



Ultra-compact non-volatile GSST-MIM plasmonic memory with in-circuit optical programming as a binary weighting element for neuromorphic networks

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ABSTRACT

This paper presents a numerical investigation of an ultra-compact, non-volatile plasmonic memory cell based on the $\text{Ge}_2\text{Sb}_2\text{Se}_4\text{Te}_1$ (GSST) phase-change material platform integrated within a metal-insulator-metal (MIM) waveguide cavity. The optical dispersion of the silver (Ag) metallic substrate is modeled using the Drude-Lorentz formulation, with air and GSST serving as the dielectric media. Numerical simulations conducted via the two-dimensional Finite-Difference Time-Domain (2D-FDTD) method demonstrate that at the operating resonance wavelength of 1362 nm, the proposed architecture yields an optical readout contrast of 73% between the amorphous and crystalline states, alongside a high extinction ratio (ER) of 23.24 dB. The signal attenuation during state read and write operations is rigorously evaluated: during the State '1' write and read operations, the insertion loss (IL) is 4.15 dB and 3.7 dB, respectively, while for the high-attenuation State '0', the writing and reading insertion losses reach 24 dB and 18.18 dB. Boasting an ultra-compact footprint of $0.004 \mu\text{m}^2$ and an integration density of $250 \text{ bits}/\mu\text{m}^2$, this architecture addresses operational alignment risks of external lasers by incorporating an auxiliary 90° -bent MIM control waveguide for in-circuit optical pulse routing. Transient time-domain response analysis confirms that readout discrimination relies on ultrafast optical propagation delay ($\tau_d = 7 \text{ fs}$), distinctly decoupled from the thermal phase-transition kinetics. Given these quantitative characteristics, the memory cell offers strong potential application as a reconfigurable binary optical weighting element in photonic synapses for integrated neuromorphic computing.

1. Introduction

With the exponential growth of data volumes and the inherent constraints of the conventional Von Neumann architecture, developing novel information storage and processing technologies has become a fundamental challenge in modern engineering [1]. In recent years, the demand for compatible nanophotonic technologies and optical computing systems has increased aggressively to replace electrons with photons as information carriers [2]. In this context, optical memories—particularly plasmonic memories based on phase-change materials (PCMs)—have emerged as a highly promising paradigm for achieving high-speed, non-volatile, and high-density data storage [3]. The capability of PCMs to transition reversibly between amorphous and crystalline phases induces drastic alterations in their optical and electrical properties [4]. Merging plasmonics with phase-change materials enables a significant enhancement of light-matter interactions at the

subwavelength scale, consequently reducing the switching power and boosting the overall efficiency of optical devices [5].

Phase-change materials are categorized into various types depending on their excitation mechanisms and phase-transition characteristics [6]. As the most prominent class of PCMs, chalcogenide materials feature reversible switching capabilities between amorphous and crystalline states, accompanied by substantial contrasts in both their refractive indices and absorption coefficients. Consequently, the integration of these materials is no longer confined to electronic technologies but spans a wide spectrum of photonic and plasmonic architectures [7].

Among the most widely researched chalcogenide compounds are Sb_2Te_3 [8], GeTe [9], $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) [10], Ag-In-Sb-Te (AIST) [11], and $\text{Ge}_2\text{Sb}_2\text{Se}_4\text{Te}_1$ (GSST) [12], each tailored for distinct applications. For instance, GST has been extensively utilized in optical memories [13], photonic switches [14], and plasmonic synapses [15]. Vanadium dioxide (VO_2) has been successfully deployed in the design of optical

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modulators [16] and plasmonic switches [17]. Furthermore, GSST, as an ultra-low-loss PCM, has been extensively adopted in the development of reconfigurable plasmonic metasurfaces [18], optical switches [19], and neuromorphic photonic synapses utilizing Mach-Zehnder interferometers (MZIs) and directional couplers [20]. Lastly, GeTe and Sb₂Te compounds have found vital applications in the design of phase-change memories and optoelectronic devices [9].

Within the 1550 nm telecommunication band, GSST exhibits lower optical losses in both its amorphous and crystalline phases compared to GST, owing to its significantly reduced extinction coefficient (k). Unlike VO₂, which requires a continuous injection of electrical or thermal energy to maintain its volatile phase state, GSST offers non-volatile and long-term phase stability. Nevertheless, due to the presence of selenium (Se), GSST demands a more complex chemical bond rearrangement during phase transitions, resulting in a relatively lower switching speed compared to traditional GST [12].

The reversible phase transition between the amorphous and crystalline states in GSST is fundamentally driven by a large contrast in its real refractive index (Δn), while the corresponding variations in its absorption coefficient remain remarkably small. In the design of such photonic devices, the physical mechanism triggering the phase change in GSST is photothermal heating induced by electromagnetic energy absorption, which subsequently modulates the device's overall optical response. Consequently, as expressed in Eq. (X), the complex refractive index ($\tilde{n} = n + ik$) demonstrates that the optical response of the material is dominated by variations in the real part (n), whereas fluctuations in the imaginary part (k , the extinction coefficient) are negligible.

Fig. 1 illustrates the spectral profiles of the real (n) and imaginary (k) parts of the refractive index for the GSST phase-change material in both its amorphous and crystalline states. Within the near-infrared telecommunication window at a wavelength of 1.25 μm , the real refractive index (n) is approximately 3.52 in the amorphous state and escalates to roughly 5.26 upon crystallization. At the same operating wavelength, the extinction coefficient (k) is nearly zero in the amorphous phase and reaches approximately 0.50 in the crystalline phase. Because the imaginary component of the refractive index directly dictates the optical absorption losses of the material, the primary mechanism driving switching and modulation in GSST-based architectures is predominantly governed by the phase-induced modulation of the real part of the refractive index [20].

Alongside phase-change materials, transparent conducting oxides (TCOs) such as indium tin oxide (ITO) have attracted substantial interest for active nanophotonic devices. For instance, combining ITO with vanadium dioxide (VO₂) enables compact electro-absorption modulators, fostering the continuous development of photonic integrated circuits (PICs) [21,22]. Furthermore, leveraging the synergistic properties of ITO and graphene heterostructures holds immense potential in

plasmonics and photonics for realizing high-performance optical switches [23–25] as well as high-speed, low-insertion-loss modulators [26–28]. Building upon these active multi-material paradigms, the present work focuses on a non-volatile GSST-based plasmonic memory platform tailored for high-density optical computing architectures.

The physical operation of phase-change materials relies inherently on thermal excitation. For chalcogenide compounds, the temperature range required to trigger the amorphous-to-crystalline phase transition (crystallization) is typically documented between 373 K and 523 K, whereas the reverse crystalline-to-amorphous transition (amorphization or resetting) demands a higher temperature range of 823 K to 923 K [29, 30].

The amorphization process of the GSST alloy is executed in three distinct stages. As demonstrated in [31], the material is initially heated to its complete melting point of 650°C, subsequently allowed to drop to 550°C, and finally subjected to a rapid quenching (cooling) profile to freeze the disordered atomic structure into the amorphous state. Conversely, during the crystallization process, the temperature of the GSST layer is elevated into the range of 180°C to 250°C and maintained to undergo a slow, controlled cooling phase, enabling proper atomic rearrangement into the crystalline lattice [32].

Table 1 summarizes the key optical and thermal properties of the constituent materials utilized in the proposed architecture. The high density and robust thermal stability of GSST facilitate its efficient monolithic integration into photonic integrated circuits (PICs), paving the way for energy-efficient, all-optical devices [33,34].

In photonic device design, GSST has been extensively deployed in various cutting-edge architectures, including Mach-Zehnder interferometer (MZI) modulators [35], optical switches [36], reconfigurable metasurfaces [37], and neuromorphic synapses [38]. Furthermore, this material has been successfully leveraged in the implementation of

Table 1

Mechanical and thermal properties of the materials utilized in this work, extracted from references [33,34].

Material	Refractive Index ($\tilde{n}$)	Thermal (C_p [J/K])	Heat (K [W/mK])	Density (δ [g/cm ³])
GSST _{cr}	$5.50 + 0.42i^*$	210	0.48	5.53
GSST _{am}	$3.47 + 0.0002i^*$	210	0.20	5.27
Ag	$0.145 + 11.445i$	235	420	-
Air	$1 + 10^{-10}i$	1005	0.026	-

*Temperature-dependent parameters; reported values measured at room temperature.

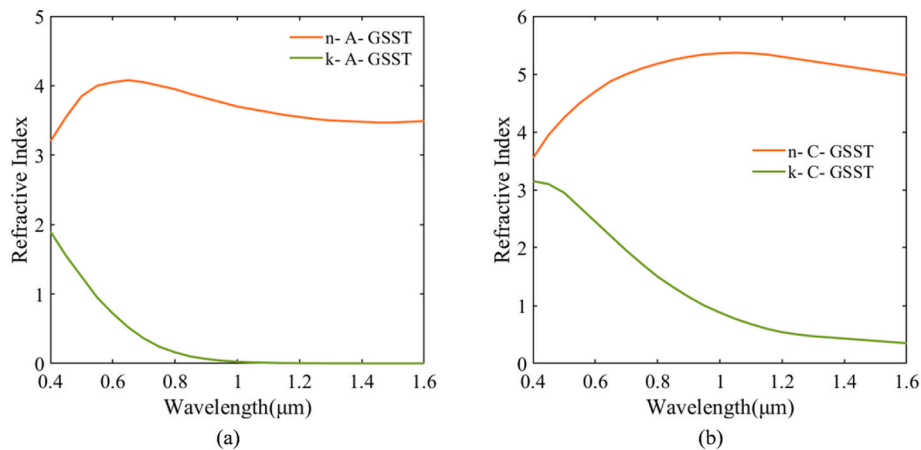


Fig. 1. Spectral curves of the complex refractive index of the GSST phase-change material in the (a) amorphous and (b) crystalline phases.

plasmonic switches [39], perfect absorbers [40], and plasmonic memories [41].

For instance, a reconfigurable polarizer based on a GSST layer integrated with a silicon waveguide has been demonstrated; this configuration enables efficient switching between TE and TM transmission modes by exploiting the stark contrast in optical absorption between the amorphous and crystalline states [42]. Additionally, a Fabry-Perot photonic crystal cavity featuring defects embedded with GSST has been investigated, revealing that its absorption response is highly sensitive to both the incidence angle and light polarization. In this structure, optical absorption induces variations in the crystalline fraction, subsequently triggering an enhancement in dielectric contrast and a corresponding redshift in the resonance wavelength [43]. To optimize phase-transition efficiency, a core-shell nanostructure has been proposed where the plasmonic absorption of the Au core effectively photothermally excites and accelerates the phase-change dynamics of the GSST shell under low-intensity optical illumination [44].

Similar to their electronic counterparts, optical memories are broadly categorized into volatile and non-volatile configurations. In electronic regimes, phase-change-based memories are classified as emerging embedded non-volatile memory (eNVM) technologies. Correspondingly, in the optical domain, plasmonic memories based on traditional GST are classified under Phase-Change Random-Access Memory (PCRAM) and Non-Volatile Random-Access Memory (NVRAM) paradigms [45].

Component compatibility is of paramount importance in photonic integrated circuits (PICs) [46]. Consequently, the design of plasmonic memories represents a critical milestone in the development and scalable integration of optical devices [47]. To date, plasmonic memories leveraging non-linear Kerr media have been widely investigated [48]; however, these architectures are fundamentally volatile and are primarily suited for generating programmed time delays within optical networks [49].

Switching endurance is a critical reliability metric for phase-change photonic memories. For GSST-based optical devices, experimental studies [50] demonstrate over 67,500 reversible switching cycles with high optical contrast, where failure was attributed to aluminum (Al) electrode breakdown rather than intrinsic GSST degradation or element segregation. Furthermore, comprehensive reviews [46] report that optimized PCM architectures can exceed 5×10^5 cycles, confirming the operational feasibility of GSST for reconfigurable photonic systems.

