

RESEARCH ARTICLE

Tailoring Capping Layers for Phase-Change Material Photonics

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Received: 12 May 2026 | **Revised:** 3 August 2026 | **Accepted:** 7 August 2026

Keywords: integrated photonic devices | laser processing | phase change materials | reconfigurable photonics

ABSTRACT

Spatial-laser programming of low-loss Sb_2Se_3 phase-change materials (PCMs) offers a flexible route toward pixelated and large-scale nonvolatile reconfigurability in photonic devices. However, complex laser-induced dynamics often limit precision control and reproducibility. We systematically investigate how encapsulation architectures, a critical yet often overlooked element, govern the phase transition behavior and introduce tailored Al_2O_3 -based hybrid capping solutions for distinct application regimes. For high-resolution patterning, an additional SiN cap creates vertical heat-conduction channels that enable subwavelength phase switching. For waveguide-based low-power phase tuning, an $\text{Al}_2\text{O}_3/\text{SiO}_2$ hybrid structure provides optimal mechanical confinement and energy efficiency. With this optimized encapsulation, we achieve a minimum nominal feature size of 200 nm (a 100-nm reduction), 31 resolvable states ($3\times$ increase) via monotonic power modulation, and a 15-mW power window for full amorphization without ablation ($7\times$ broader than a conventional 30-nm Al_2O_3 encapsulation). Furthermore, we demonstrate significantly enhanced cycling stability in micro-ring resonator phase-shifting. Our results position encapsulation engineering as a decisive enabler of high-performance laser-manipulated PCM photonics.

1 | Introduction

The fast, reversible, and non-volatile phase transitions in phase-change materials (PCMs) yield a large optical contrast between their amorphous and crystalline states. This unique characteristic positions them as enabling materials for a range of photonic technologies, such as rewritable optical storage [1], optical displays [2], nonvolatile photonic memory [3], reconfigurable metasurfaces [4], and in-memory computing [5, 6]. Recent

progress in low-loss PCMs, such as $\text{Ge}_2\text{Sb}_2\text{Se}_4\text{Te}_1$ (GSST) [7], Sb_2Se_3 [8], Sb_2S_3 [9], and Se [10], has overcome a key limitation of conventional PCMs (e.g., $\text{Ge}_2\text{Sb}_2\text{Te}_5$). By maintaining optical transparency in at least one phase across infrared wavelengths, particularly the telecommunication band, these materials effectively reduce the insertion loss of devices. In particular, phase-only-modulation PCMs like Sb_2Se_3 with ultralow absorption in both states have enabled new applications in nonvolatile phase tuning, including reconfigurable optical phase shifters [11], filters

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[12, 13], inverse-designed photonic devices [14, 15], and device trimming [16, 17].

Switching methods are central to the tunability of PCMs, including electrical [2] and electrothermal switching [18], waveguide-integrated optical [19] and spatial laser manipulation [20]. Among these, spatial laser manipulation was one of the earliest methods utilized to control the phase change in PCM-integrated metasurfaces [21] and waveguides [22], offering unique advantages for both large-area modulation and high-resolution control. At wavelengths where the PCM exhibits effective optical absorption, the incident laser energy generates sufficient heat to induce phase transitions. Recent advances in spatial laser switching have focused on miniaturizing the phase-change pixel and achieving free-form reconfigurability [23–27] enabling the digital programming of waveguide devices and arrays, end-to-end rewritable free-form photonic circuits. Consequently, precise phase control via spatial laser pulses is becoming a vital tool in PCM-integrated photonics.

The intricate dynamics of the laser-induced phase transitions, however, pose significant challenges for achieving high precision, controllability, and reproducibility. While previous research has extensively focused on optimizing laser parameters for complete phase switching and cycling endurance, such as the write/erase wavelength (which governs absorption and penetration depth) [28] and pulse conditions (including power, duration, and shape) [20, 29], the role of the encapsulating layers in spatial laser switching has been largely overlooked. The oversight is notable, as adequate encapsulation proved critical in electrothermal switching of thick GSST micropatterns, where mechanically robust and chemically stable capping layers were necessary to withstand the material's drastic volume change and transient high temperatures [30]. For spatial laser switching, where energy delivery is highly localized and optical-thermal interactions are paramount, the influence of encapsulation is expected to be even more complex and pronounced.

Herein, we systematically study the influence of encapsulation architectures on the spatial laser switching of Sb_2Se_3 photonic devices, revealing their critical role via coupled optical, thermal, and mechanical effects. Our work identifies how specific encapsulation layers distinctly govern key performance metrics: direct-writing resolution, multilevel state control, and cycling reproducibility. This insight provides a design principle: for applications ranging from localized film patterning to waveguide modulation of nanostructured PCM patches, encapsulation can be tailored to prioritize desired device characteristics. Our results reveal that encapsulation engineering is a fundamental design dimension, beyond mere protection, for achieving high-performance, laser-programmable low-loss PCM photonic devices.

2 | Results and Discussion

2.1 | Capping Layer Design for Spatial Laser Switching of PCMs

Spatial laser manipulation of low-loss PCMs is driven primarily by two functional objectives: high-precision pixel-level patterning

and nonvolatile subwavelength phase tuning. As illustrated in Figure 1, we developed dedicated encapsulation engineering strategies optimized for each of these applications. For high-resolution patterning, the focus is on minimizing phase-change feature size through spatial heat flux control while maintaining structural integrity. In contrast, for waveguide phase tuning, encapsulation design prioritizes mechanical constraint along with stable device operation, reproducible phase shifts, and low switching power. Within this design framework, these capping strategies can be systematically optimized to balance multi-level modulation capability, laser-power tolerance, and fabrication practicality. For the encapsulation design, atomic-layer-deposited (ALD) Al_2O_3 is a widely used insulating and capping material, valued for its high density, exceptional conformality, and strong adhesion to PCMs, where it acts as an essential protective barrier in phase-change encapsulation. However, the dramatic morphological changes and mechanical stress accompanying the Sb_2Se_3 phase transition can cause thin Al_2O_3 layers to fail under repetitive laser switching, especially for thicker PCM films. This failure phenomenon has also been reported in the electrothermal switching of GSST [31]. Note that the inherent low deposition rate of ALD makes the fabrication of adequately thick Al_2O_3 layers inefficient from a throughput standpoint. To address these limitations, we developed an Al_2O_3 -based hybrid encapsulation scheme, integrating supplementary sputtered SiN and/or SiO_2 capping layers to fine-tune the system's mechanical resilience, photothermal behavior, and phase-change dynamics.

