor stage (see Supplementary Section S1 for our experimental setup). The PIC canvas was fabricated by depositing multiple materials on a silicon substrate in the order of 3.5 μm SiO$_2$, 15 nm Sb$_3$S$_3$, 20 nm Al$_2$O$_3$ and 400 nm Si$_3$N$_4$ (see Supplementary Section S2 for fabrication process steps), as shown in the inset of Figure 1a. This multilayer design enables the low-loss dielectric-assisted waveguide mode (see Supplementary Figure S2)$^9$ and is key to low-loss waveguiding. We started with a c-Sb$_3$S$_3$ PIC canvas by annealing the chip at 325 °C on a hot plate. Patterns or waveguides were formed by amorphizing the Sb$_3$S$_3$ using the nanosecond pulsed laser and were erased by another hot plate annealing. To measure the written PIC devices, probe light with a wavelength of 1465 nm was coupled in and out of the chip through prefabricated Si$_3$N$_4$ grating couplers (see Supplementary Section S3) for high-efficiency probing of the waveguiding phenomena. The waveguides or arbitrary photonic structures can be written and erased between the grating coupler pairs. These predefined grating couplers could be removed since the gratings can be made out of the PCM itself,$^{15}$ but the coupling efficiency in our case remains inferior to an etched grating. The optical response of the laser-written devices was then measured via a vertical fiber coupling setup.

We first tested various laser pulse conditions and identified suitable ones (see Supplementary Section S4). The laser-switched areas were verified as a-Sb$_3$S$_3$ using Raman spectroscopy. Multiple laser conditions could amorphize Sb$_3$S$_3$, and we chose pulses with a duration of 13 ns and peak power of 50 mW for this experiment. Of the viable pulses and peak powers, we chose the second shortest pulse setting, 13 ns, and the second lowest peak power, 50 mW, to have reliable switching while maintaining a short exposure time. The short exposure ensures the amorphous state is favored after irradiation, while the low power reduces the chances of material degradation such as Rayleigh instability.

The diffraction-limited resolution of our setup is estimated to be 250 nm with our 450 nm laser and a 0.9 numerical aperture (NA) objective lens. We note that the minimum step size of the stage is 100 nm, so the resolution could be further improved with a shorter laser wavelength or a higher NA objective. We then characterized the resolution experimentally by laser writing a resolution chart consisting of sets of vertical lines with varying pitch. Figure 2 (left) shows the optical micrograph of the chip after laser writing and the pixel values along the solid black line are plotted in Figure 2 (right). The prominence of the peaks starts to decrease at ∼700 nm line pitch and is not reliably distinguishable for a 500 nm pitch. The lines with 600 nm pitch are differentiable from the background but are marginal in the optical contrast. Therefore, we consider a 600 nm line pitch as the maximum resolution of our setup. This corresponds to a 300 nm spot size, close to the diffraction limit of 250 nm. With this relatively high resolution, it is possible to pattern devices, such as ring resonators, Mach−Zehnder interferometers, and grating couplers. It is worth noting that Figure 2 was taken on an optical microscope, whose diffraction limit also potentially limits the resolution characterization.

A helpful property of Sb$_3$S$_3$ for laser writing is its slow crystallization speed.$^7$ This implies that the amorphous state is heavily favored during the sharp thermal transients of laser heating. Therefore, the same region of Sb$_3$S$_3$ can be exposed multiple times without switching amorphous Sb$_3$S$_3$ back into
the crystalline state. We used this multipass scheme to achieve a more uniform pattern for the waveguide structures exceeding 0.7 mm. For these longer waveguides, the areas around the grating couplers could undergo inconsistent switching due to focus drift over the long travel distance. These areas were re-exposed no more than a total of 3 times to ensure the structure guided the light as it exited the grating coupler.

Figure 3 shows two patterns which were written over a period of 2 and 25 min, respectively. In the top (bottom) row, we show a pattern of the letters “UW” (a husky picture), consisting of 88 (over 9,000) coordinate pairs. The patterns were written on a pristine area of c-Sb$_2$S$_3$, then the sample was annealed on a hot plate to recrystallize the Sb$_2$S$_3$ under 325 °C. A reflection of the same pattern was then written over the same region of Sb$_2$S$_3$. The black lines and crossings in the figures are laser-ablated regions to show that the writing region is unchanged. Although we only demonstrate two cycles of rewritability, Sb$_2$S$_3$ can be reversibly switched at least 2000 times. This high endurance, paired with the capability of arbitrary patterning, would enable thousands of PICs to be written and tested on the same chip, enabling rapid prototyping of PIC devices and systems.