Neuromorphic photonics offers a powerful paradigm for implementing artificial neural networks using photons, effectively eliminating the conventional Von Neumann bottleneck while delivering massive parallel processing, high bandwidth, and ultra-low latency [51]. In this computing architecture, synaptic weights are implemented by modulating the amplitude, phase, or absorption of light within components such as waveguides and interferometers [20]. Merging photonic and plasmonic structures with phase-change materials (PCMs) enables the realization of non-volatile optical synapses characterized by highly tunable synaptic weights, low power consumption, and high integration density [52]. Within these neuromorphic systems, optical pulses serve as spikes for information transmission and processing [53]. A key challenge in this field is the physical realization of scalable, non-volatile memories; here, PCMs emerge as an ideal candidate due to their large optical contrast and rapid switching capabilities [54], making them a cornerstone for optical synapses.

In this work, we numerically evaluate an ultra-compact, non-volatile plasmonic memory cell based on the GSST phase-change platform using two-dimensional Finite-Difference Time-Domain (2D-FDTD) simulations. The cell is initially analyzed under off-chip optical readout and programming configurations. To mitigate the alignment complexity, integration constraints, and photothermal damage risks associated with direct external laser delivery onto nanometric photonic integrated circuits (PICs), the architecture is expanded to incorporate an integrated 90°-bent MIM control waveguide. This configuration successfully

validates the physical feasibility of in-circuit all-optical pulse routing during writing and erasing cycles. Furthermore, by leveraging the distinct insertion loss levels between the amorphous and crystalline states, the proposed memory cell demonstrates strong potential application as a reconfigurable binary optical weighting element in photonic synapses for integrated neuromorphic computing platforms.

The remainder of this paper is organized as follows: Section 2 details the cell geometry, material parameters, and 2D-FDTD setup; Section 3 analyzes the readout operation and off-chip optical programming; Section 4 substantiates in-circuit optical programming via the 90°-bent control waveguide, backed by the photothermal framework in Section 4.1; Section 5 evaluates the potential application as a binary optical weighting element; Section 6 investigates the transient optical readout dynamics; Section 7 outlines the nanofabrication roadmap and thermal encapsulation; and Section 8 concludes the study.

2. Design methodology

SPPs emerge at metal-dielectric interfaces through the coupling of electromagnetic waves with a metal's free electrons. The dispersion relation for the fundamental surface plasmon TM mode can be obtained as follows [55]:

$$K_{SPP} = \sqrt{\frac{\epsilon_d \epsilon_m(\omega)}{\epsilon_d + \epsilon_m(\omega)}} \frac{\omega}{c} \quad (1)$$

In Equation (1), k_{SPP} is the plasmonic wave vector, $\epsilon_m(\omega)$ is the permittivity of the metal, ϵ_d is the permittivity of the dielectric and c is the speed of light in vacuum. The optical response of noble metals such as silver and gold in plasmonic nanostructures has been modeled using the Drude formalism Equation (2), which describes the free-electron behavior across visible and infrared spectral regimes. $\epsilon(\omega)$ is the complex dielectric function, ϵ_∞ is the high-frequency dielectric constant, ω_p is the plasma frequency, γ is the damping constant and $\omega = \frac{2\pi c}{\lambda}$ is the angular frequency of the incident light [56–58].

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \quad (2)$$

To evaluate continuous and complex electromagnetic domains via numerical simulations, the device architecture must undergo discretization into a nanometer-scale mesh grid [59]. While deploying a finer grid spatial resolution enhances the numerical precision, it inevitably escalates computational overhead. In this study, a uniform spatial grid step of $\Delta x = \Delta y = 2$ nm is established. Based on Equation (3), the maximum allowable numerical time step (Δt) is strictly governed by the Courant-Friedrichs-Lewy (CFL) stability criterion to prevent spatial divergence [60]:

$$(\Delta t) \leq \frac{1}{c \sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2}}} \quad (3)$$

To accurately characterize the optical response, discrete FDTD field and power monitors are deployed at strategic spatial locations. Specifically, a Frequency-Domain Field and Power Monitor alongside a Time-Domain Monitor are positioned at the exit port of the MIM output waveguide. A 2D Frequency-Domain Profile Monitor covers the entire coupling junction to visualize spatial E-field distributions, while a Refractive Index Monitor tracks the localized complex permittivity profile of the GSST domain. Perfectly Matched Layer (PML) boundary conditions configured with 100 layers are implemented along all computational boundaries to prevent parasitic numerical back-reflections [61]. The simulation is executed under a Courant stability factor of 0.99 with an auto-shutoff energy threshold set to 10^{-7} to ensure complete field decay. The key numerical parameters, material fitting coefficients, and FDTD simulation settings are summarized in Table 2.

To ensure strict numerical stability and grid convergence, the spatial

Table 2

Numerical parameters utilized in the 2D-FDTD simulations.

A- GSST ($\lambda = 1362$ nm)	C- GSST ($\lambda = 1362$ nm)	Δw (nm)	ϵ_{∞}	ω_p (eV)	Γ (eV)	Δt	C (m/s)	Convergence Criteria
n = 3.451 k = 0.002	n = 5.182 k = 0.45	1000 - 2500	3.7	9.1	0.081	0.99	3×10^8	1e-07

discretization step was systematically decreased from $\Delta x = \Delta y = 6$ nm to 2 nm (Fig. 2). Although finer meshing imposes a smaller temporal step size Δt governed by the 2D CFL stability condition (Eq. (3)), the fine spatial step of $\Delta x = \Delta y = 2$ nm provides an optimal compromise between resolving high-contrast transmission peaks and maintaining computational efficiency.

The proposed nanophotonic structure was analyzed using a 2D FDTD formulation under the assumption of structural invariance along the out-of-plane axis. For planar Metal-Insulator-Metal (MIM) plasmonic configurations, the electromagnetic mode confinement and resonant characteristics are overwhelmingly governed by in-plane surface plasmon polariton (SPP) dynamics. Consequently, 2D formulations accurately capture the fundamental transverse magnetic (TM) modes, optical coupling behaviors, and phase-change dynamics with high precision while substantially mitigating computational overhead. Although full 3D modeling can account for out-of-plane scattering losses due to finite vertical dimensions, such effects primarily exert a minor quantitative damping on total transmission without altering the underlying physical mechanisms, resonant wavelength profiles, or logic contrast ratios.

3. Design, readout operation, and off-chip optical programming of the elliptical memory cell

This paper proposes a non-volatile, single-bit plasmonic memory based on GSST phase-change material integrated with a metal-insulator-metal (MIM) waveguide. Silver (Ag) is adopted as the metallic substrate owing to its significantly lower ohmic losses compared to gold (Au) within the near-infrared spectrum [62], while air and the GSST layer serve as the dielectric media. The physical schematic of the proposed architecture comprises two rounded-half-ring resonators and two rectangular cavity resonators coupled with input and output MIM bus waveguides. The optimized geometric dimensions of these structural parameters are summarized in Table 3. In this configuration, the rounded-half-ring resonators are specifically utilized for their capability to excite sharp Fano resonances, whereas the rectangular resonators are incorporated to generate high-quality factor (Q-factor) resonance peaks for efficient light guiding and confinement [63]. To accurately model the frequency-dependent dielectric function of silver, the empirical Drude formulation is employed. All numerical simulations and

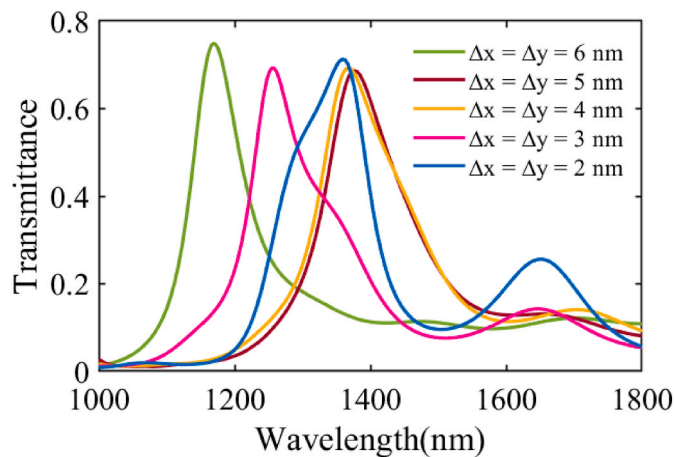


Fig. 2. 2D FDTD grid convergence study showing the transmission spectra for spatial mesh sizes from $\Delta x = \Delta y = 6$ nm to 2 nm.

Table 3

Optimized geometric dimensions of the structural parameters for the proposed plasmonic memory cell.

Parameter	R	L	d	w
Dimension (nm)	100	100	20	50

electromagnetic field distributions are evaluated using the two-dimensional Finite-Difference Time-Domain (2D-FDTD) method.

The schematic configuration of the non-volatile plasmonic memory featuring out-of-circuit programming capabilities is illustrated in Fig. 3. To execute state-writing operations within the proposed memory cell, an external control signal comprising distinct SET and RESET optical pulses is focused onto the structure using an out-of-circuit laser source, thereby encoding logical states '0' and '1'. In this framework, the amorphous phase of the GSST layer is defined as the initial state of the memory. Upon the application of the control signal's SET pulse, the localized temperature distribution induces a phase transition from amorphous to crystalline, modifying the complex refractive index of GSST and successfully writing logical state '0'. Conversely, applying the high-intensity RESET pulse alters the atomic arrangement back to the disordered amorphous phase, returning the material to its initial refractive index value and writing logical state '1'.

The logical state stored within the memory is subsequently retrieved by launching a low-power probe signal into the input port. The optical intensity of this probe signal is deliberately kept below the threshold required to induce any photothermal phase transitions or refractive index perturbations in the GSST layer. The readout mechanism relies on monitoring the transmission contrast between the amorphous and crystalline states. Fig. 4 depicts the transmission spectra of the proposed memory architecture under probe signal illumination for both structural phases of GSST. Notably, at the resonance wavelength of 1362 nm, the transmission efficiency reaches 73% in the amorphous state (state '1'), whereas it drops to approximately zero in the crystalline state (state '0').

In the design of plasmonic devices, precise optimization of the resonator dimensions is critical to determining the overall efficiency and performance of the memory architecture. To achieve the optimal geometric parameters for the proposed memory cell, a parametric sweep simulation (PSS) optimization workflow was systematically executed. Throughout this optimization process, all geometric parameters were kept constant except for one targeted variable.

The dimensions of the selected variable were iteratively swept using predefined step sizes, and the resulting spectral responses were compared. In this design, the transmission efficiency in both phase states and the corresponding resonance wavelength window served as the two primary figures of merit (FoMs) for identifying the optimal dimensions of each structural parameter.

By leveraging the PSS framework, three-dimensional (3D) transmission profiles of the proposed plasmonic memory structure were evaluated over a spectral wavelength range of 600 nm to 2000 nm as a function of the geometric variations, as illustrated in Fig. 5. Specifically, Fig. 5(a) depicts the 3D transmission contour map of the memory cell relative to variations in the parameter R. The dimensions of this parameter were swept from 50 nm to 150 nm with an incremental step size of 2 nm. It can be observed that increasing R not only induces a clear shifting of the resonance peaks toward longer wavelengths (redshift) but also causes a notable attenuation in the maximum transmission efficiency.