As shown in Figure 2a, the base stack (denoted as Group F, the baseline reference) consists of an Sb_2Se_3 phase-change layer sandwiched between a 5-nm-thick bottom and a 30-nm-thick top Al_2O_3 layer, all deposited on a standard silicon-on-insulator (SOI) substrate. In Figure 2b, additional capping layers of SiN and SiO_2 , chosen for their distinct physical properties, are introduced atop this base to form a heterogeneous hybrid encapsulation. The resulting architectural variations, organized as Groups A to D, enable systematic investigation into the influence of specific encapsulation designs on device performance.

A commercial laser direct-writing system (Heidelberg DWL66+), equipped with a 405 nm laser source, was employed for the localized amorphization of Sb_2Se_3 . This system provides high positioning accuracy and exceptional process repeatability, which helps minimize experimental variability, and ensures systematic consistency across all test groups. This, in turn, helps isolate the effects of the encapsulation layers from potential fluctuations in the laser switching system. For laser-induced crystallization, a home-built laser switching system was used, utilizing a 639 nm diode laser. This system is capable of scanning the sample in either continuous-wave (CW) or pulsed mode, with fully programmable pulse parameters.

2.2 | Encapsulation Design for High-Fidelity Laser Patterning of PCM Films

2.2.1 | High-Resolution Laser Switching of PCM Films

Compared to crystallization, laser-induced amorphization benefits from a significantly shorter photothermal interaction time and the effectively suppressed edge roughness associated with

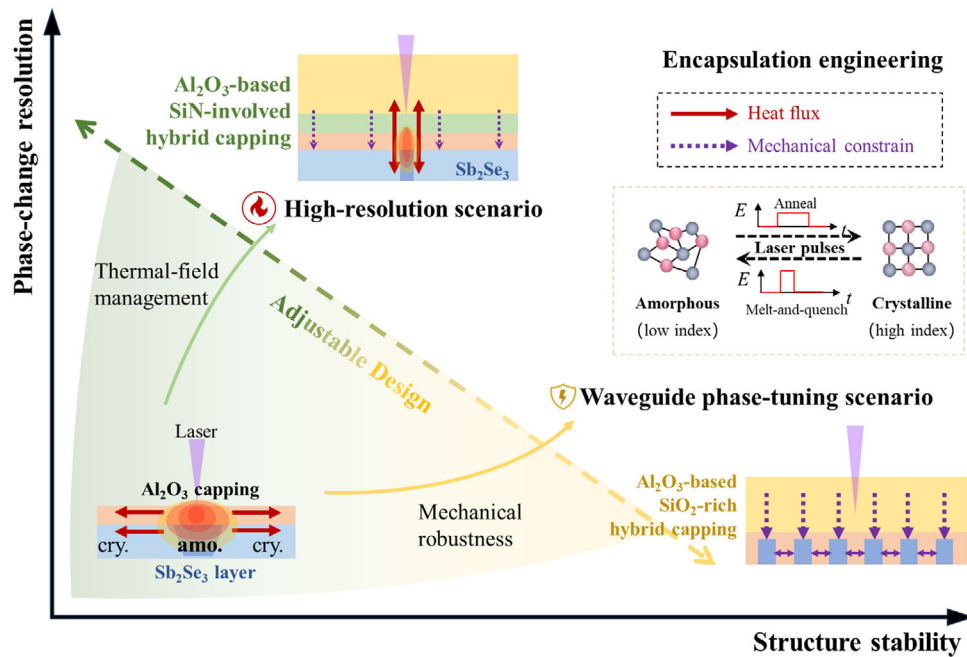


FIGURE 1 | Schematic of tailored encapsulation strategies for specific application scenarios. The bottom-left inset shows a conventional Al_2O_3 -only capping design. For high-resolution patterning, an additional SiN layer on top of the Al_2O_3 enables vertical heat dissipation for high-resolution phase switching (top inset). For waveguide-integrated phase tuning applications, a thick SiO_2 layer is introduced on top of the Al_2O_3 to improve mechanical confinement. Inset: Working principle of the laser-driven switching in the PCM.

stochastic grain growth. This enables the formation of localized phase-change patterns with finer features and reduced scattering losses, making it a key mechanism for pixel-level reconfigurable photonics. Due to the power-threshold response of PCMs, an amorphized pixel could inherently be smaller than the Gaussian beam spot. In this work, we further demonstrate how thermal-field management driven by the hybrid capping layers localizes the phase transition, allowing even smaller feature sizes and improved amorphization resolution.

To investigate this, we first simulated the laser-induced thermal field in the film stacks. Finite-difference time-domain (FDTD) simulations were employed to model laser propagation and the resulting absorption profile within the 50-nm-thick Sb_2Se_3 film. The resulting optical power density was converted to an equivalent volumetric heat source and imported into a thermodynamic model to resolve the spatiotemporal temperature evolution. Figure 2c (left) illustrates the simulated thermal distribution within the reference structure (Group F) upon exposure to a 1-mW laser pulse at the end of a 500-ns duration (the simulation settings are intended to elucidate the relative impact of the capping configuration on the thermal field, and do not constitute absolute benchmarks for the experimental pulse parameters). Given the PCM's low intrinsic thermal conductivity, heat dissipation is dominated by lateral transport through the 30-nm Al_2O_3 capping layer. This causes the photothermal field to concentrate near the PCM surface, leading to enlarged surface features, and is unfavorable for full-depth amorphization. In contrast, Figure 2c (right) shows the thermal profile for Group D, which adds a SiN/ SiO_2 capping. The laser power was increased to match the same peak temperatures as in Group F; the 890 K [32] isotherm (green dashed line) delineates the region that reaches the melting point of Sb_2Se_3 . Despite requiring

2.5 times higher incident power, due to the increased thermal mass, the thick, high-thermal-conductivity capping introduces an efficient out-of-plane dissipation channel. This effectively redistributes the peak temperature toward the interior of the PCM layer and shrinks the above-threshold surface width by 23%. The resulting vertical thermal redistribution facilitates uniform phase-change switching throughout the PCM volume, a crucial advantage for thicker films. The simulation setup and material parameters are summarized in Supplementary S1: Note 1 and Table S1.

