

Non-volatile Tuning of Cryogenic Silicon Photonic Micro-ring Modulators - Supplementary Information

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Supplementary Note 1: PCM Post-processing

We monolithically integrated GST with the AMF silicon photonics chip using a few post-processing steps at the die level ($3\text{ mm} \times 3\text{ mm}$) in the Washington Nanofabrication Facility (WNF). This post-processing method is easily scalable, as it involves a minimal number of steps and uses coarse-resolution lithography. We began by mounting the die onto a large Si carrier chip for ease of handling, using AZ10XT, and then spin-coated it with AZ1512 photoresist. The die was patterned using the Heidelberg DWL66+ laser writer to block metal pads and grating couplers during GST deposition. After developing the patterned chip in AZ MIF developer, we sputtered a 12.5 nm thick GST film, followed by a 60 nm thick Al_2O_3 layer using atomic layer deposition (ALD) at 323 K, to prevent crystallization of GST, which occurs around 423 K. Lift-off was performed as the final step to remove residual photoresist. Fig. S1a shows the complete chip layout before post-processing. The blanket deposition of GST makes this technique suitable for integration with large-scale programmable circuits. In our layout design, multiple device batches were placed in a grid pattern, as shown in Fig. S1b, which displays only the post-processed section of the chip. Fig. S1d provides a microscope image of a single PIN micro-heater device with an 8 μm -long oxide window opening.

Supplementary Note 2: Endurance Test of GST at Cryogenic Temperatures

We conducted GST endurance measurements to evaluate its lifespan at cryogenic temperatures. For these measurements, we used an MRM variant with a 4 μm oxide window opening and a

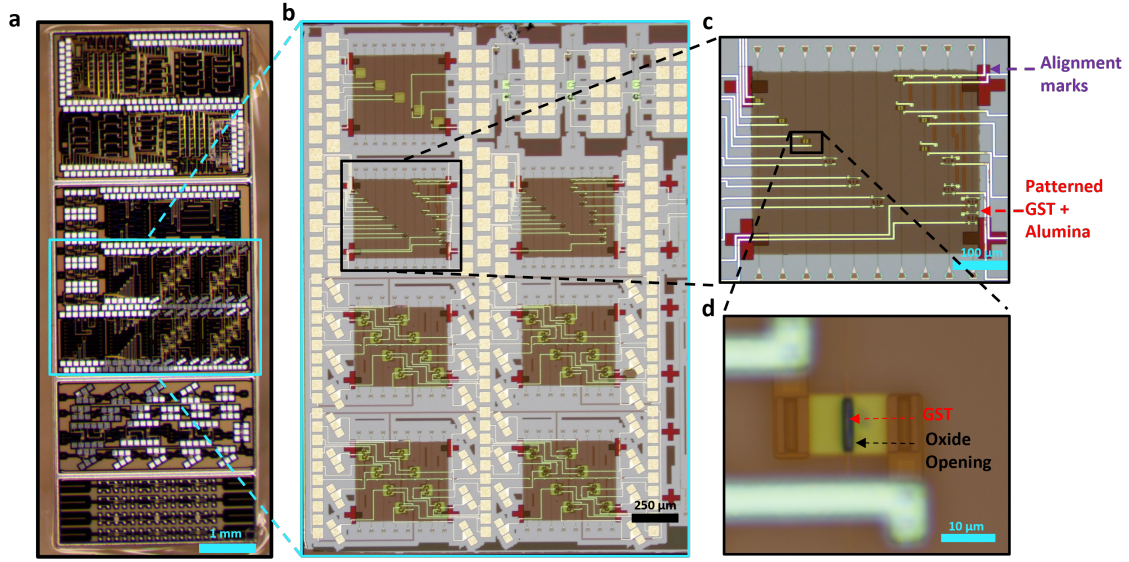


Figure S1: (a) Microscope image of the unprocessed chip, (b) microscope image of post-processed section of the chip, (c) microscope image of a single post-processed section, and (d) the PCM micro-heater with oxide opening for GST deposition.

12.5 nm GST thin film deposited in the opening. A resonance shift of 0.15 nm was observed when switching the GST states. To perform the endurance test, we first tuned the laser wavelength close to the device's resonance wavelength with the GST in its amorphous state. Next, we recorded the transmission contrast at that laser wavelength across several GST switching events. Although each switching event occurs as quickly as $\sim 100 \mu\text{s}$, we introduced a 5 s delay between events to account for instrument delays and to ensure the device had more than sufficient time to cool to 4 K. Fig. S3 shows the cryogenic test setup pictured along with the post-processed chip, used for all experiments in the main article and the supplementary.

We recorded 1500 switching events and observed a 10 dB variation in the a-GST transmission (Fig. S2). Analysis of the transmission plots showed that, after 1500 switching events, the extent of switching behavior diminished, with a reduction in Q-factor indicating additional loss in the device. We attribute these losses to potential GST degradation and reflow issues. Furthermore, it is likely that, over time, different pulse conditions may be necessary to achieve consistent switching; maintaining constant pulse conditions throughout the endurance test may have led to inadequate switching behavior. GST lifespan may be enhanced by using patterned GST deposition only on the waveguide, followed by full encapsulation with an alumina layer to prevent any melted GST from re-flowing. Future studies can provide a deeper understanding of GST endurance by further characterizing these phenomena and de-embedding the various loss mechanisms contributing to this behavior.