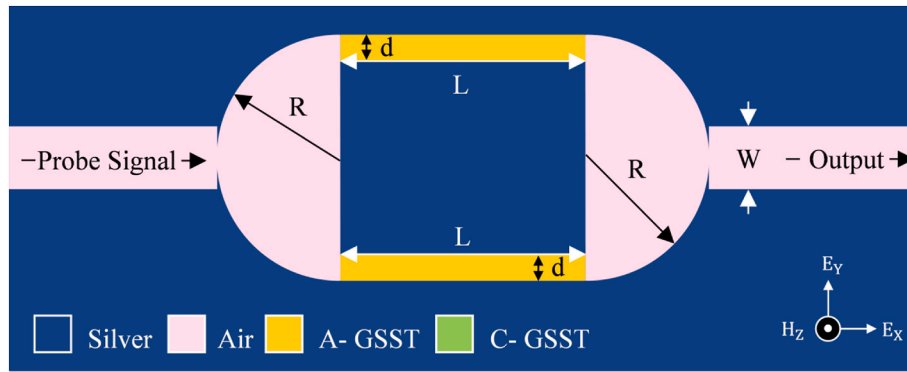


Fig. 3. Schematic configuration of the non-volatile, read-only plasmonic memory architecture based on GSST phase-change material integrated with an MIM bus waveguide.

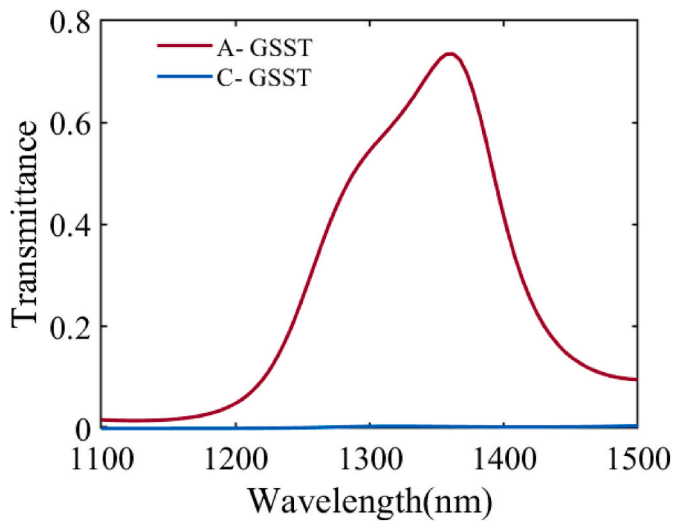


Fig. 4. Transmission spectra of the read-only plasmonic memory structure under the amorphous and crystalline phases of the GSST medium.

Furthermore, Fig. 5(b) displays the 3D transmission profile of the proposed memory as a function of the parameter d . The dimension of this parameter was varied within a range of 5 nm to 55 nm with a step size of 2 nm. The numerical results demonstrate that an increase in d triggers a shift in the resonance peaks toward shorter wavelengths (blueshift) alongside a reduction in transmission amplitude.

Lastly, the 3D transmission characteristics of the proposed architecture with respect to the parameter L are illustrated in Fig. 5(c). This parameter was swept from 50 nm to 110 nm using a 2 nm step size. As visualized in the contour plot, an increase in the dimension of L consistently translates to a systematic displacement of the resonance peaks toward longer operational wavelengths (redshift).

The selection of the operating wavelength at $\lambda = 1362$ nm—falling within the standard optical O-band window—is dictated by the localized Fano resonance mode of the double-ring structure. At this wavelength, the optical transmission in the crystalline phase (T_c) approaches zero, achieving a peak optical contrast of 73% and an extinction ratio of 23.24 dB. As demonstrated by the geometric sensitivity sweeps in Fig. 5, shifting the target resonance to 1550 nm leads to significant off-resonance attenuation, degrading the memory readout contrast. Thus, $\lambda = 1362$ nm provides the optimal trade-off for high-density, on-chip optical computing and neuromorphic architectures.

Based on the experimental study reported in [31], the amorphization process of the GSST material requires elevating the temperature to approximately 650°C to ensure the complete melting of the crystalline

lattice. Upon reducing the applied temperature to around 550°C, the melting phase is fully completed. By subsequently applying a rapid quenching profile, the disordered atomic structure is prevented from rearranging, thereby freezing the material into its amorphous state. Within the proposed memory architecture, the high-power, short-duration RESET pulse precisely replicates these thermal dynamics, successfully triggering the phase transition of the GSST layer into the amorphous state.

Conversely, during the crystallization annealing process of the GSST alloy, as documented in [32], the material temperature is elevated to a range of 180°C to 250°C. Subsequent slow, controlled cooling facilitates orderly atomic rearrangement, enabling the formation of the stable crystalline lattice.

The SET pulse, characterized by lower power and a longer pulse width relative to the RESET pulse, supplies the exact thermal energy required to reach this crystallization temperature window, thereby deterministically switching the material into its crystalline phase. Fig. 6 schematically illustrates the distinct profiles of these excitation pulses and the corresponding reversible phase transitions of the GSST medium.

To validate the readout capability of the proposed memory cell for logical state '1', the steady-state electric and magnetic field distributions have been rigorously analyzed. These field profiles provide critical insights into the excitation of surface plasmon resonances (SPRs) and the subsequent electromagnetic field transmission. Fig. 7(a) depicts the magnetic field ($|H|$) distribution of the structure during the logical state '1' readout operation. It can be observed that owing to the low optical absorption losses of GSST in its amorphous phase, maximum surface plasmon resonance excitation is successfully sustained within the rectangular cavity resonators. Furthermore, Fig. 7(b) displays the corresponding electric field ($|E|$) profile of the architecture. The plot clearly demonstrates strong field confinement within the GSST-infiltrated rectangular resonators, allowing the electromagnetic energy to efficiently couple into the output waveguide. In this amorphous state, the high-efficiency power transmission to the output waveguide is defined as logical state '1'.

Upon the application of the laser-driven control signal containing the SET pulse, the GSST layer transitions into its crystalline state, thereby encoding logical state '0' within the proposed memory cell. In its crystalline phase, GSST exhibits a high real refractive index and an elevated dielectric constant, the physical effects of which are clearly discernible in the steady-state electromagnetic field distributions. Fig. 8(a) illustrates the magnetic field ($|H|$) profile of the architecture, demonstrating that the excited surface plasmon polaritons (SPPs) are strongly confined and absorbed within the GSST-infiltrated rectangular cavity resonators. Furthermore, the corresponding electric field ($|E|$) distribution is depicted in Fig. 8(b). It can be observed that due to a severe phase mismatch induced by the crystalline PCM, the injected electric field is strongly attenuated, effectively preventing any optical power

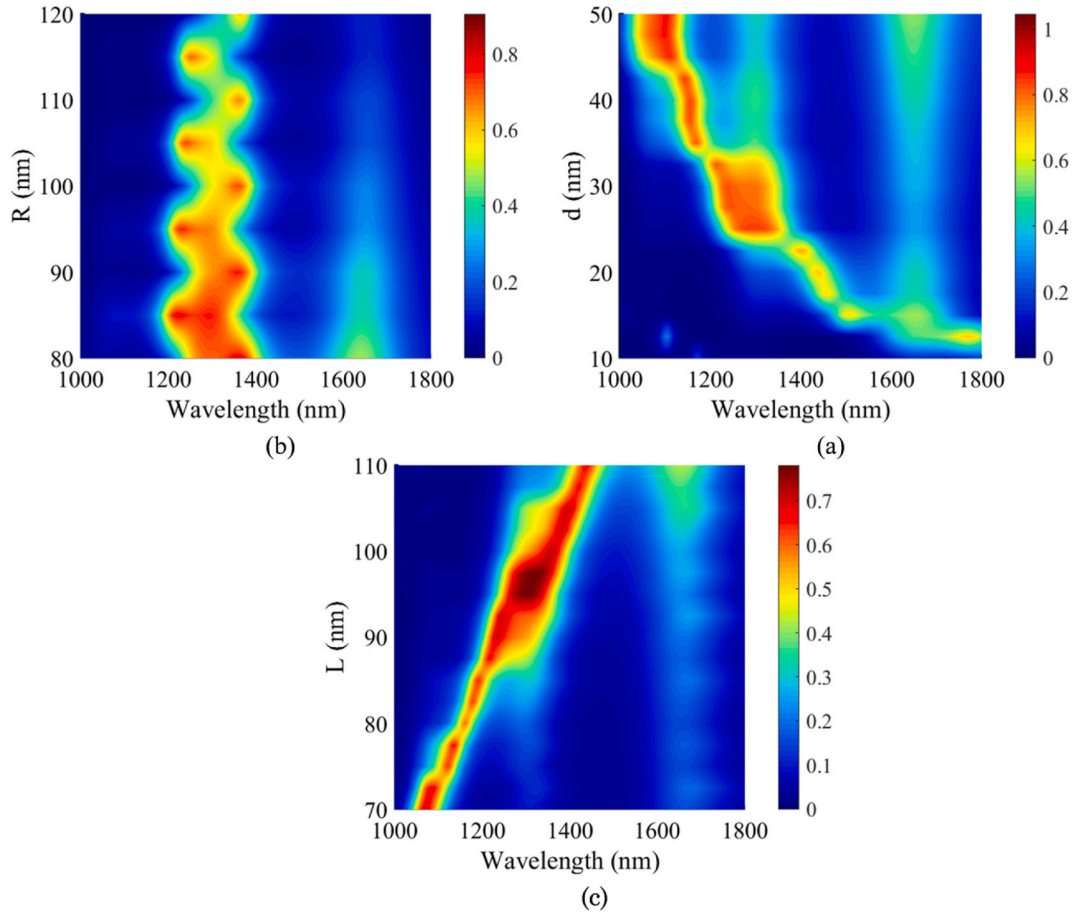


Fig. 5. Three-dimensional (3D) transmission profiles of the proposed memory architecture as a function of geometric variations in the parameters (a) R, (b) d, and (c) L.

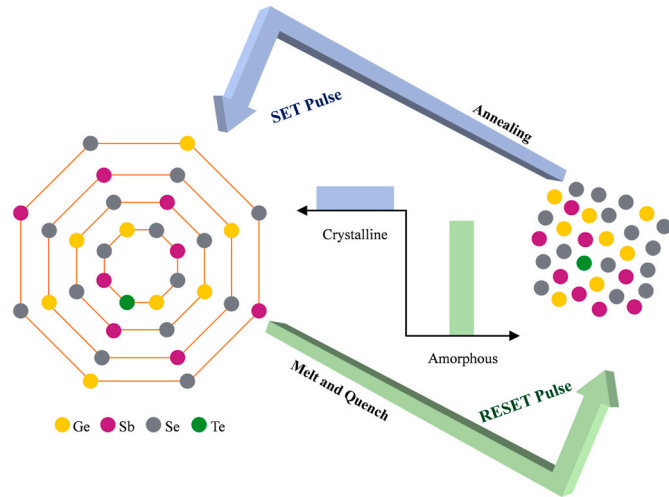


Fig. 6. Schematic representation of the reversible atomic lattice rearrangement and phase transitions of the GSST alloy under active SET and RESET pulse excitations.

propagation toward the output port.

$$\text{Contrast} = |T_{\text{am}} - T_{\text{cr}}| \times 100\% \quad (4)$$

$$\text{Extinction Ratio (dB)} = 10 \log_{10} \frac{T_{\text{am}}}{T_{\text{cr}}} \quad (5)$$

$$\text{Storage Density} \left(\frac{\text{bits}}{\mu\text{m}^2} \right) = \frac{\text{Total Number of Bits}}{\text{Total Area} (\mu\text{m}^2)} \quad (6)$$

$$\text{Insertion Loss (dB)} = -10 \log_{10} T \quad (7)$$

$$\text{FOM} = \frac{\text{ER (dB)}}{\text{IL (dB)}} \quad (8)$$

$$\text{FWHM} = \lambda_H - \lambda_L \quad (9)$$

$$Q = \frac{\lambda_0}{\text{FWHM}} \quad (10)$$

In the engineering of phase-change-based plasmonic memories, the capability of the architecture to robustly discriminate between distinct material states is a crucial figure of merit. At the resonance wavelength of 1362 nm, the proposed memory design delivers an optical contrast of 73% between the amorphous and crystalline states of the GSST medium. This parameter is quantitatively evaluated using Eq. (5), where T_{am} and T_{cr} denote the transmission efficiencies of the proposed structure in the amorphous (state '1') and crystalline (state '0') phases of the GSST material, respectively. The calculated optical contrast spectrum of the proposed plasmonic memory is presented in Fig. 9.