Writing the low-loss waveguide requires aligning the laser spot to the edge of the grating coupler. A rotational stage was used to iteratively correct any rotational misalignment by aligning the laser spot to the edges of the left and right grating couplers multiple times. After the alignment and rotational correction, the 3-axis stage executed a preprogrammed serpentine pattern to write each waveguide cladding. During the laser writing, a dynamic focusing script adjusted the objective height to keep the focal spot in the same plane as the chip. A 500-μm-long waveguide took approximately 30 min to write. We anticipate that the process could be accelerated by more than a factor of 4 using an objective with a lower NA of 0.2 to achieve a larger spot size. Additionally, the larger depth of field in a lower NA objective would reduce the chance of ragged waveguide claddings from mechanical instability, allowing the stage to translate faster without reducing the reliability of the system.

In total, 18 waveguides were written, with three waveguides of length 500, 600, 700, 800, 900, and 1000 μm. Each
waveguide was given a cladding at least 3 μm wide and a core width of 3–4 μm. The core width was designed to be 2.5 μm, but alignment to the 4-μm-wide grating coupler taper was more reliable than centering the written pattern by hand. Additionally, this mismatch between the laser-written core width and the grating coupler end width could cause reflection at the interface, contributing additional and variable optical loss. After laser writing, the waveguides were measured through a cut-back measurement in which waveguides of different lengths were written and their losses compared. Each waveguide was normalized to a Si₃N₄ reference waveguide, fabricated through etching on the same column. Figures 4a and 4b show optical micrograph images of the laser-written waveguides and the Si₃N₄ reference waveguide (more images can be found in Supplementary Section S5).

To verify the waveguiding effect, we compare the laser-written waveguides with blank grating pairs with no waveguides written between them. The written waveguides increased transmission by an average of 9.93 dB compared with the blank gratings (see Supplementary Section S6), showcasing waveguiding behavior within the c-Sb₂S₃ core. We note that the grating demonstrated the most consistent coupling efficiency at 1465 nm (see Supplementary Figure S5), which was the wavelength used in the cutback measurement.

We then characterized the unit loss of the laser-written integrated waveguide. Figure 4c shows the cutback measurement results, where the measured power transmission of the written waveguides was averaged among three samples for each waveguide length. The measured transmission spectra from 1420 to 1500 nm can be found in Supplementary Figure S5. Assuming the reference Si₃N₄ waveguides are lossless, we estimate the coupling efficiency as 15.5 dB/facet, indicated by the y-intercept. The error bar represents the standard deviation, with the average standard deviation being 1.1 dB. A linearly fitted trendline had a slope of 17.2 dB/mm, which matched well with the theoretical value of 10 dB/mm. This variation could be attributed to several factors, such as (1) the anisotropy of c-Sb₂S₃ crystals, (2) mode leakage during propagation, (3) variation in the grating couplers, (4) misalignment between the axis of the writing laser and the chip, and (5) variation in the waveguide widths and cladding thicknesses. Among the etched Si₃N₄ waveguides, there was a standard deviation from the mean of 3.5 dB, implying variation in the material and gratings. The remaining error is likely from mode leakage or experimental nonidealities. The mode confinement could be improved with a thicker Sb₂S₃ layer, and we show that 45 nm Sb₂S₃ could also be laser amorphized (see Supplementary Figure S10). We note that although traditional SOI waveguides typically suffer from loss due to surface roughness, our PCM canvas is less susceptible. Such loss is due to Rayleigh scattering, which decreases with lower refractive index contrast between the core and cladding. In our case, the refractive index contrast is ~0.6 in only a thin layer of Sb₂S₃, so the scattering is significantly smaller than conventional SOI waveguides. Moreover, the laser writing system creates a gradual index change at the boundary, further reducing the confinement factor and hence the scattering loss. As for the roughness itself, the rectilinear movement of our stage was smooth and any ragged edges due to focus drift were corrected with multiple passes.