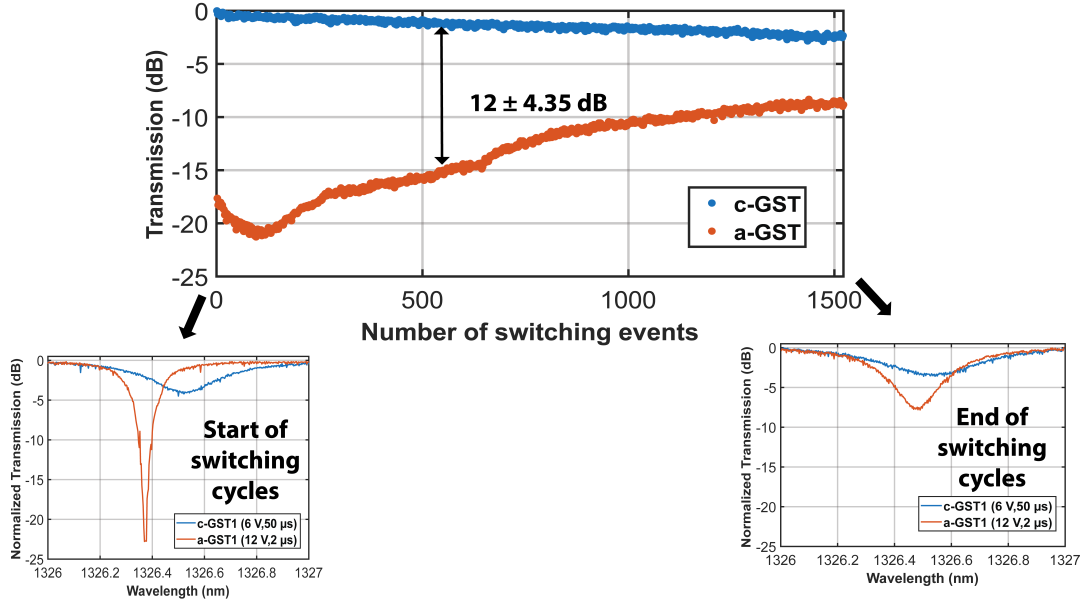


Figure S2: The endurance measurement results of GST-integrated MRM at 4K for 1500 switching events with normalized recorded transmission shown at the start and end of the measurement.

Supplementary Note 3: Comparison between cryogenic and room-temperature switching of GST

We further characterize the tuning in GST films to draw comparisons between their room temperature (RT) and cryogenic (4 K) performance. For an MRM variant with a 10 nm thick GST film deposited in a 4 μm opening, we observed that the resonance shifts by 50 pm at RT (Fig. S4a), when the GST is switched from amorphous to crystalline state. At 4 K for the same device, we observe a resonance shift of 30 pm (Fig. S4b), showing a close match with the RT tuning range. However, it is difficult to directly compare the two shifts, as the extent of switching in each case is not clearly known, and the refractive index values of the materials will also differ at the two temperatures. Based on our estimations, the refractive index contrast between amorphous and crystalline GST comes to $\Delta n_{\text{GST}} = 1.14$ at 4 K which is smaller than $\Delta n_{\text{GST}} = 2$ at RT. At 4 K, GST was amorphized by applying a 10 V pulse for 2 μs and crystallized by applying a 5 V pulse for 50 μs with a 36 μs falling edge. Additionally, at RT, the applied pulse for amorphization operation is 10 V and 500 ns, and for crystallization operation, it is 4.75 V and 50 μs with a 30 μs falling edge. The cryogenic environment facilitates rapid cooling of melted GST and prevents recrystallization during the amorphization process, allowing for much longer pulse durations compared to RT.

As we have previously noted, the cryogenic environment in fact enhances the amorphization process and enables switching of much thicker GST films. To perform a comparison of switching behavior in thicker GST films, we used an MRM variant with a 4 μm oxide window opening and a 20 nm GST film deposited in the opening. During RT measurements, we did not observe repeatable

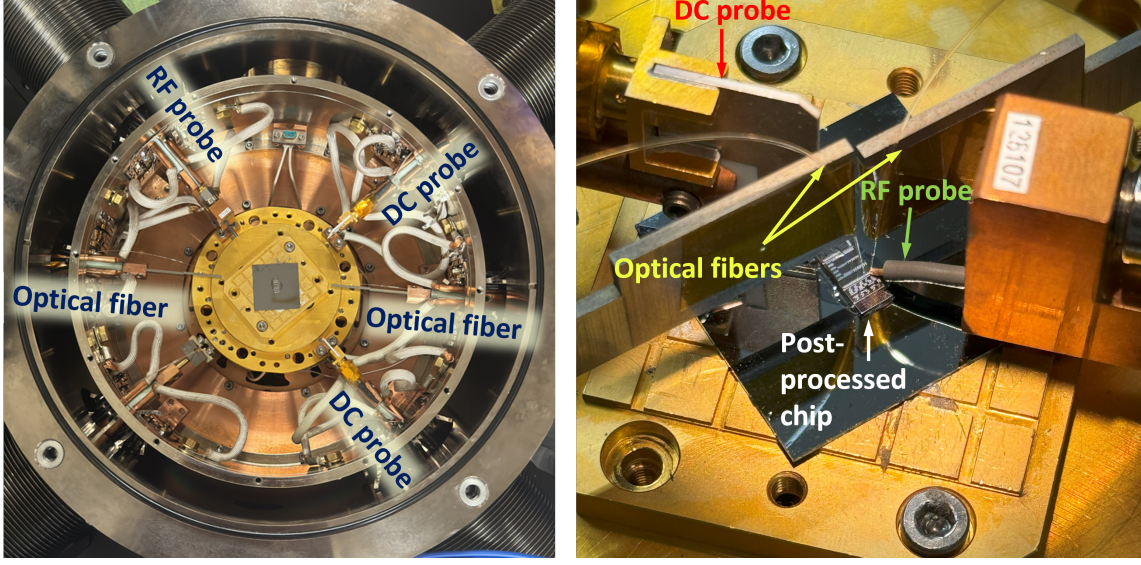


Figure S3: Cryogenic measurement test setup showing the post-processed chip, optical fibers, DC and RF probes.

switching and found it challenging to re-amorphize the 20 nm thick GST film, even with very long pulse durations, as shown in Fig. S4c. This behavior may be attributed to insufficient and non-uniform heating of the entire GST volume over short amorphization timescales, potentially leading to switching issues or material degradation. We repeated the switching measurement at 4 K on a different device. At 4 K, we observed precise and repeatable switching behavior (Fig. S4d) in the 20 nm thick GST film, with a resonance shift of 0.2 nm. Here, GST was amorphized by applying a 12 V pulse for 1 μ s and crystallized by applying a 5 V pulse for 50 μ s. This confirms that longer amorphization pulse durations in a cryogenic environment can provide effective control over thicker PCM films, enabling precise and repeatable switching operations.