Another crucial parameter determining the reliability of an optical memory is its capability to robustly distinguish between the logical states '0' and '1'. The extinction ratio (ER) is quantitatively evaluated using Eq. (6). Fig. 10 illustrates the calculated extinction ratio spectrum of the proposed memory architecture. At the resonance wavelength of 1362 nm, the device delivers an outstanding ER of 23.24 dB, confirming excellent logical state discrimination.

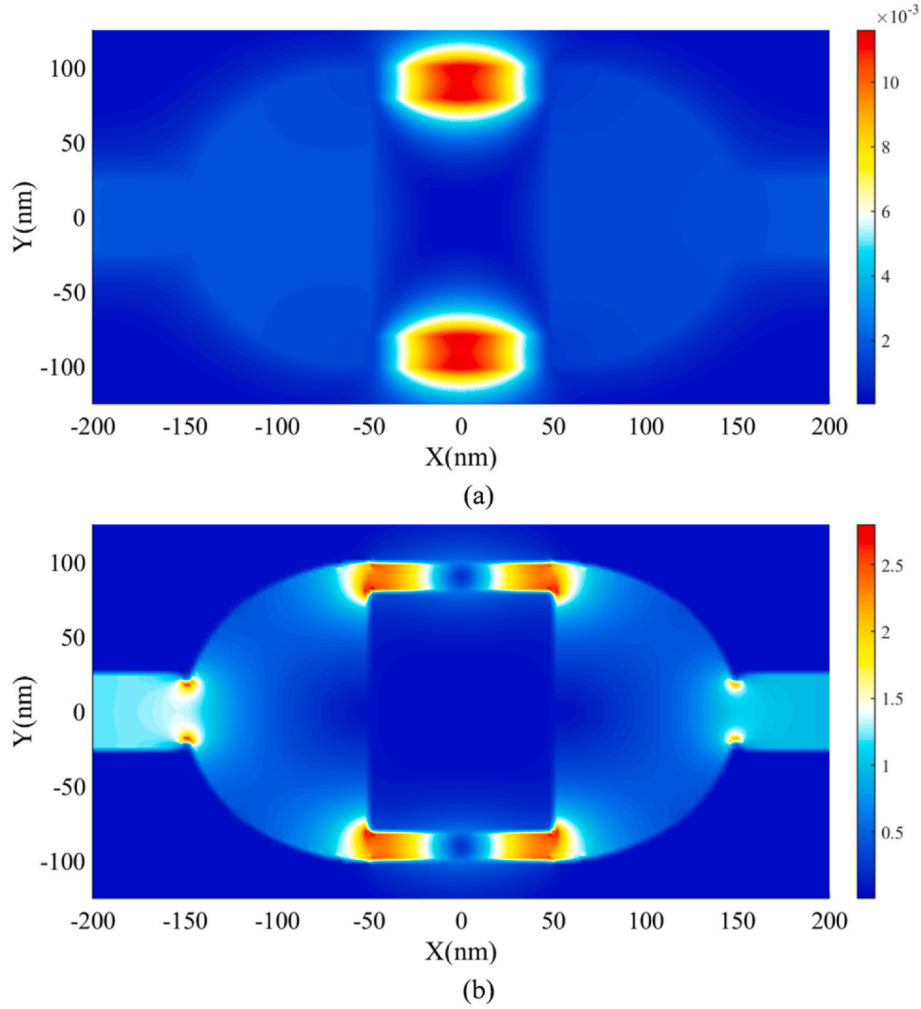


Fig. 7. Readout operation of logical state '1' at the resonance wavelength of 1362 nm analyzed via the steady-state field profiles of the (a) magnetic field ($|H|$) and (b) electric field ($|E|$).

In addition to the aforementioned performance metrics, the physical footprint and storage density are essential figures of merit when evaluating optical memories. The proposed memory cell features an ultra-compact footprint of $0.004 \mu\text{m}^2$, enabling an exceptionally high storage density of 250 bits/ μm^2 . The spatial storage density is computed via Eq. (7). Achieving such a high storage density in non-volatile plasmonic configurations represents a major milestone toward the scalability of photonic integrated circuits (PICs). Nevertheless, reliance on an out-of-circuit laser source for optical programming imposes a fundamental constraint on the practical deployment of this architecture. To address this limitation, an in-circuit programming capability is integrated into the proposed memory cell in the following section.

4. In-circuit optical programming via integrated 90°-Bent control waveguide and photothermal justification

Within photonic integrated circuits (PICs), deploying external laser beams to program plasmonic memories introduces severe operational risks due to the subwavelength, nanometric dimensions of the fabricated devices. Aligning a laser beam at the nanoscale demands extreme spatial precision; consequently, even minor environmental vibrations or alignment drift can cause irreversible photothermal damage to adjacent components, leading to catastrophic failures in the overall circuit functionality [64]. Therefore, incorporating an in-circuit programming capability into the proposed plasmonic memory architecture is of paramount importance.

Given the geometric constraints of the initial design, routing an on-chip control signal to perform in-circuit write and erase operations is highly challenging. This bottleneck primarily stems from the intricate waveguide-to-resonator coupling configuration at the central cavity region. The optimized structural parameters for this upgraded configuration are summarized in Table 4. By introducing an auxiliary MIM control waveguide with a nanofabricated width of 50 nm and a 90° sharp bend coupled to the primary input bus waveguide, the localized SET and RESET routing control signals can be efficiently delivered directly into the memory cell. Unlike the low-power probe signal, this control signal carries high optical power and field amplitude, supplying the thermal energy density required to induce phase transitions and modulate the refractive index of the GSST layer. The complete schematic of this in-circuit programmable architecture is illustrated in Fig. 11. Crucially, during the active write and erase cycles of the proposed memory, the probe signal is maintained in the OFF state to prevent signal interference.

In this design, the deployment of plasmonic MIM waveguides facilitates an intense confinement of the electromagnetic field within sub-wavelength dimensions. This strong field localization significantly enhances the localized absorption of optical energy within the active GSST region, thereby generating a highly localized photothermal heating profile. Consequently, this mechanism effectively minimizes the switching energy threshold, accelerates the device response time, and suppresses thermal cross-talk or dissipation to adjacent components of the circuit [65].

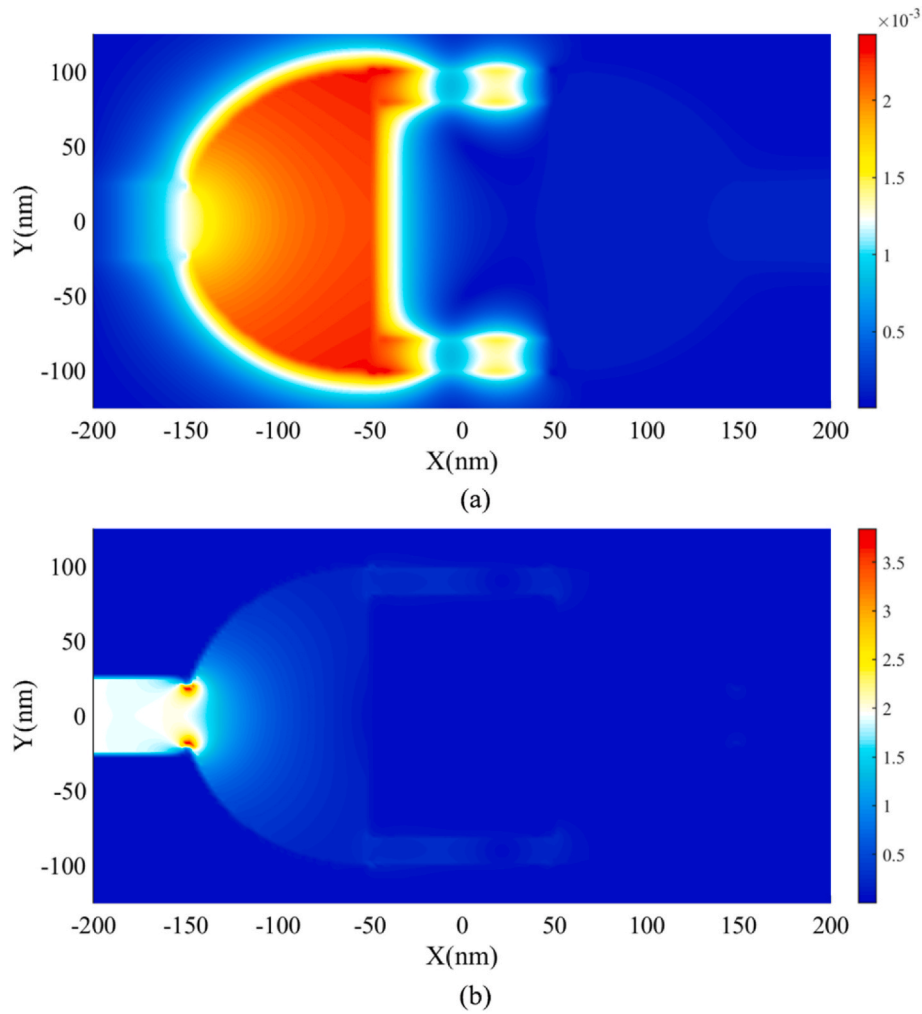


Fig. 8. Readout operation of logical state '0' at the resonance wavelength of 1362 nm analyzed via the steady-state field profiles of the (a) magnetic field ($|H|$) and (b) electric field ($|E|$).

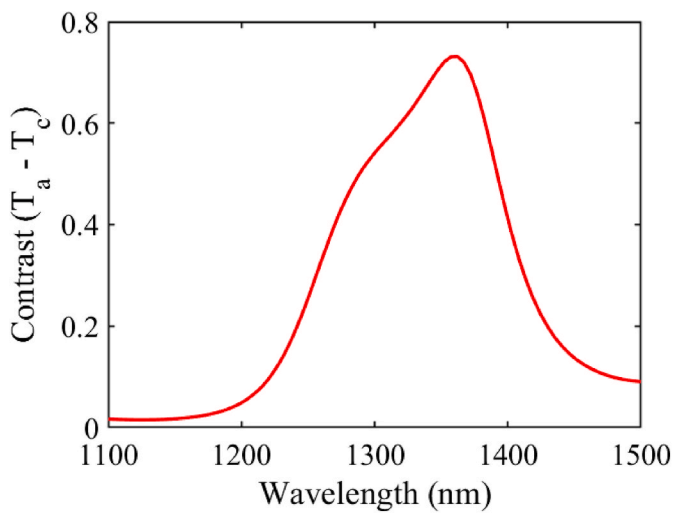


Fig. 9. Calculated optical contrast spectrum of the proposed plasmonic memory cell highlighting the peak performance at the operational resonance wavelength of 1362 nm.

To execute the in-circuit RESET (memory erase) operation and write State '1', a high-power optical control pulse is launched into the

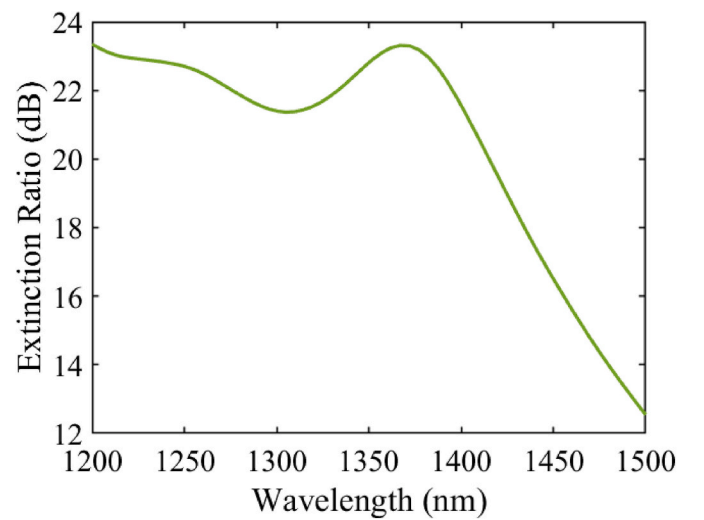


Fig. 10. Extinction ratio (ER) spectrum of the proposed plasmonic memory architecture evaluated at the 1362 nm resonance wavelength.

crystalline GSST cell, triggering amorphization. As shown in Fig. 12(a) and (b), the control pulse excites strong localized surface plasmon resonances within the GSST-infiltrated rectangular cavity resonators,

Table 4

Optimized geometric dimensions of the design parameters for the upgraded in-circuit programmable plasmonic memory cell.