Figure 2d presents the laser-written amorphization results using a standard line-and-space pattern, with nominal feature sizes ranging from 150 nm to 1 μm at a 50% duty cycle. For each group, the minimum laser power required for complete amorphization was applied. The darker lines correspond to the amorphized regions; however, as the pitch decreases, lateral heat diffusion and phase-change broadening cause these features to merge, ultimately defining the resolution limit of the system. Note that the color variations in the images result from automatic white balance adjustments triggered by the distinct optical constants of each capping scheme. Direct topographic characterization of feature size is precluded by the thick capping layers. Instead, to visually evaluate writing resolution, we extracted grayscale intensity profiles from optical images across different nominal sizes, with the emergence of distinct peaks indicating well-resolved features.

Group A (200-nm-thick SiN additional capping) and Group D (100-nm SiN and 400-nm SiO_2) exhibit the best pattern fidelity, with a minimum feature size of nominal 200 nm—a 100-nm reduction compared to the SiN-free groups (F and B). This is attributed to the vertical heat-sinking channels introduced

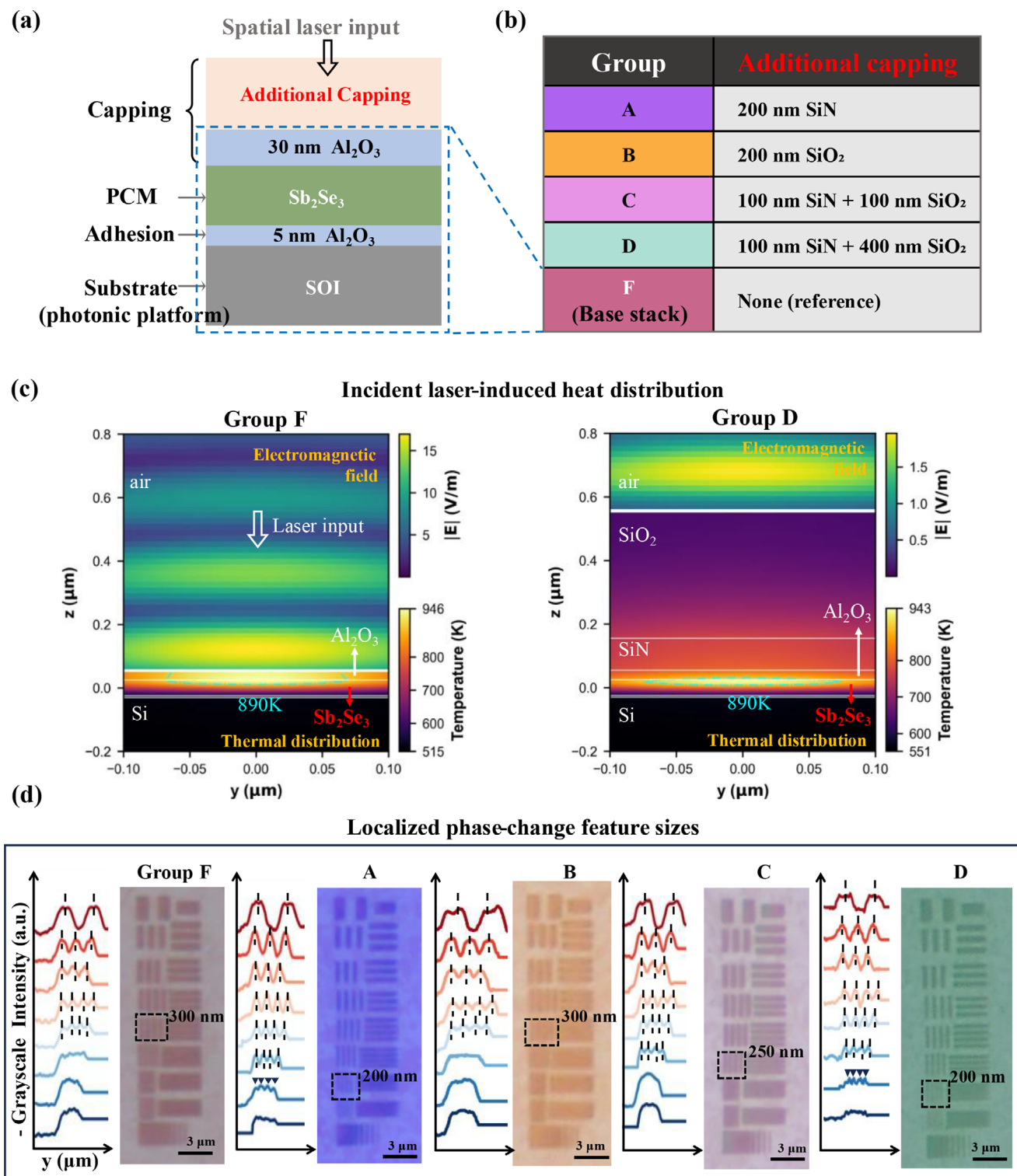


FIGURE 2 | Performance characterization of hybrid encapsulation for high-resolution amorphization. (a) Schematic cross-section of the Al_2O_3 -based hybrid encapsulation strategy. (b) Layer-by-layer configuration of Groups A–D compared to the baseline Group F (no additional capping). (c) Simulated electromagnetic field of the spatial laser inputs and laser-induced thermal profiles for Groups D and F after a 500-ns pulse. (d) Optical micrographs and corresponding grayscale intensity profiles of the amorphized vertical line-space patterns. The dash boxes mark the highest resolution pattern with the minimum feature size in each group. The laser power for each group was tuned to its individual resolution limit, yielding a minimum feature size of about 200 nm for Groups A and D.