Supplementary Note 4: Comparison of Cryogenic Photonic Micro-ring Modulators

In our work, cryogenic photonic MRM operation is based on the free-carrier plasma dispersion effect, and the cross-section of the MRM PN junction can be seen in Fig. S6d. To further characterize our modulator performance, we have measured the IL and ER as a function of the modulation voltage while maintaining the received optical power (ROP) at -7 dBm. These measurements were conducted at 4 K temperature as well as RT for comparison. We observe a slight drop in the IL with the rise in modulation voltage from 0.8 V to 3.5 V (Fig. S5a). We observe at RT that IL goes from 4.96 dB to 4.69 dB, whereas at 4 K it goes from 4.38 dB to 3.98 dB with the rise in modulation voltage. The ER shows a more noticable rise with the increase in modulation voltage as seen in Fig. S5b, going from 2.2 dB (1 V) to 3.98 dB (3.5 V) in the RT measurements and from 1.8 dB to 3.52 dB

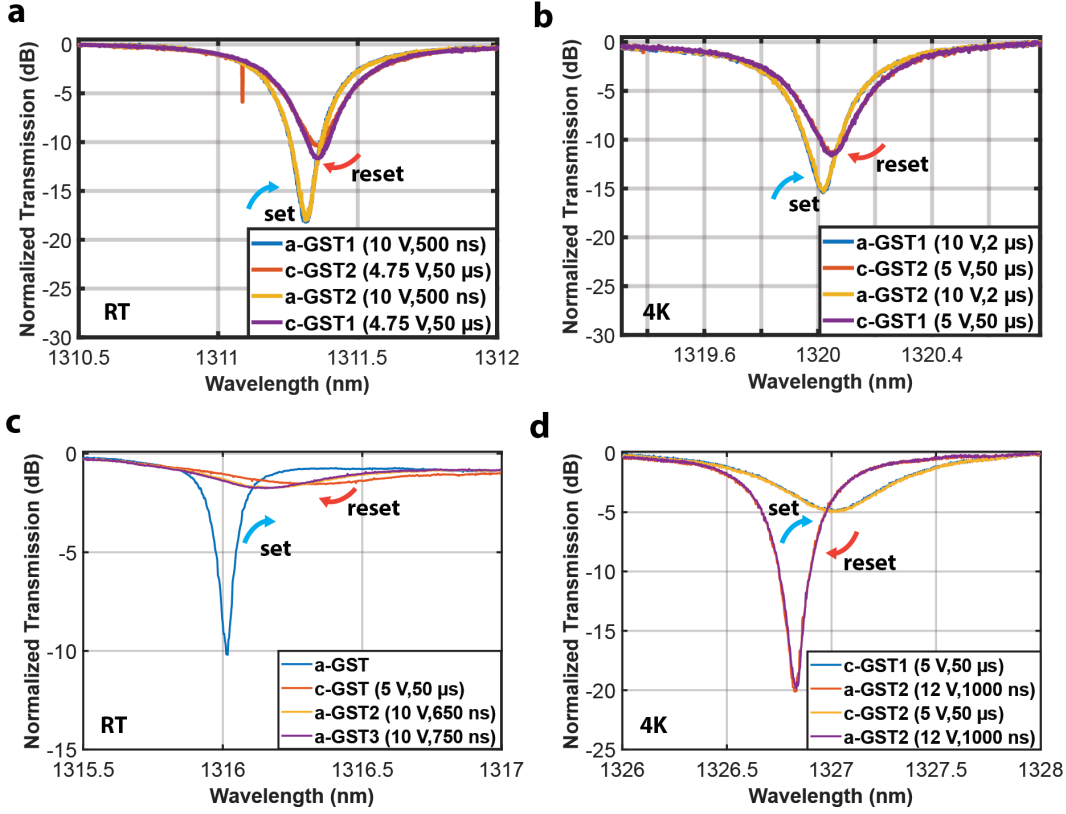


Figure S4: (a) Normalized transmission plot for switching in 10 nm thick GST at RT, (b) Normalized transmission plot for switching in 10 nm thick GST at 4K, (c) Normalized transmission plot demonstrating one-time switching of 20 nm thick GST at RT, (d) Normalized transmission plot demonstrating two switching cycles of 20 nm thick GST at 4K.

under the same conditions at 4 K. We also measured the Bit Error Rate (BER), with the ROP of -7 dBm at the PD, as a function of modulation voltage both at 4 K and RT as shown in Fig. S5c. While the acceptable BER depends on system design and application requirements, we achieve a BER as low as 10^{-8} at 4 K and a very low BER of 5×10^{-12} at RT. These values support error-free operation and also satisfy the forward error correction (FEC) threshold if needed.

We have compared various resonator-based cryogenic photonic modulators in Table. S1. There are several recent modulation methods demonstrated at cryogenic temperatures operating at as high as 20 Gb/s but so far none of these modulators have had an independent phase-shifting capability for tuning the resonance wavelength. Magneto-optical effects have been reported recently [23] operating at 2 Gb/s, but they require large electrical currents in the order of 100 mA range for modulation of resonance with less than 50 pm shift. Hence, while this effect is stronger than thermo-optics at 4 K (by about $5\times$), it still cannot provide large wavelength ranges for resonance tuning. Additionally, the integration of required materials for magneto-optics with foundry silicon photonics is extremely challenging.