Parameter	R1	R2	θ	R	L	d	w
Dimension (nm)	150	200	90°	100	100	20	50

modulating the complex refractive index of the phase-change material. The resulting electric field enhancement at the cavity corners and efficient power coupling into the output waveguide physically substantiate the successful execution of the in-circuit State '1' write cycle.

Conversely, launching the optical SET control pulse triggers the

amorphous-to-crystalline phase transition, encoding logical state '0'. As depicted in Fig. 13(a) and (b), the control pulse drives localized plasmonic resonance within the rectangular cavity resonators, delivering the required thermal energy for crystallization. Owing to the significantly higher extinction coefficient (k) and ohmic losses of crystalline GSST, the electric field is heavily attenuated within the cavity and fails to transmit into the output waveguide, physically confirming the state '0' write operation.

In addition to the static electric and magnetic field distributions, the physical validity of the optical write and erase operations within the proposed elliptical memory cell is comprehensively demonstrated through the transient transmission spectra illustrated in Fig. 14.

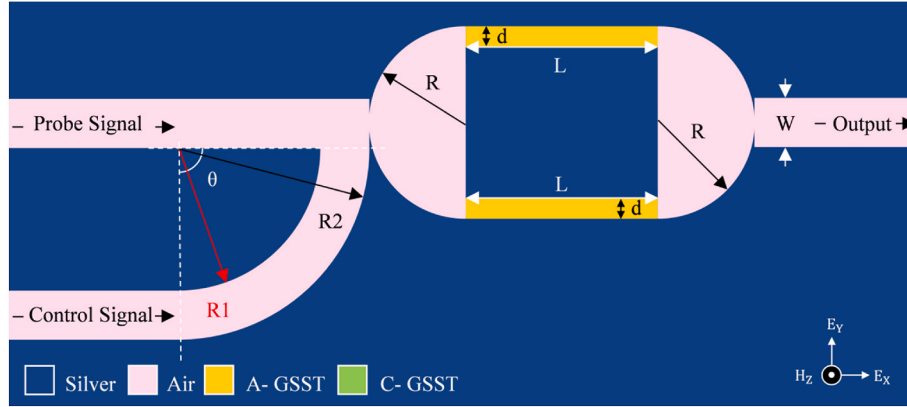


Fig. 11. Detailed physical schematic of the single-bit, non-volatile plasmonic memory cell featuring integrated co-designed channels for in-circuit programming.

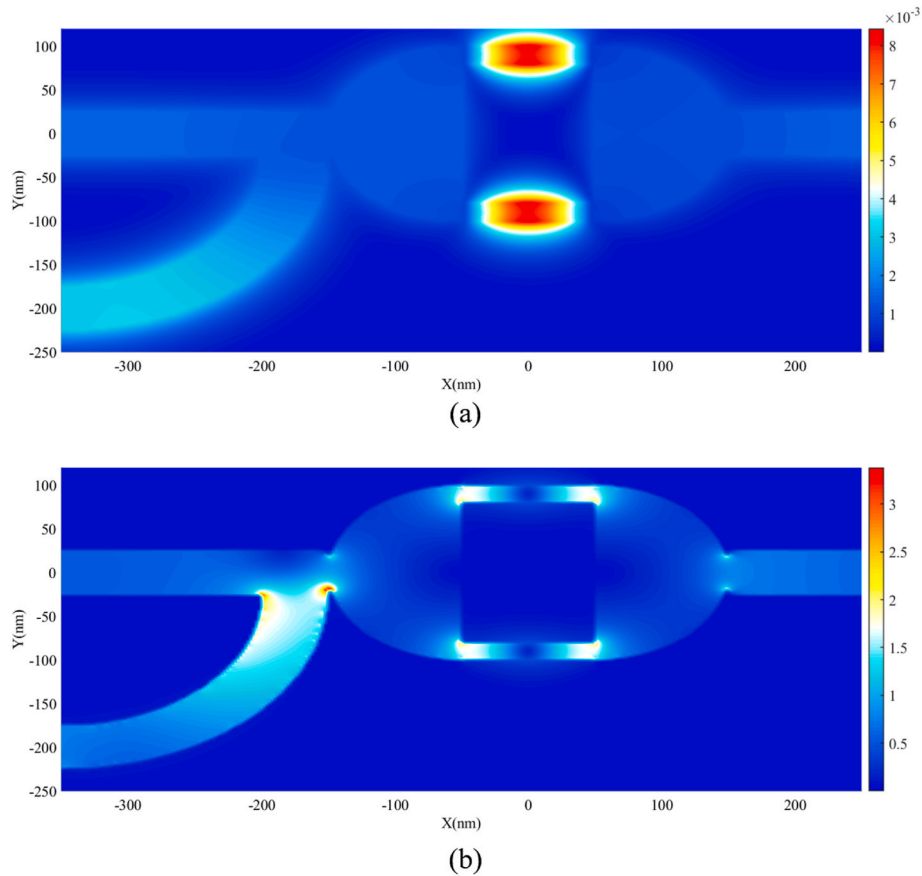


Fig. 12. Electromagnetic field profiles during the in-circuit logical state '1' writing and memory erasing operations at the 1362 nm resonance wavelength: (a) magnetic field ($|H|$) and (b) electric field ($|E|$).

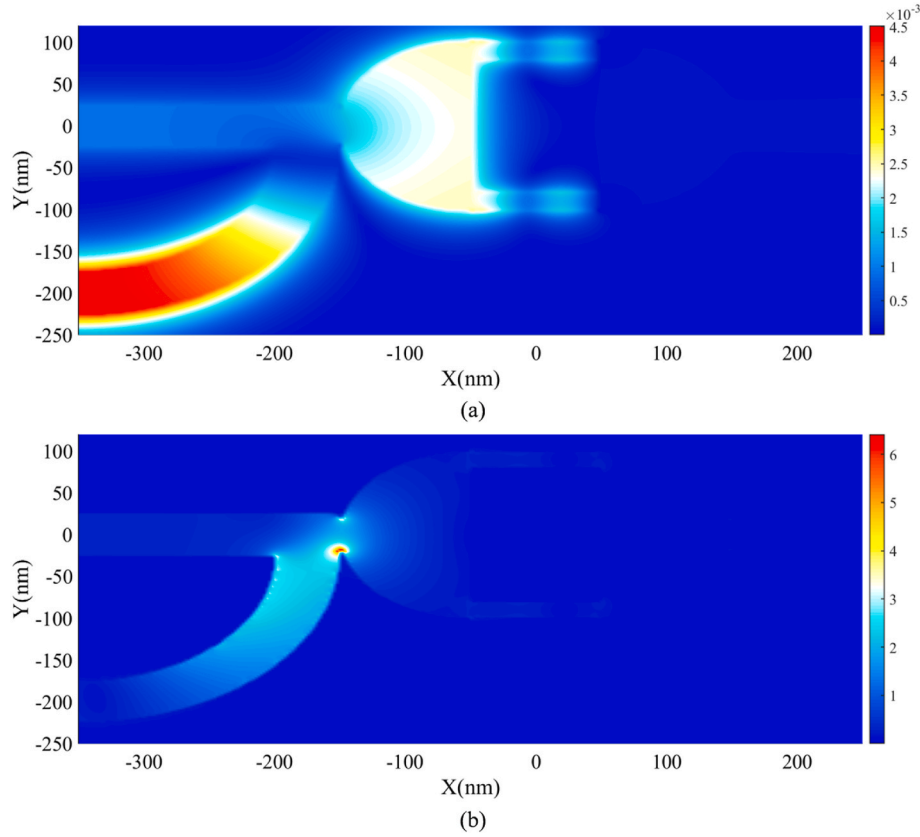


Fig. 13. Electromagnetic field profiles during the in-circuit logical state '0' writing operation at the 1362 nm resonance wavelength: (a) magnetic field ($|H|$) and (b) electric field ($|E|$).

Assuming the embedded GSST layer is initially in the crystalline phase (Logic State '0'), an optical control signal bearing a high-power RESET pulse is launched through the 90°-bent auxiliary MIM waveguide. Owing to the high optical absorption coefficient of crystalline GSST, a significant portion of the control pulse energy is absorbed, triggering localized thermal heating above the melting temperature (T_m) followed by rapid thermal quenching (the melt-and-quench process). This photothermal sequence transitions the material into the amorphous phase, corresponding to the writing operation of Logic State '1'. As observed in the transmission spectrum, the optical transmission

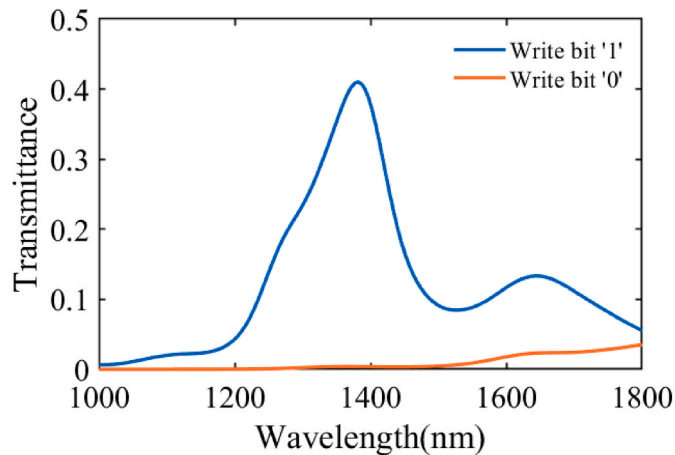


Fig. 14. Optical transmission spectra illustrating the write and read operations of the proposed plasmonic memory cell, showing the energy dissipation during RESET (crystallization-to-amorphization) and SET (amorphization-to-crystallization) pulses alongside the high-contrast readout states.

efficiency during this writing operation reaches 38%, indicating that approximately 62% of the applied control pulse energy is absorbed to drive the amorphization dynamics.

Conversely, during the readout operation of Logic State '1', the low-power optical probe signal operates well below the phase-change threshold, ensuring non-destructive state retrieval. Under this probe excitation, the transmission efficiency rises significantly to 73%. This 35% transmission differential between the high-power write pulse and the low-power read pulse physically validates the distinct operational regimes of state programming versus state interrogation.

Subsequently, when the device resides in the amorphous state (a-GSST), a longer-duration SET pulse is supplied via the auxiliary control waveguide. Although amorphous GSST exhibits lower intrinsic optical absorption, the extended temporal pulse width provides sustained thermal exposure required for atomic rearrangement and recrystallization (the annealing process). This transitions the memory cell back to the crystalline state, executing the write operation for Logic State '0' and dropping the transmission efficiency from 38% down to near-zero.

Physically, the optical dissipation profiles show that approximately 62% of the control signal energy is absorbed during the amorphization (melt-and-quench) phase, whereas 38% is utilized during the crystallization (annealing) phase. This close alignment between the numerical electromagnetic transmission characteristics and the photothermal phase-change dynamics confirms the robust functionality of the proposed plasmonic memory architecture.

Another crucial performance metric for evaluating the operational efficiency of a plasmonic memory is the signal attenuation sustained during the read and write cycles of both logical states. This parameter, quantified as insertion loss (IL), is mathematically evaluated via Eq. (8).