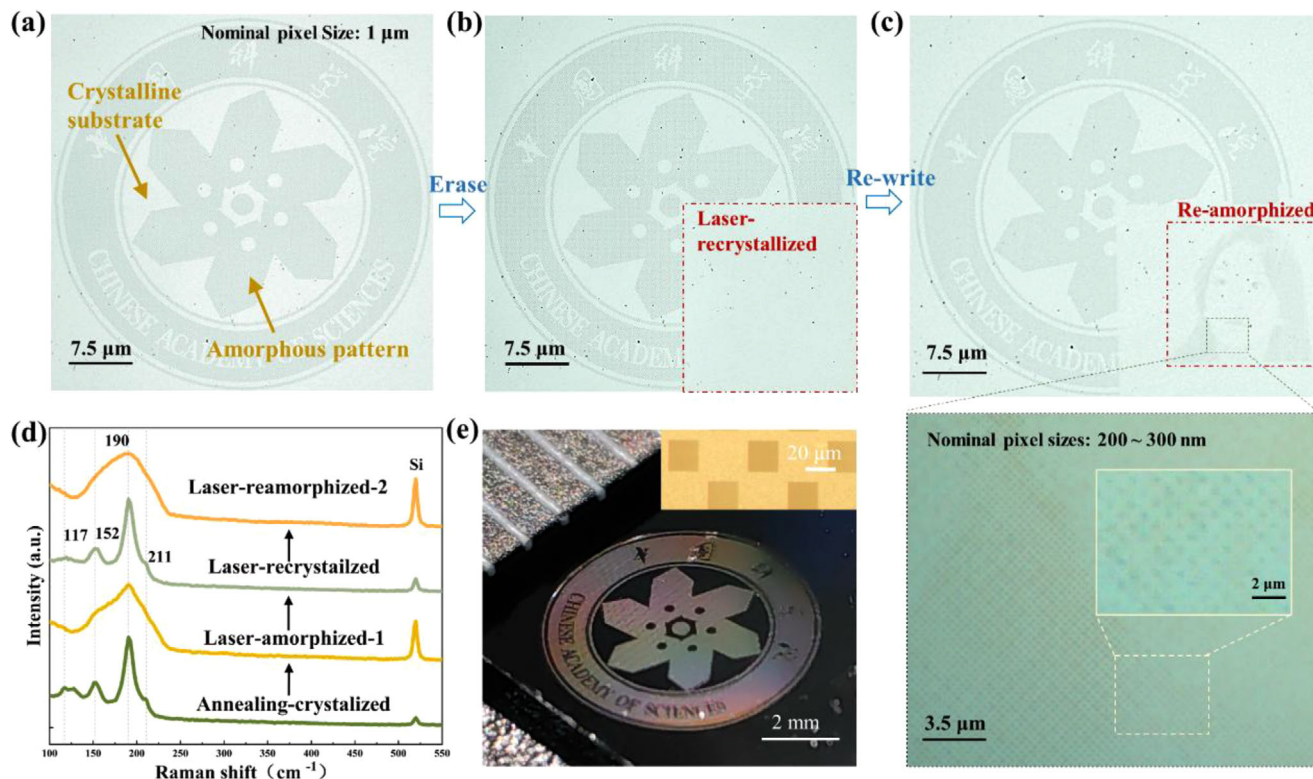


FIGURE 3 | Erasable and rewritable phase-change display. Optical micrographs of (a) laser-amorphized, (b) selectively erased (laser-recrystallized), and (c) rewritten (laser-amorphized) patterns, demonstrating cyclic non-volatile reconfiguration. (d) Raman spectra from the same region during the write–erase–rewrite cycle. (e) An optical image of a 6-mm-diameter rewritable pattern, illustrating scalability to the millimeter scale (inset: an optical micrograph of the laser-written phase-change pattern with a 20-μm pixel dimension).

by the high-thermal-conductivity capping, which effectively reduces the lateral thermal diffusion. However, SiN films are found to be susceptible to fracture and delamination buckling (see Supplementary Note 2) during thermal processing, likely related to inherent stress and thermal expansion mismatch. We instead employed a heterogeneous capping strategy consisting of a SiO₂ layer atop a 100-nm-thick SiN layer. Even when the SiN layer is thinned to 100 nm, it still conducts the majority of heat from the PCM surface into the capping stack. In this configuration, the thicker SiO₂ layer above the thin SiN compensates for the remaining thermal transport, which leads to the higher resolution observed in Group D compared to Group C.

Leveraging the optimized encapsulation strategy of Group D, we demonstrate a high-precision, erasable, and rewritable non-volatile phase-change display. As shown in Figure 3a, the logo of the University of Chinese Academy of Sciences (600 μm in diameter) was written via amorphization on the crystalline Sb₂Se₃ background, using 1-μm pixels, at a nominal laser power of 31.25 mW. Subsequently, one-quarter of the patterned area was erased (recrystallized) using a 639-nm continuous-wave laser (20 mW) scanning at 0.1 mm/s (Figure 3b). The erased region was then rewritten with the 405-nm laser at 37.5 mW to define a portrait pattern composed of nanoscale pixels down to 200 nm (Figure 3c). Notably, a higher rewriting power density was required to achieve these finer feature sizes. Reversible switching of Sb₂Se₃ between the amorphous and crystalline states was confirmed by Raman spectroscopy, as shown in Figure 3d, where each state presents

distinct and repeatable characteristic peaks. Furthermore, the nonvolatile patterning is scalable, demonstrated in Figure 3e with a 20-μm pixel pitch over a millimeter-scale area. Taken together, these results illustrate precise, erasable, and rewritable phase-change patterning across millimeter, micrometer, and nanometer dimensions. This approach readily extends to free-form rewritable photonic integrated circuits, offering a versatile platform for highly reconfigurable optical devices.