The Pockels effect in BaTiO₃ [7] has also been used in cryogenic devices for modulation at

20 Gb/s, but tuning a device using this method over sufficiently large ranges requires applying extremely large voltages of ~ 100 V (resonance shift of 0.645 nm would require 150 V). Similarly, there have been other demonstrations of high-speed energy-efficient cryogenic photonic modulators in Silicon including micro-ring modulators (MRM) [11], micro-disk modulators [10], and InP-on-Si quantum well MRM [24]. The InP-based modulator demonstrates a really promising cryogenic modulation capabilities with record-low modulation voltage and high energy efficiency. However, it remains unclear how this approach could be efficiently extended to WDM links. Nonetheless, all of the above devices lack a sufficiently strong effect for resonance tuning. In the Si-spoked MRM [11], the free-carrier plasma-based tuning range of 0.8 nm can be utilized for resonance tuning across small wavelength spans. However, it still lacks two independent control knobs for high-speed operation and resonance tuning, which is a limiting factor. Moreover, PCMs can be integrated with resonant modulators employing other electro-optic modulation schemes. We believe that the promising cryogenic modulators discussed above could greatly benefit from PCM integration, as it provides a practical tuning mechanism for implementing WDM, similar to our approach of incorporating PCM into conventional MRMs.

There have also been notable demonstrations of non-resonator-based modulators with footprints of $10\times$ to $100\times$ larger than resonant modulators. Mach-Zehnder modulators (MZM) based on Pockels effect using LiNbO_3 [27, 32, 12] have shown promise in recent demonstrations, but the high V_π resulting in large device footprints of these modulators can restrict their scalability. Other modulation schemes demonstrated in a cryogenic environment include opto-mechanical effect using piezo-electric effect in AlN [4], DC Kerr effect [2], electro-absorption based [3], and silicon-organic hybrid (SOH) MZM [26]. While these devices could achieve data rates as high as 50 Gb/s, their area and energy inefficiencies might be limiting their use in future cryogenic computing systems.

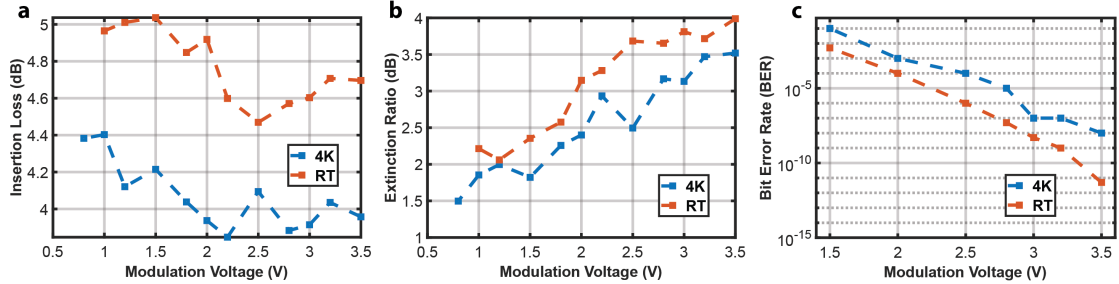


Figure S5: (a) Insertion Loss (IL) of the modulator as a function of applied modulation voltage, (b) Extinction Ratio (ER) of the modulator as a function of applied modulation voltage and (c) Bit Error Rate (BER) of the modulator as a function of applied modulation voltage

Supplementary Note 5: Modeling of PCM-Integrated Micro-ring modulator

In an ideal setting, the amount of optical losses in GST should cause a very large shift in Q-factor, making it unsuitable for resonance tuning applications. Still, we have employed various strategies,

Reference	Modulation Method	Device	Data rate	Modulation	Electrical	Resonance
		Structure	(Gb/s)	Voltage (V)	Energy (fJ/bit)	Tuning
[23]	Magneto-optic effect	Micro-ring	2	-	3900	NA
[7]	Pockels effect in BaTiO ₃	Micro-ring	20	1.7	45	NA
[19]	Graphene on SiN	Micro-ring	20	3	20	NA
[24]	InP-on-Si QW	Micro-ring	4	0.11	1.3	NA
[10]	Free-carrier plasma dispersion in Si	Micro-disk	10	1.8	80	NA
[11]	Free-carrier plasma dispersion in Si	Micro-ring	20	1.5	54	NA*
This work	Free-carrier plasma dispersion in Si	Micro-ring	10	3.6	75	Non-volatile using PCM

Table S1: Comparison of various cryogenic resonant modulators (NA: Not Applicable, *Resonance cannot be independently tuned in this device).

including over-coupling of the device and selecting the appropriate length and thickness of the GST film to maintain consistency over the tuning range. Here, we perform further modeling of our PCM-Integrated Micro-ring modulator to address the uncharacteristic behavior of GST. As we know, there are several factors which can impair the contribution of GST losses to the resonator response, including partial switching due to ineffective heating of the full volume of GST, thinning of the GST layer due to material reflow during the amorphization process, the shadowing effect in oxide opening causing thinner deposition, and the topographical change in GST volume during the crystallization process [14] resulting in additional thinning. This introduces a lot of ambiguity in the PCM performance, and including these artifacts of thinning and partial crystallization in our analysis can help address some discrepancies. In the Section Supplementary Note 6, we have estimated the reduction in the thickness of GST by matching the incurred GST losses in our experiments, coming from round-trip losses, to the expected GST losses. From that analysis, we estimated a 75% reduction in GST. In our current modeling, we apply a 75% thickness reduction to the 12.5 nm thick GST, leading to a remaining thickness of 3.125 nm in the 8 μ m long oxide opening. Additionally, we incorporate the change in refractive index of GST due to partial crystallization can be estimated by employing effective medium theory [31, 30].