Fig. 15(a) depicts the insertion loss spectrum of the proposed architecture during the readout operation. Notably, at the resonance wavelength of 1362 nm, the insertion loss of the low-power probe signal

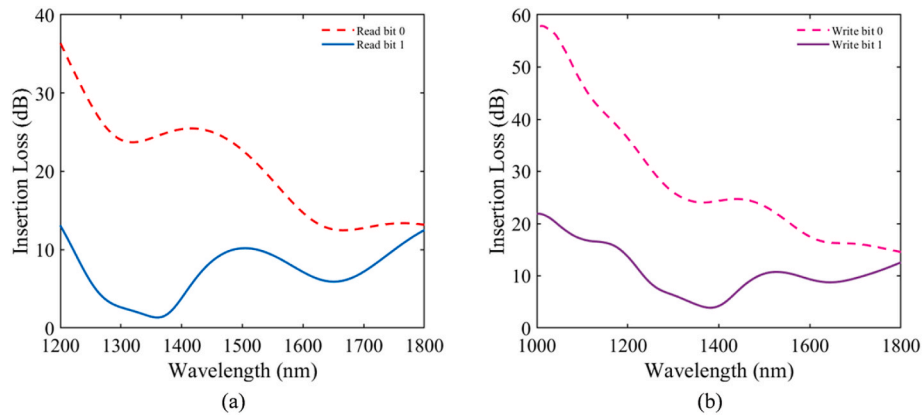


Fig. 15. Insertion loss (IL) spectra of the integrated memory cell at the 1362 nm resonance wavelength during the active (a) readout and (b) state-writing operations.

is calculated to be 3.7 dB for logical state '1' (amorphous state) and rises sharply to 18.18 dB for logical state '0' (crystalline state). Correspondingly, Fig. 15(b) displays the IL profiles during the state-writing operations. At the identical resonance wavelength of 1362 nm, the insertion loss of the control signal is measured at 4.15 dB during the state '1' write cycle and escalates to 24 dB during the state '0' write cycle.

Due to the significantly higher absorption characteristics intrinsic to the crystalline lattice of GSST, the insertion loss recorded during both the reading and writing of logical state '0' is substantially greater than that of logical state '1'. Concurrently, because the probe signal operates at a low power and field amplitude threshold, the signal attenuation during the logical state '0' read operation exhibits a more pronounced insertion loss compared to its counterpart during the state '0' write operation.

To establish a quantitative metric for benchmark comparison with previously reported state-of-the-art designs, the Figure of Merit (FoM) of the proposed elliptical memory cell is calculated using Equation (8). Defined as the ratio of the extinction ratio (ER) to the optical insertion loss during readout of Logic State '1' (IL_{read1}), the FoM is evaluated as 6.28, confirming the high optical transmission efficiency and superior

state contrast of this architecture.

Furthermore, to rigorously evaluate the spectral selectivity and resonance characteristics of the optical memory cell, the Full Width at Half Maximum (FWHM) and the Quality Factor (Q) are extracted based on Equation (9) and Equation (10), respectively. In these formulations, $\lambda_0 = 1362$ nm represents the central resonance wavelength, while $\lambda_H = 1405$ nm and λ_L denote the upper and lower half-power cutoff wavelengths, respectively. The inverse relationship between FWHM and Q-factor indicates that a narrower linewidth yields a higher quality factor, thereby enhancing wavelength-selective readout accuracy in integrated photonic circuits.

Table 5 provides a comprehensive comparative analysis of the critical performance figures of merit (FoMs) evaluated in this work against previously reported state-of-the-art optical and plasmonic memory architectures. The benchmarked parameters include optical contrast, extinction ratio (ER), physical footprint, and insertion loss (IL).

4.1. Photothermal and phase-transition feasibility framework

To rigorously justify the physical feasibility of the photothermal

Table 5

Performance comparison and benchmark parameters of the proposed in-circuit programmable plasmonic memory cell against state-of-the-art optical memory designs.

Ref	Year	Material	Simulation	λ (nm)	Contrast (%)	ER (dB)	IL (dB)	FOM	Rise Time (fs)	Fall Time (fs)	Q	Footprint (μm^2)
[66]	2021	Kerr	Plasmonic	1485	49	12.38	2.83	4.37	-	-	-	0.31
[64]	2022	GST	Plasmonic	1550	15.8	-	A:2.3C:1	-	-	-	-	0.0045
[48]	2025	Kerr	Plasmonic	830	68.6	-	-	-	-	-	-	1.2
[49]	2025	Kerr	Photonic Crystal	1550	66.6	-	-	-	-	-	-	30
[65]	2025	GST	Plasmonic	1598	67	-	-	-	-	-	-	0.031
[67]	2025	GST	Plasmonic	1178	74	-	-	-	-	-	-	0.14
[68]	2025	GST	Plasmonic	1550	47	4.1	1.2	3.41	-	-	-	-
[20]	2025	GSST	Photonic Crystal	1320	96.9	18	-	-	-	-	-	-
[53]	2026	GST	Photonic Crystal	1550	80	0.28	-49	-0.005	-	-	248	14.8
[69]	2026	GST	Plasmonic	1776	84	43.66	Read: Am:7.86 Cr:27.86 Write: Am:9.8 Cr:28	5.55	Am:71 Cr:3	Am:72 Cr:52	18.1	0.09
[70]	2026	GST	Plasmonic	1814	87	44.04	1-bit: Read: Am:0.60 Cr:45.60 2-bit: Read: Am:5.44 Cr:45.38 4-bit: Read: Am:9.12 Cr:52.21 8-bit: Read: Am:14.09 Cr:57.62	73/4	Am:62 Cr:24	Am:53 Cr:50	10.8	0.219
[71]	2026	GST	Plasmonic	1912	95	25	Read: Am:0.19, Cr:25.2	131.57	Am:82 Cr:2	Am:84 Cr:48	17.7	0.095
This Work		GSST	Plasmonic	1362	73	23.24	Read: Am:3.7, Cr:18.18 Write: Am:4.15 Cr:24	6.28	Am:31 Cr:2	Am:29 Cr:47	9.7	0.004

switching process within the proposed memory cell, a theoretical multiphysics framework is established. Although the primary numerical modeling in this work employs 2D-FDTD for electromagnetic characterization under pre-defined material states, the photothermal phase dynamics can be analytically described through coupled light-heat-phase relations.

The electromagnetic field response and wave propagation within the proposed structure are governed by Maxwell's curl equations in the time domain:

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad (11)$$

$$\nabla \times \mathbf{H} = \epsilon_0 \epsilon_r \frac{\partial \mathbf{E}}{\partial t} \quad (12)$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field vectors, μ is the vacuum permeability, ϵ_0 is the vacuum permittivity, and ϵ_r represents the relative complex permittivity of the medium. The volumetric power density Q_{optical} generated by optical absorption within the GSST cell is calculated directly from the FDTD-calculated electric field distribution:

$$Q_{\text{optical}}(x, y, z) = \frac{1}{2} \omega \epsilon_0 \text{Im}(\epsilon_r) |\mathbf{E}|^2 \quad (13)$$

where ω is the angular frequency and $\text{Im}(\epsilon_r)$ is the imaginary part of the GSST dielectric function. In a physical device implementation, this absorbed optical power acts as a heat source term in the Fourier heat conduction equation to determine the spatiotemporal temperature distribution $T(t, r)$:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T) + Q_{\text{optical}} \quad (14)$$

where ρ , C_p , and K denote the density, specific heat capacity, and thermal conductivity of GSST, respectively.

Based on experimental studies reported for GSST [31,32], the structural phase transition during crystallization (SET operation) is initiated by elevating the material temperature within the range of 180°C to 250°C [32]. The resulting temporal evolution of the crystalline volume fraction $X(t)$ ($0 \leq 1$) is described using the Johnson-Mehl-Avrami-Kolmogorov (JMAK) kinetics:

$$X(t) = 1 - \exp(-[K_{\text{JMAK}}(T) \cdot t]^n) \quad (15)$$

with the crystallization rate constant $k(T)$ defined by the Arrhenius activation relation:

$$K_{\text{JMAK}}(T) = \nu \exp\left(-\frac{E_a}{k_B T}\right) \quad (16)$$

where n is the Avrami exponent, E_a is the activation energy, ν is the pre-exponential factor, and k_B is the Boltzmann constant. Conversely, the amorphization process (RESET operation) requires elevating the local temperature to approximately 650°C to ensure complete melting of the crystalline lattice (fully melting near 550°C) [31], followed by rapid thermal quenching to freeze the material into its amorphous state.

Finally, the effective dielectric function of the evolving GSST layer is analytically updated using the Lorentz-Lorenz Effective Medium Approximation (EMA):

$$\frac{\epsilon_{\text{eff}}(t) - 1}{\epsilon_{\text{eff}}(t) + 0} = X(t) \left(\frac{\epsilon_c(t) - 1}{\epsilon_c(t) + 2} \right) + (1 - X(t)) \left(\frac{\epsilon_a - 1}{\epsilon_a + 2} \right) \quad (17)$$

Where ϵ_{eff} is the effective dielectric permittivity of the GSST layer, while ϵ_a and ϵ_c are the dielectric permittivities of the fully amorphous and fully crystalline states of GSST, respectively.

This theoretical framework confirms that the localized optical power density delivered via the auxiliary control channel provides sufficient power dissipation to physically induce the required thermal windows for

reversible phase transitions, thereby validating the photothermal switching mechanism supporting our FDTD optical findings.

Furthermore, because the optical transmission is directly controlled by the complex dielectric permittivity of the active medium, the well-documented capability of GSST to undergo fractional crystallization [12] allows for intermediate phase states ($0 < X(t) < 1$). Governed by the coupled photothermal relations and Avrami phase kinetics (Eqs. (14)–(17)), controlling the optical pulse power density Q_{optical} enables precise tuning of continuous phase fractions. Consequently, the proposed architecture inherently extends beyond binary logic, offering strong physical support for multi-level optical transmission and analog synaptic weight modulation in optical neuromorphic computing networks.

5. Potential application as a reconfigurable binary optical weighting element and memristive device

In photonic computing and artificial neural network (ANN) architectures, the primary function of a reconfigurable weighting node is to store and modulate optical signal amplitudes in a non-volatile and energy-efficient manner. In the proposed plasmonic memory design, an auxiliary MIM waveguide featuring a 90° sharp bend is integrated to route on-chip optical control signals. These localized optical SET and RESET pulses execute write and erase operations, enabling seamless reconfigurability of the non-volatile optical states.

Because the complex refractive index of the phase-change material GSST is fundamentally dictated by its crystalline-amorphous phase, the optical transmission characteristics of the device depend not only on the instantaneous probe signal, but also on the history of prior optical excitations. This history-dependent transmission behavior represents one of the defining physical features of optical memristive elements. Furthermore, the non-volatile nature of GSST ensures that once the phase transition is completed, the structural state remains stable without requiring continuous holding power, eliminating static energy dissipation. During the readout process, the low-power optical probe signal induces no phase transition, rendering the state interrogation non-destructive and highly stable.

At the resonance wavelength of 1362 nm, the proposed memory structure establishes two distinct optical weighting states. Specifically, the transmission efficiency reaches 73% in the amorphous state (a-GSST, State '1'), whereas it drops to near zero (0.055) upon transition to the crystalline state (c-GSST, State '0'). The achieved optical contrast of 73% alongside an extinction ratio of 23.24 dB demonstrates robust discrimination between discrete logic states. Evaluation of the insertion loss (IL) shows that the device exhibits readout loss values of 3.7 dB and 18.18 dB for States '1' and '0', respectively, while the writing cycle insertion losses are evaluated at 4.15 dB and 24 dB. These distinct attenuation profiles correspond physically to optical signal modulation mechanisms, effectively acting as hardware equivalents of potentiation and depression states within photonic neural network frameworks.