2.2.2 | Laser-Power Tolerance and Multi-level Phase Switching

Amorphization stands as a pivotal yet highly challenging process in phase-change switching. The high-power density required for amorphization often results in a narrow processing window: insufficient control can easily lead to irreversible ablation or structural degradation. Therefore, this section is focused primarily on optimizing the amorphization process through strategic encapsulation engineering. As the incident laser power for amorphization (P_{write}) increases, crystalline Sb₂Se₃ undergoes four distinct evolutionary stages, as depicted in Figure 4a: (i) Sub-threshold regime with no detectable response (blue region); (ii) Partial amorphization featuring intermediate states (off-white region); (iii) Complete amorphization (green region); and (iv) Onset of irreversible thermal ablation (red region). These transitions can be characterized by changes in surface morphology and optical reflectance. The applicable laser-power window is defined as the range spanning from the initial amorphization threshold

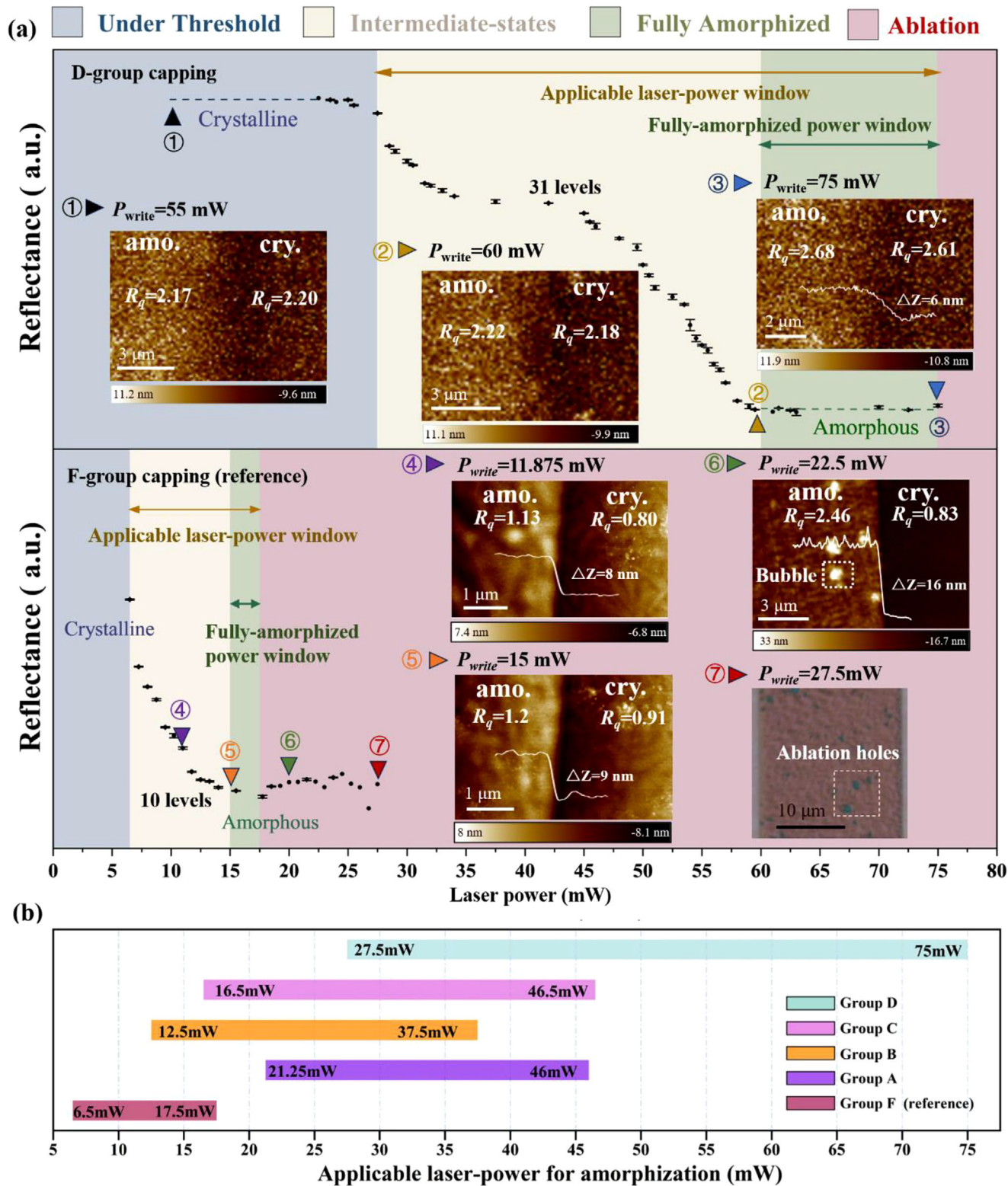


FIGURE 4 | Power-dependent reflectance and processing windows for laser-induced amorphization. (a) Reflectance evolution with the monotonic increase of amorphization laser power for Group D (upper panel) and Group F (lower panel). Insets show AFM height images of Group D (points ①~③) and Group F (points ④~⑦) acquired at corresponding laser powers, and an optical micrograph showing ablation morphology for Group F at point ⑦. (b) Applicable laser-power windows for amorphization of $40 \times 40 \mu\text{m}^2$ squares across Groups A–D compared with the reference Group F.

(P_{th} , the onset of partial switching) to the ablation threshold (P_{ab} , the onset of irreversible structural damage). This window encompasses both partial and complete amorphization states, while ensuring the material maintains reversible modulation and safe operation.

Figure 4b compares the applicable laser-power window for amorphization using the hybrid capping schemes (Groups A–D) against the baseline reference (Group F). Group F exhibits a narrow operational window, and the thin capping layer thermally fails immediately after the full-amorphization threshold ($P_{th,f}$) is reached. Atomic force microscopy (AFM) mapping confirms the poor ablation resistance of the Group F configuration (see Figure 4a, lower panel). Within the normal phase transition region (represented by points ④ and ⑤), a height contrast of 8–9 nm is observed, which corresponds to a thickness change of approximately 12.1%–13.5% relative to the measured amorphized-film thickness due to the phase transition. As the P_{write} increases to 17.5 mW, the height contrast rises to 14 nm, suggesting the onset of interface deformation rather than purely phase-induced density variation. At the P_{write} of 22.5 mW (point ⑥), the height difference further increases to 16 nm, accompanied by the formation of nanobubbles; at even higher power levels (e.g., point ⑦) extensive surface rupture occurs. Consequently, for the Group F configuration utilizing a thin Al_2O_3 capping layer, a modest increase in laser power readily drives the Sb_2Se_3 film from the desired amorphization state into irreversible ablation.