$$\frac{\varepsilon_{\text{eff}}(p) - 1}{\varepsilon_{\text{eff}}(p) + 2} = p \times \frac{\varepsilon_c - 1}{\varepsilon_c + 2} + (1 - p) \times \frac{\varepsilon_a - 1}{\varepsilon_a + 2},$$

Where, ε_a and ε_c are complex permittivity for crystalline and amorphous. $\varepsilon_{\text{eff}}(p)$ can be used to obtain the partial complex refractive index of GST (Fig. S6b). The refractive indices at room temperature were used in this modeling as there is no extensive characterization of the optical properties of GST at cryogenic temperatures. We have also performed an estimation of GST optical properties in Section Supplementary Note 6, but for it to be accurate it requires a more extensive experimental characterization. Additionally, carriers present in the PN junction of the modulator section of MRMs (Fig. S6d) shall also contribute to losses and were also accounted for in the model.

We observed that by incorporating all of the above effects, the maximum tuning range achieved at 50% crystallization of GST is ~ 0.5 nm, which is very close to what we measured in experiments. A rise in the amount of crystallization percentage introduces additional round-trip loss, as seen

from transmissions in Fig. S6a. The transmission characteristics can be preserved over the whole tuning range by properly adjusting the ring’s input coupling power. We have also recorded the ratio of crystalline and amorphous Q-factors as a function of the coupling power, where at the ideal operating point this ratio has minimal variation over all crystallization percentages (Fig. S6c). We can see here how over-coupling the ring can be beneficial for implementing reliable tuning using GST and in case of MRMs it also helps boost the modulator bandwidth. However, this model requires further refinement to fully align with the experimental data. There can be more factors influencing the GST performance and endurance, such as void formations, PCM dewetting, and delamination [25], which could be further explored and incorporated in the model.

In practical applications, the resonance of an MRM should be tunable across the required wavelength range, which varies depending on the optical link system’s use case [5, 22, 1, 29]. For instance, to account for fabrication variations in absolute laser wavelengths or resonator shifts, a tuning range of 1 nm to 2 nm may be sufficient. In DWDM links, this range can adequately cover the channel-to-channel spacing (typically 1 nm to 2 nm). However, ideally, the entire FSR range should be tunable to ensure robust modulation regardless of temperature shifts, process variations, and other artifacts. While our device currently achieves a tuning range of 0.42 nm (for a resonator FSR = 4.5 nm), this can be easily increased by using a longer GST length or increasing its thickness to induce a larger phase shift. A significant drawback of using GST for resonance tuning, however, is its high optical loss in the crystalline state, which limits the achievable phase shift without a substantial drop in the cavity’s Q-factor. To address this, ultra-low loss PCMs, such as SbSe or SbS, could be used to achieve phase shifts and significantly extend the tuning range.

Here, we simulated a ~ 20 nm thick, low-loss PCM to estimate the phase shifter length required for a full FSR shift. Due to the lack of optical properties of these low-loss PCMs at cryogenic temperatures, the room temperature refractive index values were used in these simulations to provide a perspective about the effectiveness of these class of materials in resonance tuning applications, there have also been experimental demonstrations showing their promise of these low loss PCM materials [6, 14]. SbSe has a refractive index of $4.49 + 0.00065 i$ and $3.18 + 0.00045 i$ in the crystalline and amorphous states. SbS has a refractive index of $3.48 + 0.03 i$ and $2.78 + 0.0003 i$ in the crystalline and amorphous state. The loss in the modulators was estimated based on the carrier concentration values provided by the foundry and incorporated in the simulations. The coupling coefficient is unique and was set separately for each PCM material, such that they are both set in their respective overcoupled regimes to preserve the extinction of the modulator even when the materials are fully switched from their respective amorphous to crystalline states. For a ring with a radius of $12.5 \mu\text{m}$, a full FSR shift (~ 7.3 nm) was achieved with a $16 \mu\text{m}$ long SbSe-based phase shifter, showing minimal changes in Q-factor and ER between the amorphous and crystalline states (Fig. S6a). Similarly, we see that a half FSR shift was achieved with a $8 \mu\text{m}$ long SbSe-based phase shifter. For an SbS-based phase shifter, a longer length of $36 \mu\text{m}$ is required to achieve a full FSR shift, due to a smaller effective refractive index contrast, and a $18 \mu\text{m}$ phase-shifter achieves half FSR shift. Higher absorption loss in SbS resulted in a more significant variation in Q-factor and ER (Fig. S6b). Overall, these simulation results indicate a promising approach to extend the tuning range up to (~ 7.3 nm) in the future by using low-loss PCM, increasing the PCM section length,

and optimizing PCM thickness.