The proposed non-volatile plasmonic memory cell can be strategically deployed as a binary optical weighting element within a supervised learning framework for Spiking Neural Networks (SNNs), as schematically illustrated in Fig. 16. In this system architecture, co-integrated optical control signals execute dynamic weight selection for each node, routing the modulated optical spikes toward a post-synaptic photonic neuron. During active inference, incoming optical pulse trains pass through the weighted plasmonic memory cells, undergoing amplitude modulation before reach the neuron. The photonic neuron subsequently aggregates the total weighted optical energy and evaluates whether the integrated potential satisfies the threshold condition to fire an output spike. Within the automated control feedback loop, the network's generated output is cross-examined against ground-truth target values from the training dataset. If a classification error is detected, the learning algorithm initiates a weight update sequence by selectively applying optical SET and RESET pulses to modulate the phase state of the embedded GSST layer.

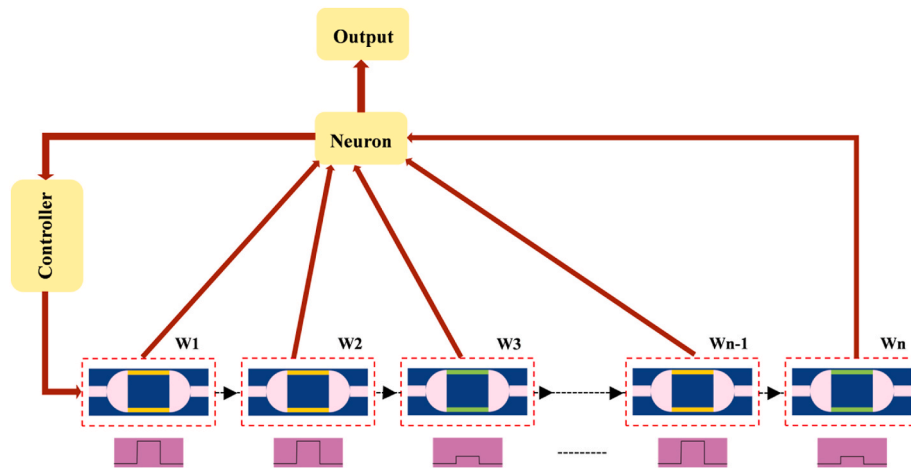


Fig. 16. Comprehensive operational schematic of the proposed plasmonic memory functioning as a reconfigurable binary optical weighting element within a supervised learning network training framework.

Combined with an ultra-compact footprint $0.004 \mu\text{m}^2$, a high spatial integration density of $250 \text{ bit}/\mu\text{m}^2$, and ultrafast femtosecond-scale readout dynamics, this non-volatile GSST-based plasmonic memory architecture holds significant potential as a high-density, low-power binary optical weighting element for next-generation photonic AI acceleration and integrated optical computing platforms.

6. Transient optical readout dynamics and temporal response analysis

While the phase transition write, erase, and reconfiguration kinetics of phase-change materials such as GSST are inherently governed by photothermal mechanisms operating on nanosecond or picosecond timescales, the operational speed of the memory unit during the readout phase is determined strictly by the optical propagation delay and transient electromagnetic response of the plasmonic cavity. To quantitatively evaluate the dynamic response during information retrieval, a

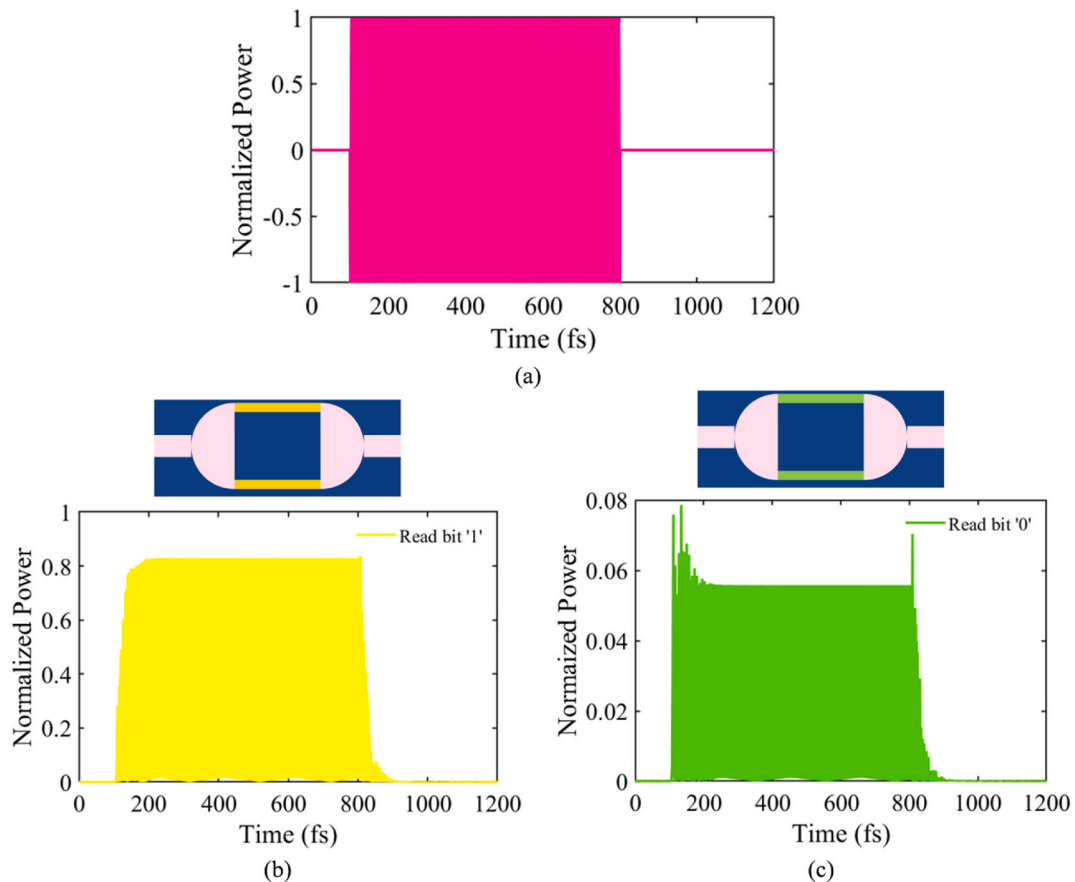


Fig. 17. Transient temporal response of the proposed memory architecture during the active readout operation: (a) normalized square-wave pulse excitation launched into the input bus waveguide, (b) transient power profile of logical state '1' (bit 1), and (c) transient power profile of logical state '0' (bit 0).

transient FDTD simulation was performed by injecting a temporal step-like square pulse into the input port of the waveguide. The input excitation signal for the temporal analysis is illustrated in Fig. 17(a). The excitation signal is a time-normalized square pulse in the femtosecond regime, where the power is zero during the first 100 fs, equals unity from 100 fs to 800 fs, and returns to zero from 800 fs to 1200 fs. This pulse with abrupt temporal transitions enables evaluating the response speed, propagation delay, power attenuation, and output stability of the proposed memory cell.

Applying this temporal excitation pulse to the input waveguide yields the transient readout responses for Logic State '1' and Logic State '0', as depicted in Fig. 17(b) and (c), respectively. In the amorphous state of GSST (Logic State '1'), shown in Fig. 17(b), the temporal response closely tracks the overall profile of the excitation pulse with a minimal propagation delay of $\tau_d = 7$ fs. The transient behavior observed along the rising edge in the interval of 107–200 fs originates from the energy coupling dynamics between the input MIM waveguide and the elliptical resonator. Between 200 fs and 800 fs, the normalized output power stabilizes at a quasi-steady-state value of $P_{out} \approx 0.83$. Following the excitation termination, the power decays exponentially in the 800–900 fs window, demonstrating a stable dynamic response. Based on the 0.83 quasi-steady-state baseline, the 10%–90% rise time (τ_{rise}) from 10% power (0.083 reached at 109 fs) to 90% power (0.747 reached at 140 fs) is evaluated as $\tau_{rise} = 31$ fs. The fall time (τ_{fall}) required for the power to decay from 90% (0.747 at 808 fs) to 10% (0.083 at 837 fs) is evaluated as $\tau_{fall} = 29$ fs.

Conversely, in the crystalline state of GSST (Logic State '0'), shown in Fig. 17(c), although the dynamic response profile aligns with the input excitation signal, high optical attenuation reduces the quasi-steady-state output power to $P_{out} \approx 0.055$. The substantial power contrast between

the two phases confirms reliable non-volatile readout functionality. For Logic State '0', the time required for the normalized output amplitude to transition from 10% power (0.0055 reached at 108 fs) to 90% power (0.0495 reached at 110 fs) yields a rise time of $\tau_{rise} = 2$ fs. The fall time from 90% power (0.0495 at 809 fs) to 10% power (0.0055 at 856 fs) is evaluated as $\tau_{fall} = 47$ fs. The sub-50-fs rise and fall times, alongside the 7 fs latency, demonstrate that while phase programming relies on photothermal kinetics, the state interrogation and optical readout operations of the proposed memory cell achieve ultra-fast femtosecond-scale dynamics, satisfying the high-speed requirements of integrated photonic logic.

7. Device fabrication feasibility and process flow integration

The architecture of the proposed non-volatile plasmonic memory is tailored for smooth compatibility with conventional Back-End-of-Line (BEOL) CMOS fabrication workflows. Fig. 18 outlines the step-by-step nanofabrication sequence.

- **Substrate Preparation and Buffer Isolation:** A high-quality 100 nm SiO_2 insulating layer is thermally grown on an RCA-cleaned silicon (Si) wafer via dry oxidation at 1000°C.
- **Metallization Stage:** A thin 5 nm titanium (Ti) adhesion film followed by a 100 nm bottom silver (Ag) layer is deposited using electron-beam physical vapor deposition (EB-PVD) under ultra-high vacuum conditions ($< 10^{-6}$ Torr) at a controlled deposition rate ($0.5 \text{ \AA/s}$) to achieve sub-nanometer surface smoothness ($\text{RMS} < 1 \text{ nm}$).
- **Nanopatterning and Dry Etching (Pattern Transfer and Cavity Definition):** A central 50 nm Ag film is coated with PMMA resist and patterned using high-precision electron-beam lithography (EBL)