All configurations with an additional capping layer exhibit a wider applicable laser-power window than the reference group with the only 30-nm-thick Al_2O_3 single capping layer, confirming that a sufficient total capping thickness is the primary factor in enhancing device resilience. The strong correlation between thickness and mechanical robustness is further substantiated by comparing Group D with Group C, which share identical layer sequence but differ in SiO_2 thickness. Beyond thickness, material composition critically influences thermal management. Among devices with a fixed 200-nm additional capping thickness (Groups A, B, and C), the hybrid SiN/SiO_2 capping (Group C) achieves a ~20% larger laser-power window than either the pure SiN (Group A) or pure SiO_2 (Group B) variants. This result demonstrates that, once a structurally robust foundation is established, the high thermal conductivity of SiN actively extends the operational window by facilitating rapid dissipation of transient heat flux, thereby mitigating thermal ablation.

Building on this optimized balance of thickness and thermal design, Group D, featuring the greatest total thickness and an effective incorporates a hybrid $Al_2O_3/SiN/SiO_2$ capping, achieves an applicable laser-power window four times wider than that of Group F, demonstrating significantly enhanced operational robustness. Complete amorphization is achieved at the power of 60 mW, with no observable ablation even when the power is further increased by 15 mW. This stability is corroborated by AFM measurements, which show only 6-nm height contrast between amorphized and crystalline region at point ③ ($P_{write} = 75$ mW), corresponding to a thickness change of ~9.4%. These results indicate a much higher tolerance to laser-power fluctuations and improved overall device reliability.

The hybrid additional capping simultaneously enhances multi-level switching performance by enabling a larger capacity of intermediate phase states. A phase-change array was written by exposing discrete cells ($40 \times 40 \mu m^2$) to sequentially increasing laser power densities, and the optical reflectance at 820-nm wavelength of each cell was subsequently characterized using a UV–vis–NIR microspectrophotometer (see Figure S3). For each cell, the reflectance value was determined by averaging three independent measurements. As shown in Figure 4a, Group D supports 31 discrete reflectance levels with the monotonic increase of amorphization laser power, nearly tripling the 10 levels observed in the reference Group F. This is because the insufficient heat dissipation through the single 30-nm Al_2O_3 capping layer in Group F leads to rapid heat accumulation, making the system highly sensitive to changes in laser power; while the smoother temperature response afforded by the hybrid capping facilitates finer modulation of the crystalline fraction and facilitates more intermediate states in multi-level switching. It is important to note that the multiple switching levels achieved here via monotonic power modulation primarily characterize the state capacity of the phase-change system, rather than constituting a proof of repeatable, arbitrary multi-level switching (see Supporting Information S1: Note 3, Figures S4 and S5). Nevertheless, this high state capacity provides an essential foundation for applications requiring high-precision tuning, such as photonic in-memory computing and post-fabrication device trimming.

2.3 | Encapsulation Design for Robust Phase Tuning on Waveguides

Finally, we turn to the application of conventional silicon photonic devices integrated with phase-change patches. Here, the priority of encapsulation shifts from high spatial writing resolution to robust and reproducible phase tuning. To evaluate laser-driven nonvolatile phase tuning, phase-change patches were integrated onto Si micro-ring resonators (MRRs). Figure 5a shows optical micrographs of the fabricated devices, with the fabrication flow detailed in Supporting Information S1: Note 4. We considered the capping strategies that prioritize low switching power, selecting Group F (30-nm-thick Al_2O_3 capping) and Group B (Group F/ 200-nm SiO_2) for comparison. The 30-nm-thick Sb_2Se_3 was patterned into arrays of 46 nanodisks (400 nm diameter, 100 nm gap), as shown in the SEM inset of Figure 5a. This nanodisk design suppresses unstable photothermal response at waveguide sidewalls and reduces dewetting risks by enhancing the mechanical anchoring of the capping; this strategy aligns with the recent work [33] achieving a record-long cycling endurance through microheater-assisted electrothermal switching. Laser powers were calibrated on flat-film regions of the same chip before device modulation. The induced phase shifts, extracted from MRR resonant peak shifts, are shown in Figure 5b. Because devices with different PCM morphologies yield varying absolute phase shifts and modulation efficiencies, the data were normalized to their initial values to more clearly compare relative stability and cycle-to-cycle variations.

The main drawback of the standalone 30-nm Al_2O_3 capping (Group F) is its inadequate mechanical confinement. The surface-