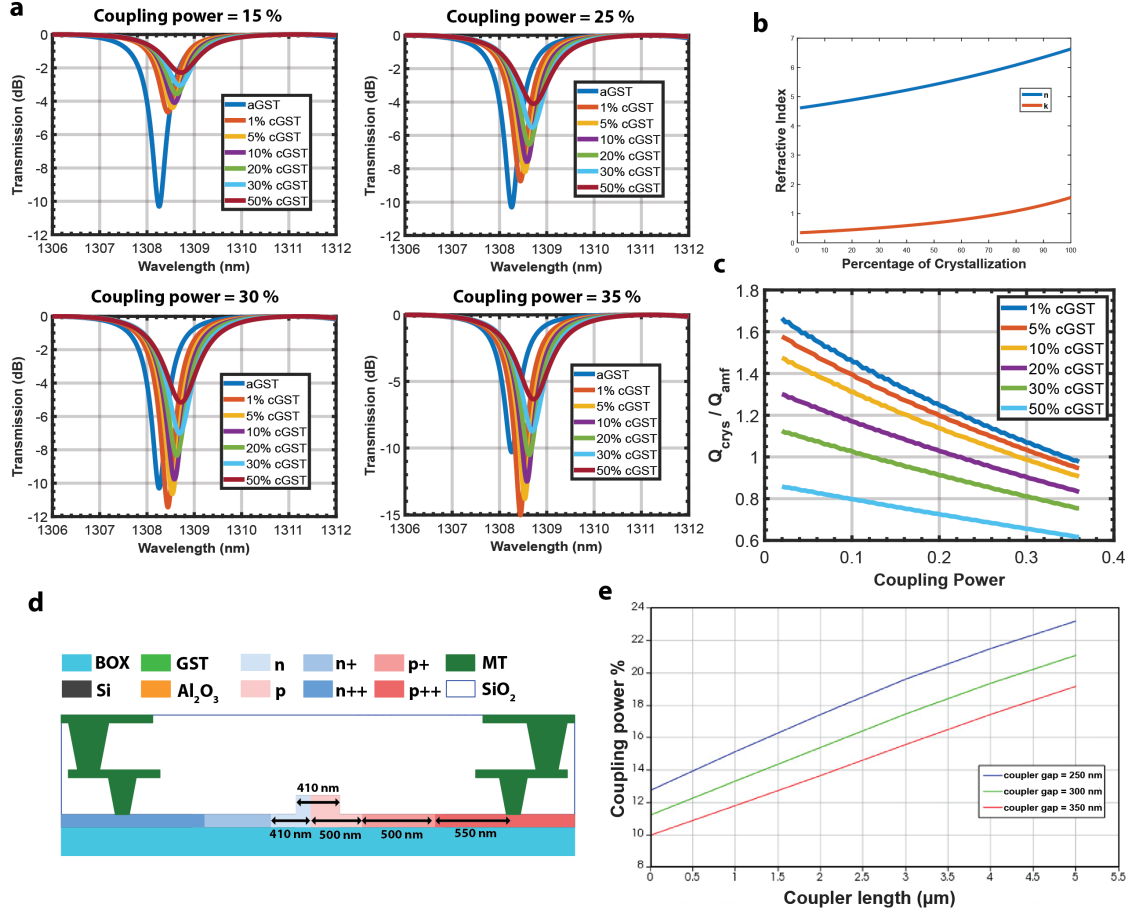


Figure S6: (a) Simulated transmissions for the PCM-integrated MRM for various coupling powers and percentage of crystallization, (b) Refractive index of GST for varying crystallization percentage, (c) Simulated ratio of crystalline and amorphous Q factors for varying coupling powers, (d) Cross-section of the MRM PN junctions, and (e) FDTD simulations of bus waveguide to ring coupling power percent as a function of coupler length and gap.

Supplementary Note 6: Extraction of Refractive Indices and Extinction Coefficients of GST at Cryogenic Temperature

Round trip loss in the micro-ring modulators (MRMs) can be extracted from the resonance spectrum, by measuring the finesse and extinction [21]. The round trip loss, a of the MRM would consist of losses not only due to absorption in the GST clad section of the hybrid ring, but also due to doping and surface roughness. These other losses, a_{nogst} were calculated using the same method, through resonance spectrum of MRMs not activated by GST. The resultant loss due to GST in each round trip is then $a_{\text{gst}} = a/a_{\text{nogst}}$. Losses due to GST clad section can also be written as

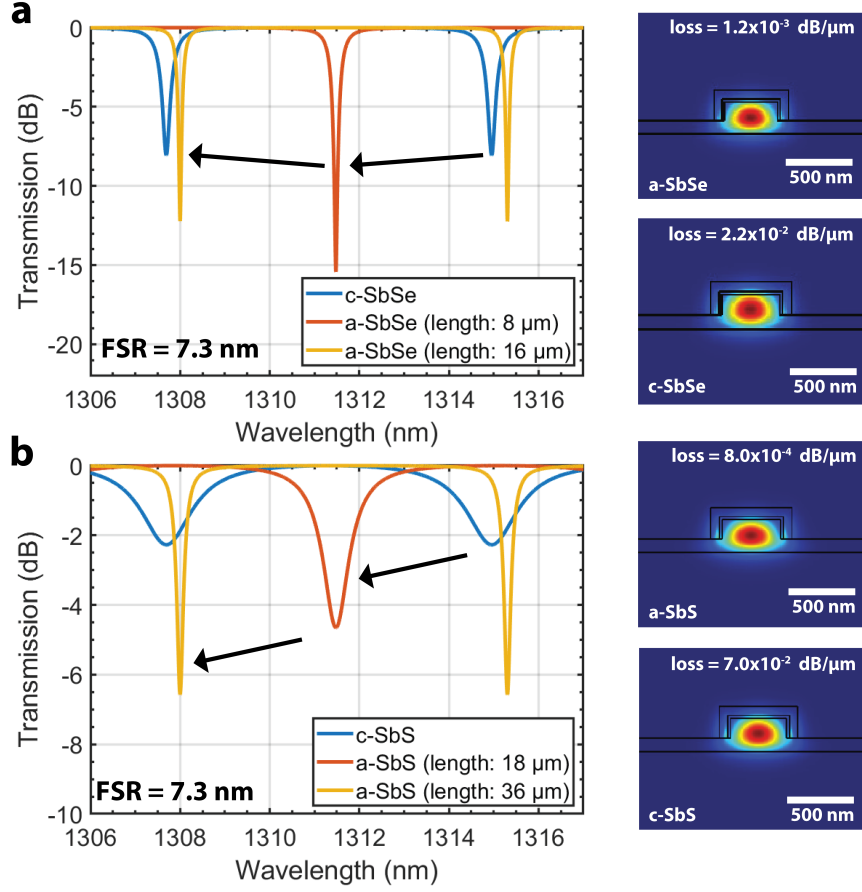


Figure S7: Transmission plots and mode profile comparing a full FSR shift induced using (a) SbSe and (b) SbS

$a_{\text{gst}} = \exp(-\frac{2\pi}{\lambda_{\text{res}}} \cdot k_{\text{eff}} \cdot L_{\text{gst}})$. Using this expression, k_{eff} of the GST section can be calculated from experimental data. For estimation of extinction of GST, Lumerical Mode simulations can be utilised, where k_{gst} is optimized to yield calculated values of k_{eff} .