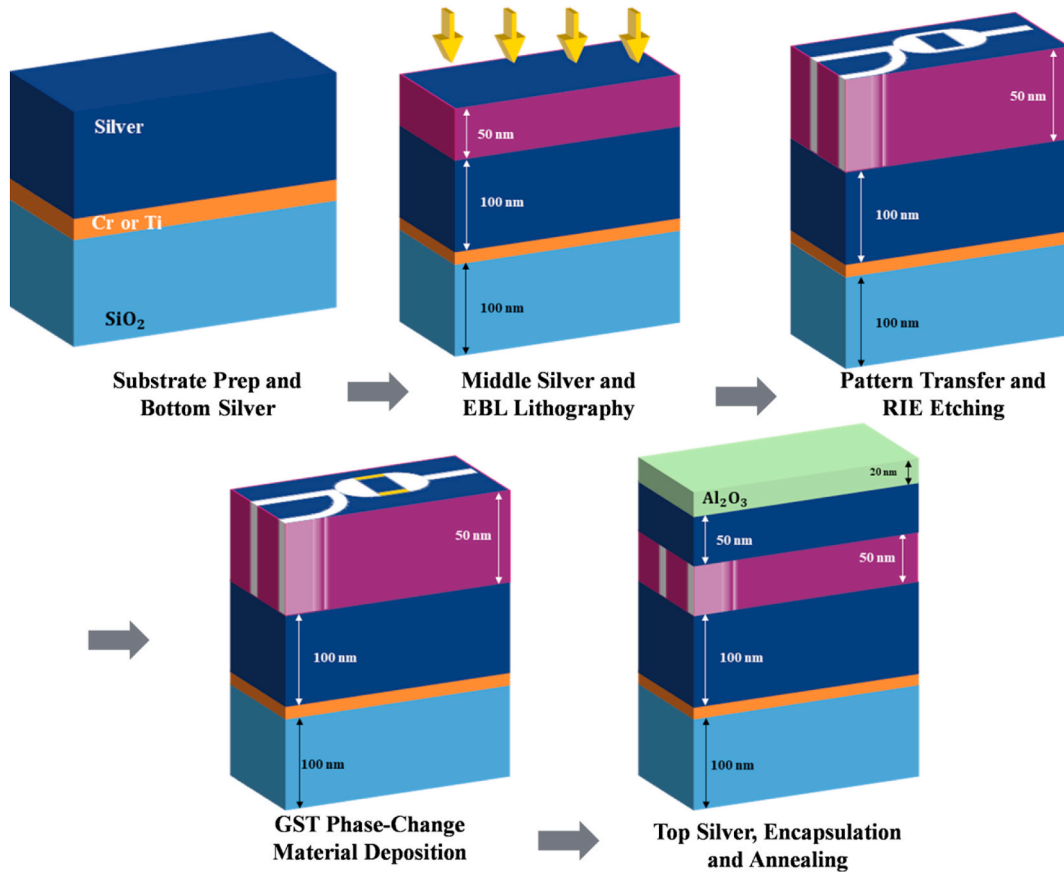


Fig. 18. Schematic and cross-sectional views of the five primary nanofabrication stages of the plasmonic memory architecture, highlighting substrate preparation, sequential silver depositions, EBL nanopatterning, selective GST deposition, and final protective encapsulation.

with an alignment accuracy below 10 nm. To transfer the pattern to the intermediate metal layer, Reactive Ion Etching (RIE) using a Cl_2/Ar gas mixture is implemented instead of low-precision wet chemical etching. Operating at an RF bias power of 50-100 W, a temperature of 10-20°C, and a chamber pressure of 5-10 mTorr, the high concentration of Argon plays a critical role in physically sputtering non-volatile reaction byproducts such as silver chloride

(AgCl). This anisotropic etching provides high-aspect-ratio vertical sidewalls for the plasmonic resonators, preventing metal particle redeposition on the cavity interior walls. At the completion of this step, the rectangular and semi-disk resonators along with the input/output waveguides are precisely defined [72]. The monolithic zero-gap ($g = 0$ nm) coupling design removes inter-component

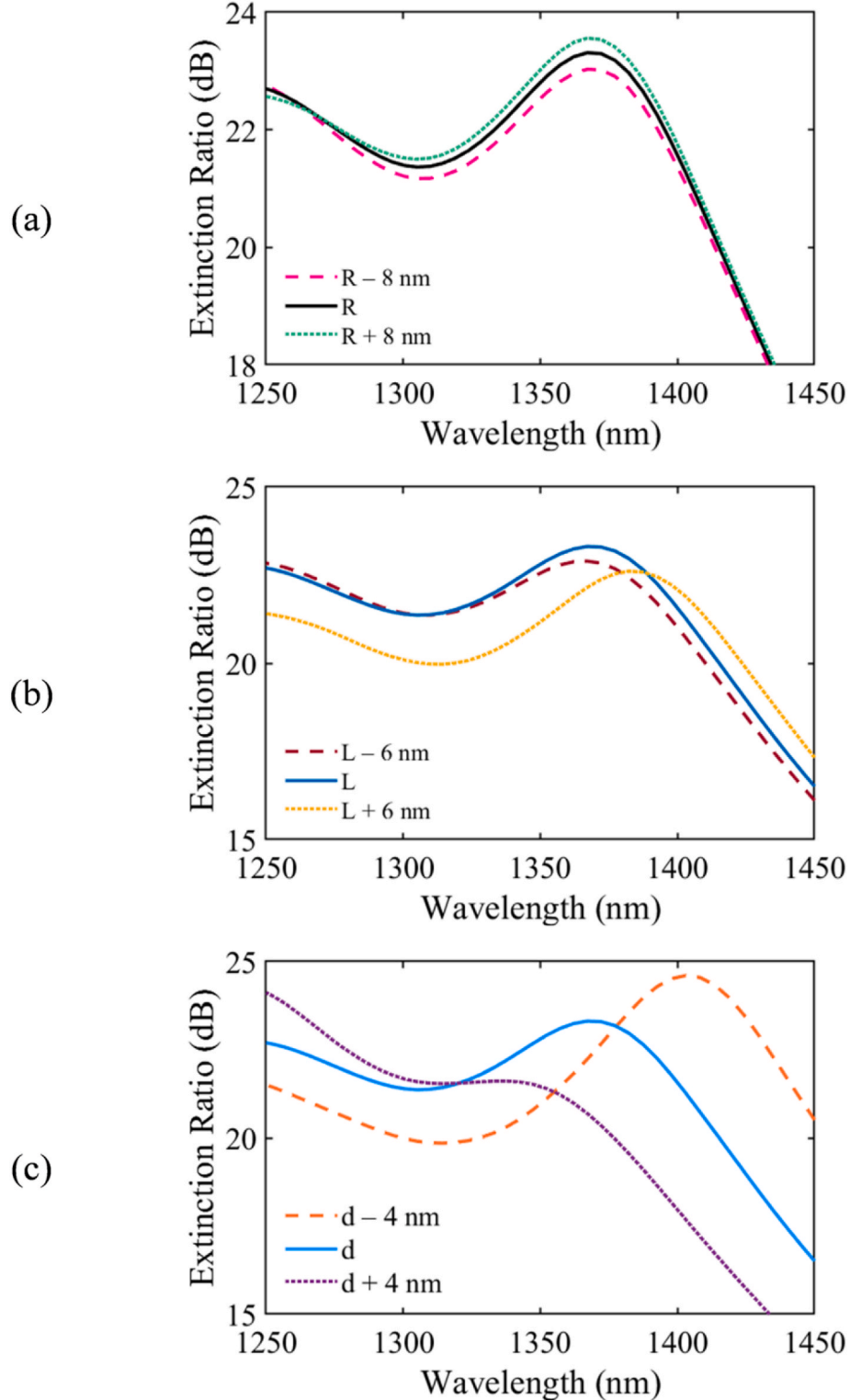


Fig. 19. Fabrication tolerance and sensitivity analysis of the proposed plasmonic memory cell based on the Extinction Ratio (ER) performance under dimensional deviations of: (a) cavity radius (R), (b) cavity length (L), and (c) coupling slot gap spacing (d).

overlay margins, simplifying patterning to a single lithographic cycle.

- **Active PCM Deposition:** Radio-frequency (RF) magnetron sputtering is employed to selectively deposit GSST into the core cavity, followed by a lift-off step combined with gentle Ar ion beam milling.
- **Encapsulation and Upper Metallization:** A 100 nm top Ag layer is deposited to finalize the MIM stack, after which a 20 nm conformal Al_2O_3 passivation coat is applied via Atomic Layer Deposition (ALD) at 100°C to mitigate silver oxidation.

Notably, the thermal budget across all post-substrate operations remains strictly below 200°C, well underneath the standard 400°C threshold allowed for BEOL CMOS processing. Furthermore, photo-thermal phase conversion (SET $\approx$ 180-250°C, RESET $\approx$ 550-650°C) takes place locally via nanosecond optical pulses within deep-subwavelength domains, where the encompassing Ag region functions as an efficient heat dissipater to suppress thermal interference between adjacent components.

To rigorously evaluate the operational robustness of the proposed plasmonic memory cell against realistic nanofabrication imperfections and lithographic tolerances, a systematic sensitivity analysis was conducted on the critical geometrical parameters, including the elliptical cavity radius (R), cavity length (L), and coupling slot gap (d). To prevent spatial discretization errors during 2D-FDTD modeling, all dimensional deviations were specified as integer multiples of the spatial grid resolution ($\Delta x = \Delta y = 2$ nm).

As illustrated in Fig. 19, the Extinction Ratio (ER) of the nominal structure is reported as 23.24 dB. For the cavity radius parameter (R), applying dimensional tolerances of $\Delta R = -8$ nm and $+8$ nm yields ER values of 23.96 dB and 23.49 dB, respectively (Fig. 19(a)). This minor fluctuation (~ 0.6 dB) confirms strong resilience against radius variations. Similarly, applying deviations of $\Delta L = -6$ nm and $+6$ nm to the cavity length (L) results in ER values of 22.88 dB and 21.88 dB, maintaining acceptable performance within a 1 dB degradation margin (Fig. 19(b)). Finally, tolerance testing of the slot spacing parameter (d) at $\Delta d = -4$ nm and $+4$ nm produces ER values of 21.83 dB and 20.99 dB (Fig. 19(c)). Although the gap distance d exhibits the highest relative impact on performance due to strong localized evanescent field coupling, the memory cell consistently retains a high extinction ratio exceeding 20.99 dB, verifying high immunity against typical electron-beam lithography (EBL) and etching variations.

8. Conclusion

In this study, an ultra-compact, non-volatile plasmonic memory cell based on the low-loss chalcogenide phase-change material platform (GSST) and a metal-insulator-metal (MIM) waveguide cavity has been numerically evaluated. By addressing the photothermal and spatial alignment challenges associated with off-chip laser delivery on nanometric photonic integrated circuits (PICs), an auxiliary integrated 90°-bent control waveguide configuration was incorporated to validate the physical feasibility of in-circuit optical pulse routing during writing and erasing operations. Numerical FDTD modeling demonstrates that at the operating resonance wavelength of $\lambda = 1362$ nm, the proposed architecture yields an optical readout contrast of 73% between the amorphous (a-GSST) and crystalline (c-GSST) states, alongside a maximum extinction ratio of 23.24 dB. Transient time-domain simulations confirm that low-power optical readout discrimination is governed by sub-picosecond wave propagation latency (propagation delay $\tau_d = 7$ fs), distinctly decoupled from the longer photothermal phase-transition kinetics of the chalcogenide alloy.

Furthermore, by exploiting these distinct insertion loss levels during state readout and writing, the cell demonstrates strong potential as a reconfigurable binary optical weighting element for photonic neuromorphic processing, where the low-attenuation state ('1') and high-attenuation state ('0') physically model discrete synaptic weighting

states. This functionality bridges the gap between numerical design and experimental viability by providing a concrete mechanism for physical signal attenuation mapping in optical neural networks. While the present numerical study specifically demonstrates discrete two-state binary optical switching and binary weighting ('0' and '1'), the underlying physical mechanism serves as a robust architectural foundation for future experimental realizations. Crucially, as well-documented in reported literature on phase-change materials, GSST possesses the intrinsic capacity for fractional phase crystallization and multi-level optical tuning via tailored optical pulse sequences. Thus, the binary framework established in this work directly provides a verified electromagnetic baseline and practical architectural roadmap toward future multi-level weight tuning and analog neuromorphic processors. With a subwavelength physical footprint of $0.004 \mu\text{m}^2$ (enabling a theoretical integration density of up to $(250 \text{ bits}/\mu\text{m}^2)$), this numerical framework offers critical design rules and a reliable baseline for experimental prototyping of integrated non-volatile photonic memories.

CRediT authorship contribution statement

Melina Kehtarmansh: Writing – original draft, Software, Investigation, Data curation. **Parviz Keshavarzi:** Validation, Supervision, Project administration. **Mohammad Danaie:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Availability of data and information

All the data, designs, and relevant information associated with this paper are accessible and will be shared upon a reasonable request to the corresponding author.

Ethical approval statement

The authors confirm that the submitted paper has not been submitted to any other journal and that this version is original and has not been published elsewhere. Additionally, all listed authors affirm the integrity of the study, data, information, and analyses, ensuring that no manipulations have been made. Furthermore, we confirm that no other individuals meet the authorship criteria for this paper beyond those listed as authors.

Declarations

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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