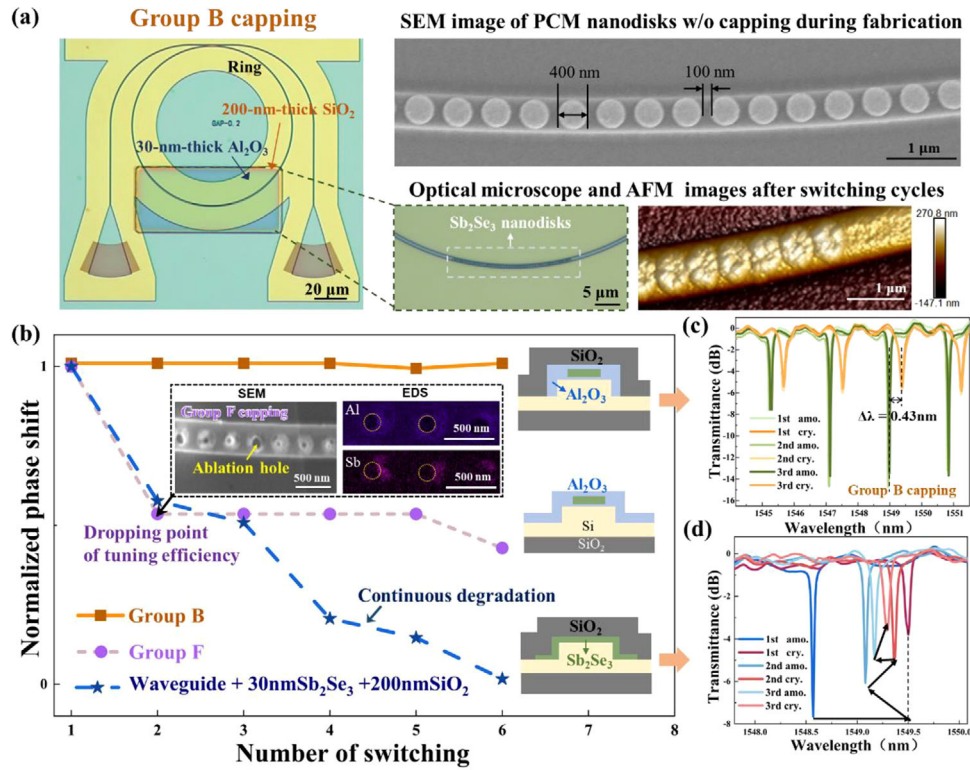


FIGURE 5 | Characterization of repeatability in nonvolatile phase tuning. (a) Optical micrograph of an Sb₂Se₃-nanodisks-integrated MRR, an SEM image of the PCM nanodisk array, and an AFM image of the functional region after switching cycles. (b) Normalized nonvolatile phase-shifts of various device configurations, accompanied by schematic cross-sectional views. Insets: SEM-EDS images showing local rupture on an Sb₂Se₃-MRR with Al₂O₃ capping (Group F). (c,d) Transmission spectra of the MRR with Sb₂Se₃ nanodisks and Al₂O₃/SiO₂ hybrid encapsulation (Group B) (c), and a micro-rectangular Sb₂Se₃ patch and a SiO₂ capping layer (d).

concentrated photothermal effect and high thermal sensitivity increase the risk of capping rupture during power fluctuations and repeated switching (see the SEM inset in Figure 5b). Following such a rupture during phase switching, energy dispersion spectrum (EDS) mapping reveals localized depletion of both Al (from the capping) and Sb (from the Sb₂Se₃ layer). This physical damage directly manifests as a pronounced drop in the MRR phase shift. Although strain released after rupture allows for transiently stable operation, the device thereafter enters an unsustainable state.

In contrast, Figure 5c shows the transmission spectra of an Sb₂Se₃-integrated Si MRR protected with the 30-nm-Al₂O₃/200-nm SiO₂ hybrid stack (Group B), which exhibits significantly improved repeatability over multiple switching cycles. The amber squares and the solid line in Figure 5b confirm stable, non-volatile phase shifts across cycles. Post-cycling inspection reveals no visible surface degradation, as supported by the AFM height image in Figure 5a. Despite the inherent surface roughness and large grain size of Sb₂Se₃, which pose a persistent challenge for encapsulation during repetitive volume changes, the Al₂O₃/SiO₂ hybrid stack provides effective mechanical protection.

While SiO₂ additional capping enhances the mechanical robustness for spatial laser switching of PCMs, it alone cannot replace discrete patterning and interface engineering. This is clearly demonstrated in a control experiment on the same MRR, which used a large 5 × 20 μm² rectangular Sb₂Se₃ patch capped with

only 200-nm-thick SiO₂, and intentionally omitted the 5 nm Al₂O₃ adhesion layer placed between the PCM and the Si. As shown by the blue stars and dashed line in Figure 5b, this configuration exhibited a progressive decline in phase shift during cycling. This early-stage rapid degradation is a typical signature of structural failure due to interfacial delamination or dewetting. Since both switching and measurements were conducted ex-situ, our stability evaluation does not yet fully account for long-term effects such as material segregation or ultimate device endurance. Nevertheless, these results underscore the critical importance of a synergistic approach that combines interface engineering and tailored encapsulation strategies in PCM-integrated photonic devices.

2.4 | Discussion on Encapsulating Strategies

Based on the preceding results, the performance metrics of various capping configurations are summarized in Figure 6. Our encapsulating strategies build upon Al₂O₃ as a foundational layer, with additional capping engineered using SiN and SiO₂. Mechanical robustness is a fundamental requirement for structural stability, and serving as a protective buffer is a common attribute shared by most additional capping strategies. SiO₂ demonstrates exceptional stress stability, likely stemming from its low Young's modulus and the superior interfacial adhesion [34] between SiO₂ and Al₂O₃. Coupled with a moderate thermal conductivity that keeps the switching power budget manageable, the Al₂O₃/SiO₂

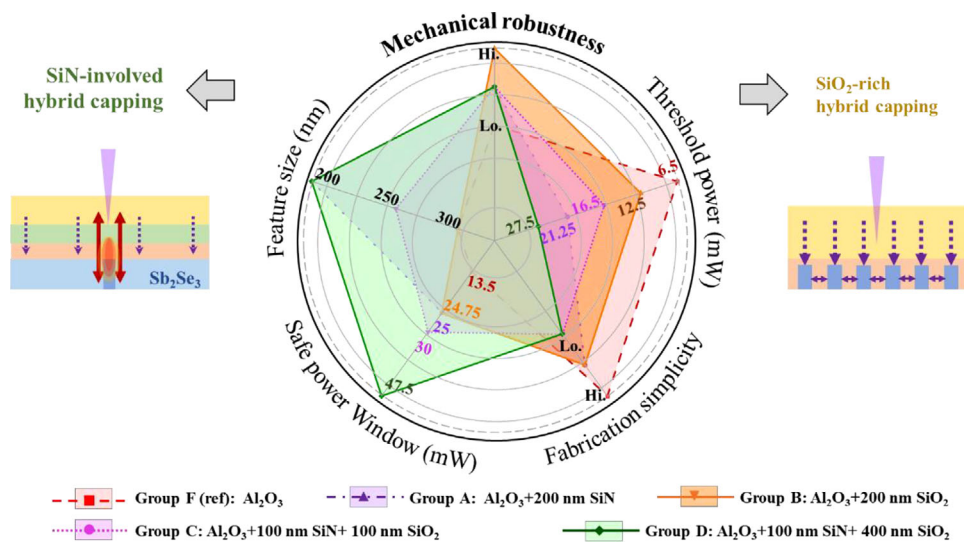


FIGURE 6 | Radar-chart comparison of laser-manipulated phase-change performance across encapsulation configurations. The chart evaluates key metrics to guide application-oriented capping-layer selection.

hybrid capping emerges as a favorable candidate for non-volatile phase tuning in waveguide-based applications.