It has been reported that the GST undergoes a topographical change where the deposited material migrates when heated beyond glass transition state [15]. Having been switched multiple times for reliability analyses, the deposited GST on the measured devices was expected to have thinned out due to the mentioned effects (see Supplementary Note 5). Assuming that the rings measured were switched to entirely amorphous and crystalline states, resonance spectra at room temperature were used to estimate thickness of GST; thickness of layer was optimized instead of the extinction coefficient. As expected, it was found that losses from GST clad section would be too large if layer was as thick as initially deposited. For the a-GST rings, the thickness was found to have reduced to 5.75 nm from 10 nm and 4.71 nm from 20 nm for the c-GST rings. The deposited lengths of GST sections for these rings were 8 μm and 4 μm respectively. a_{nogst} for non-GST clad section was found to be nominal (0.985). Extracted parameters from resonance spectra are shown in Fig.S8(c).

At cryogenic temperatures (4 K), a and correspondingly k_{eff} of GST clad section were calculated from spectra as shown in Fig.S8(b). Keeping the thickness of GST constant and equal to the updated values, extinction coefficients of GST were obtained from simulations. As summarized in Table.S2, a reduction in extinction coefficient was observed at cryogenic temperatures as compared to room temperature.

At resonance in a ring resonator, the total phase accumulated by propagating light is an integer multiple of 2π . This condition can be written as

$$m = \frac{n_{\text{eff}0} \times L}{\lambda_{\text{res}}}$$

where m is an integer signifying the mode number, λ_{res} is the resonance wavelength, L is the optical path length, equal to the total length of the ring, and $n_{\text{eff}0}$ is the effective index of the hybrid ring. A change in temperature will alter the refractive indices of constituent materials which changes the effective index, consequently shifting the resonance wavelength. However, if the same resonance is tracked, m for all the temperatures shall be equal [8]. This allows us to equate the total phase of the resonance at different temperatures.

$$\begin{aligned} & \frac{1}{\lambda(T)} [n_{\text{eff_st}}(\lambda(T), T) \cdot (2L_{\text{st}} - L_{\text{gst}}) + n_{\text{eff_r}}(\lambda(T), T) \cdot (2\pi R) \\ & \quad + n_{\text{eff_gst}}(\lambda(T), T) \cdot (L_{\text{gst}})] \\ &= \frac{1}{\lambda(T_r)} [n_{\text{eff_st}}(\lambda(T_r), T_r) \cdot (2L_{\text{st}} - L_{\text{gst}}) + n_{\text{eff_r}}(\lambda(T_r), T_r) \cdot (2\pi R) \\ & \quad + n_{\text{eff_gst}}(\lambda(T_r), T_r) \cdot (L_{\text{gst}})] \end{aligned} \tag{1}$$

Here $\lambda(T)$ is the resonance wavelength at temperature T . $n_{\text{eff_st}}$, $n_{\text{eff_r}}$ and $n_{\text{eff_gst}}$ are the effective indices of straight, bent and GST clad sections of the ring resonator. L_{st} , R and L_{gst} are length and radii of the corresponding sections. T_r is the temperature at which refractive index data of GST is available. Notably, since the temperature range in the current work spans a large range, a large shift in wavelengths (~ 9 nm) is also observed. Dispersion of materials shall introduce a non-negligible change and is also accounted for; all refractive indices and effective indices are functions of wavelength and temperature.

Location of resonance ($\lambda(T)$) is obtained experimentally by measuring the spectral response of the MRMs at varying temperatures, results for amorphous and crystalline states are shown in Fig.S8. The terms on the RHS of Eq.1 are calculated using Lumerical Mode Simulations, while utilising temperature and wavelength dependent refractive indices of Si [9, 18], SiO₂ [20] and Al₂O₃ [13]. On the LHS of Eq.1, $n_{\text{eff_gst}}$ is the unknown to be determined, and rest of terms are obtained using a methodology similar to the RHS. Refractive index of GST was optimised as a parameter to obtain this calculated effective index of GST clad section of the ring ($n_{\text{eff_gst}}$) again using Lumerical Mode simulations.

As is visible from Fig.S8b, for the ring with crystalline GST, a resonance in the mrm device is observed at 1329.22 nm at 300 K, which shifts to 1321.23 nm at 4 K. Simulated values $n_{\text{eff_st}}$ and

n_{eff_r} are 2.65503 and 2.65663 at 300 K, and 2.63022 and 2.63183 at 4 K respectively. Using the refractive index of c-GST at room temperature as 6.6308, the $n_{\text{eff_gst}}$ obtained is 3.10485. Using Eq.1 calculated mode index $n_{\text{eff_gst}} = 3.30444$ at 4 K. Using Lumerical Mode simulations, c-GST refractive index of 7.43617 was found to yield this value of $n_{\text{eff_gst}}$. Similar treatment of MRMs with amorphous GST results in a 4 K refractive index of 6.29028, shifted from 4.59303 at 300 K. The resonance shifts from 1330.67 nm to 1321.75 nm, and the corresponding values $n_{\text{eff_gst}}$ are 2.77132 and 2.83158. Notably, the effective index of GST clad section is lower not only because of the smaller refractive index of a-GST, but also due to a smaller thickness of GST (10 nm vs 20 nm in c-GST rings). Since the chosen resonances have similar wavelengths, the simulated values of $n_{\text{eff_st}}$ and n_{eff_r} , 2.65347 and 2.65508 at 300 K, and 2.62966 and 2.63127 at 4 K respectively, are close by. The results are summarized in Table.S2. An increase in the refractive index of GST with a reduction in temperature implies a negative temperature coefficient over the temperature range. Recent publications [17, 16, 28] have reported similar results, wherein GST exhibits a large negative thermo-optic coefficient for the crystalline state at RT. A negative coefficient is observed for amorphous state as well, which could be attributed to imperfect amorphization of GST.