In this work, we demonstrated low-loss, laser-written waveguides in a nonvolatile PCM platform using inexpensive benchtop components (setup cost < $22,000) that in total are 50X less expensive than the mask writing laser used in other works.¹³,²⁸ We also demonstrate the first rewritable PIC platform using the wide band gap PCM Sb₂S₃, which can enable PICs operating in the near-visible spectrum range (~800 nm). Our platform exhibits a high patterning resolution of 300 nm with reversible and arbitrary patterning capability. Additionally, we demonstrated rewritable waveguides using a dielectric-assisted waveguide structure, showcasing a low propagation loss of 0.0172 dB/μm, close to the theoretical value of 0.01 dB/μm.

Our current PCM canvas is optimized for low-loss operation and does not support waveguide bends. This follows from the fundamental trade-off between the propagation loss and the mode confinement, incurred by the finite extinction coefficient.
of \(\text{Sb}_2\text{Se}_3\). A thicker \(\text{Sb}_2\text{Se}_3\) film leads to a more confined optical mode, but at expense of a higher propagation loss due to the increased mode interaction with lossy \(c\text{-Sb}_2\text{Se}_3\) (see optical mode simulation in Supplementary Section S1). To mitigate this loss-confinement trade-off and enable sufficient confinement for waveguide bends, we need to further reduce the loss of the PCM canvas. One approach is to reduce the scattering loss due to the domain boundary scattering of polycrystalline \(\text{Sb}_2\text{Se}_3\), which can be mitigated by engineering the pulsed laser conditions to reduce the loss. For example, one can guide the crystal growth direction by laser writing crystallization instead of hot plate to reduce the boundary.\(^\text{13}\). Alternatively, since our PCM laser writing platform is PCM transferrable, another approach is to use other low-loss PCMs such as \(\text{Sb}_2\text{Se}_3\), which provides a much better mode confinement with lower loss (See Supplement Section S8 for further comparison between \(\text{Sb}_2\text{Se}_3\) and \(\text{Sb}_2\text{Se}_3\)). These properties significantly improve the bend radius/propagation loss trade-off. Future works should strive to demonstrate other functional devices, such as directional couplers, multimode interferometers, ring resonators, and grating couplers, either in \(\text{Sb}_2\text{Se}_3\) or \(\text{Sb}_2\text{Se}_3\), to demonstrate further functionality on our platform.

Looking forward, the experimentally demonstrated rewritable PIC canvas represents a new direction for PIC development. Fabricating and testing photonic structures no longer requires weeks of work by highly trained students/technicians, specialized environments, or million-dollar equipment. Our work enables etch-less and recyclable PIC fabrication, which is crucial to accelerating the PIC prototyping cycle, reducing cost, and expanding the field of PIC research to researchers without nanofabrication facilities. We anticipate that expanding the pool of PIC researchers will lead to more innovative ideas, and the experimentally tested layouts will result in higher confidence for designs that are sent to fabs for their final realization.

**Associated Content**

**Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/10.1021/acs.nanolett.4c00070.

Experimental setup details, simulated mode profiles of \(\text{Sb}_2\text{Se}_3\) waveguides, fabrication process for \(\text{Sb}_2\text{Se}_3\)-based rewritable canvas, grating coupler design, Raman spectra to verify PCM phase change, additional optical microscope images of switched devices, loss discussion, measurement results to compare our waveguiding to unguided transmission, and discussion on thicker PCM switching and curved structures (PDF).

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**Notes**

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F.M. and A.M. conceived the project. F.M. designed the dielectric-assisted waveguide structure and built the rewritable PIC setup with the help of J.F. R.C. fabricated the \(\text{Sb}_2\text{Se}_3\)-based rewritable PIC canvas. R.C., Z.F., H.R., V.T., and S.G. helped with the experiment and data processing. A.M. supervised the overall progress of the project. F.M. wrote the manuscript with input from all the authors. F.M. is supported by a Draper Scholarship. This project was funded by the Defense Advanced Research Projects Agency (W911NF-21-10368). Part of this work was conducted at the Molecular Analysis Facility, a National Nanotechnology Coordinated Infrastructure (NNCI) site at the University of Washington, which is supported in part by funds from the National Science Foundation (awards NNCI-2025489, NNCI-1542101), the Molecular Engineering & Sciences Institute, and the Clean Energy Institute.

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