For applications requiring high spatial resolution, we implement a hybrid capping strategy involving SiN. SiN provides efficient vertical thermal conduction pathways that help constrain the lateral heat-affected zone. However, SiN is inherently more brittle and susceptible to internal stress-induced fracture or wrinkling, especially when encapsulated over unpatterned Sb₂Se₃ films that exhibit drastic morphological changes during crystallization. Although mitigation was observed via stoichiometric adjustments during SiN sputtering, the low-temperature deposition of high-quality SiN poses some engineering challenges. We deploy a 100-nm SiN/400-nm SiO₂ hybrid additional capping strategy. In this configuration, the thinner SiN layer—in direct contact with the Sb₂Se₃/Al₂O₃—remains the primary contributor to lateral resolution enhancement. The SiO₂ layer functions as a supplementary thermal management layer, aiding resolution enhancement primarily by dissipating residual heat when the SiN layer is thinned, while simultaneously improving the overall mechanical stability of the capping structure. Therefore, despite the increased thermal mass—which leads to higher switching power—this strategy also significantly broadens the safe operating window, improves control tolerance, and facilitates finer temperature management, thereby enabling expanded multi-level tuning capacity.

We extended our experiments to the thin-film lithium niobate (TFLN) platform, comparing the resolution limits of the optimized Group D and the reference Group F configurations. The observed consistency between platforms confirms that while the underlying substrate contributes to thermal dissipation, the capping layer plays a dominant role in governing local thermal evolution during the spatial laser manipulation of PCM phase switching. The dominant role of the encapsulation strategy is intuitive: as the laser irradiates the device from the top down, the induced thermal field interacts more significantly with the upper capping layers. As a result, the encapsulation can be engi-

neered as a critical design lever for optimizing laser-manipulated phase-change photonic devices.

3 | Conclusion

In this work, we explored how encapsulation architectures influence the spatial laser switching of low-loss Sb₂Se₃ by coupling thermal, optical, and mechanical responses. We proposed Al₂O₃-based hybrid capping strategies tailored for distinct applications: high-resolution laser writing of phase-change patterns and reproducible nonvolatile phase tuning in waveguides. Through encapsulation engineering, we achieved a 100-nm improvement in phase-change feature size, 3-fold increase in multi-level switching capacity, and a significantly broadened (sevenfold) power window for laser-manipulated phase switching. Furthermore, the hybrid capping layers enabled markedly enhanced reproducibility in MRR phase-shifting cycles. These results firmly establish encapsulation engineering as a critical strategy for advancing high-performance laser-based manipulation of PCM-integrated photonic devices.

4 | Method

4.1 | Materials and Fabrication

Sb₂Se₃ thin films were deposited using a thermal evaporation system (Techno ZHD400Y) at a deposition rate of approximately 5 Å/s, with a base pressure of approximately 5E-4 Pa. Using spectroscopic ellipsometry, the thickness of the annealed crystalline Sb₂Se₃ thin film was ~58 nm. Al₂O₃ layer was grown in an atomic layer deposition system (Picosun R-200 Adv) at 100°C with a deposition rate of approximately 0.16 nm/cycle. SiO₂ thin films were deposited using a magnetron sputtering system (DENTON VACUUM DISCOVERY-635) with a stoichiometric SiO₂ target (76.2 mm in diameter). The process was conducted under a base pressure of 2E-7 Torr, and a working pressure of 6

mTorr with 40 sccm Ar flow. An RF power of 300 W yielded a deposition rate of 8 nm/min. SiN thin films were deposited via DC reactive sputtering (Beijing TECHNOL Science Co., Ltd.) at room temperature using a Si target (76.2 mm in diameter). The working pressure was 0.3 Pa with gas flows of 40 sccm Ar and 9 sccm N₂. The DC power and bias voltage were set to 200 W and 50 V, respectively.

4.2 | Laser-Manipulated Phase Switching

Heidelberg DWL66+ system with the Hires write head is used for amorphized pattern writing, with the writing speed kept constant at 3 mm²/min and the focus set to 4. For high-resolution phase-change patterns, laser powers of 15 mW (Group F), 23.75 mW (A), 21.5 mW (B), 30 mW (C), and 37.5 mW (D) were applied. The laser power for each configuration was systematically optimized to ensure the complete amorphization of the phase-change material (PCM) within the tens-of-micrometers-scale square regions, which was verified by the absence of visible crystalline grains under optical microscopy. For the logo patterns with nominal pixel sizes of 1 μm and 200-to-300-nm with capping configuration in Group D, the laser powers were set to 31.25 mW and 37.5 mW, respectively; for the large logo pattern with a 20-μm pixel size using the Group-F capping configuration, a laser power of 15 mW was applied. For reversible switching of the PCM-nanodisks-integrated microring resonators, the laser power of 22 mW was adopted for the optimized device configuration.

Localized crystallization of PCM was performed using a home-built system [35] equipped with a 639 nm continuous-wave laser diode (20 mW) with scanning performed at 0.1 mm/s by translating the sample stage (LBTEK), while global crystallization of PCM was performed on a hot plate at 200°C for 10 min.

4.3 | Characterization

Raman spectra were measured using a Renishaw inVia Raman microscope equipped with a 780-nm laser source. The reflectivity of intermediate states was characterized using a microspectrophotometer (CRAIC Technologies Inc20/30PV), with a sampling area of 25 × 25 μm² on 40 × 40 μm² phase-change squares for each measurement. AFM measurements were performed using a Bruker Dimension ICON in tapping mode, and SEM characterization was conducted using a ZEISS Sigma300 system. The transmittance spectra of the MRRs were measured using a home-built fiber-array vertical coupling system equipped with a tunable laser (Santec TSL-570), a polarization controller, and a power meter (Santec MPM210) scanning system.

Acknowledgements

The authors acknowledge Jiabao Sun from the Micro/Nano Fabrication Center at Zhejiang University for assistance with magnetron sputtering fabrication, and Yanhua Liu for support with AFM measurements. The authors thank the support from Nano Fabrication Center at Zhejiang Lab. Finally, the authors are grateful to Yue Wang from the Micro/Nano Fabrication Platform at Westlake University for support with ALD fabrication.

Funding

This research was supported by Natural Science Foundation of China (62305307, 62550072, 62105287); Zhejiang Provincial Natural Science Foundation of China (LMS26F050018, LD26F050003); State Key Laboratory of Photonics and Communications (Grant No. 2025QZKF015) and State Key Laboratory of Micro-nano Engineering Science (Grant No. MES202611), Shanghai Jiao Tong University, China; Research funds from Lightstandard Corporation; Research Funds of Hangzhou Institute for Advanced Study, UCAS (2023HIAS-Y001).

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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