Since complete data on material refractive indices was not available for the entire range, certain assumptions and approximations were carried out. For Si, Sellmeier equation with wavelength and temperature dependence is provided in [9] which is valid from 30 K to 300 K. The equation when extended to 5 K results in spurious values, which contradict experimental data available in [18]. However, comparison of temperature coefficients for 1.5 μm and 1.3 μm shows less than 5% variation. Hence it was assumed that temperature coefficients are constant for the wavelength range. Temperature coefficients from 30 K to 300 K data is taken from [9] and 5 K to 30 K from [18]. Additionally, the wavelength mismatch between the references shall not account for substantial errors as the temperature coefficient itself drops to 10^{-8} at cryogenic temperatures. For SiO_2 , temperature and wavelength dependent Sellmeier equation available from 30 K to 300 K is extended to 4 K. Similarly, for Al_2O_3 , Sellmeier equation available from 5 K to 295 K is extrapolated to 4 K and 300 K.

Phase	Temperature (K)	n	k
Crystalline	4	7.43617	0.873
	300	6.6308	1.0888
Amorphous	4	6.29028	0.0121
	300	4.593	0.024694

Table S2: Calculated refractive index of GST at cryogenic temperature (4 K)

It should be noted that the refractive index and extinction coefficient values provided are close estimates, as the experiment was constrained by the available characterization structures and uncertainty in the PCM state or dimensions, due to several factors discussed earlier. More extensive characterization in the future could yield more reliable GST optical data at cryogenic temperatures.

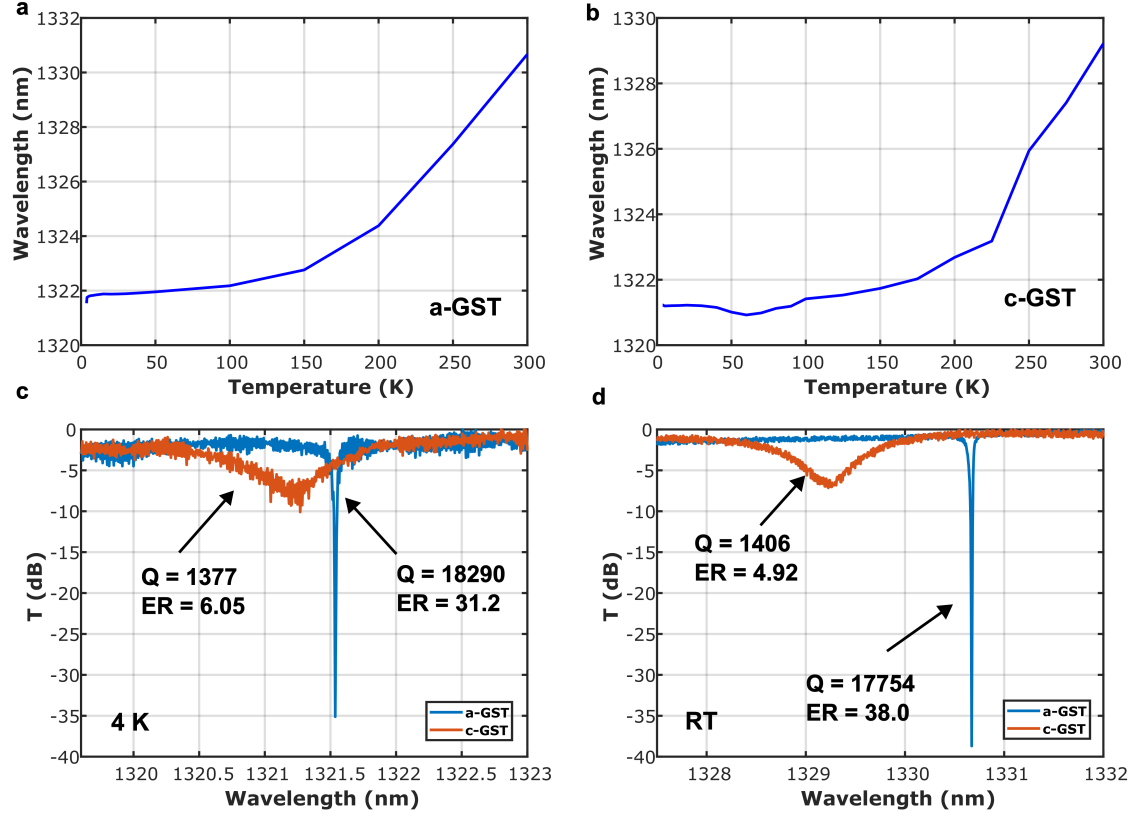


Figure S8: Variation of MRM resonant wavelengths with temperature change when GST is in (a) amorphous state and (b) crystalline state. Spectra of the tracked resonances at (a) cryogenic and (b) room temperatures. Marked values of Q factor and Extinction Ratio (ER) are extracted from Lorentzian fit curves on the resonances. Calculated values of round-trip loss a for c-GST rings are 0.563 and 0.556 at 4 K and 300 K, respectively. Similarly, for a-GST rings a is equal to 0.971 and 0.969.

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