

Article

Nonvolatile Spectral Tuning of UGR-like Resonances via Near-Merging C-Point Pairs in a GSST Phase-Change Metasurface

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Abstract

Unidirectional guided resonances (UGRs) provide a compact route to highly directional radiation without metallic reflectors, but their realization usually relies on precise structural tuning and is often restricted to isolated points in momentum or parameter space. Here, we propose a $\text{Ge}_2\text{Sb}_2\text{Se}_4\text{Te}_1$ (GSST)-based phase-change metasurface that enables nonvolatile spectral tuning of UGR-like resonances by controlling the momentum-space evolution of paired circular-polarization singularities. Instead of relying on an exact C-point merging condition at a single phase state, the proposed structure controls the approach and departure of a symmetry-related C-point pair relative to the $k_y = 0$ line, with the closest sampled approach occurring near an intermediate crystallization state. This near-merging evolution selectively suppresses air-side radiation, giving rise to continuously tunable UGR-like resonances with persistent high directionality. At the high-directionality operating point selected for each of the crystallization states considered, the eigenwavelength shifts by 202.2 nm, exceeding three times the largest eigenmode linewidth. Meanwhile, the downward-to-upward radiation asymmetry ratio η consistently exceeds 10^2 over the investigated phase states and reaches approximately 2.4×10^4 near the optimal crystallization state. A self-consistent fixed-angle analysis further shows that a fixed substrate-side direction of 16.52° , equivalent to 22.93° in air, retains $119.6 \leq \eta \leq 191.3$ throughout all 11 states considered while preserving a 186.6 nm tuning range. Despite increased crystalline-state absorption, the intrinsic substrate-side modal branching fraction remains at least 75.7%. These results establish a nonvolatile strategy for combining spectrally resolvable tuning, persistent directional radiation, and substantial dominant-side modal out-coupling in a single phase-change metasurface.

Keywords: optical metasurface; phase-change material; GSST; bound state in the continuum; unidirectional guided resonance; polarization singularity; mid-infrared



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1. Introduction

Metasurfaces provide a flexible platform for controlling optical fields in ultrathin photonic structures. By engineering subwavelength building blocks, they can tailor the amplitude, phase, polarization, and dispersion of light, enabling compact optical elements such as metalenses, beam deflectors, holograms, polarization converters, absorbers, and integrated light emitters [1–6]. Beyond conventional real-space wavefront engineering, periodic metasurfaces and photonic-crystal slabs also offer a powerful route to manipulate light in momentum space through guided resonances, bound states in the continuum

(BICs), and polarization singularities [7–12]. These resonant effects combine field confinement, enhanced light–matter interaction, and controllable radiation channels, making them attractive for a broad range of resonant photonic applications [8,9,13]. Recent developments also include the coexcitation of anapole and quasi-BIC modes in dielectric metasurfaces, broadband long-wave-infrared multilayer absorbers, and dynamically reconfigurable bilayer-graphene terahertz absorbers [14–16].

Among these momentum-space phenomena, BICs have attracted particular attention. A BIC is an eigenmode whose frequency lies within the radiation continuum but remains decoupled from open radiation channels, and therefore cannot be directly excited from the corresponding far-field channel [7,8]. In periodic photonic structures, BICs can be interpreted as polarization vortices in far-field radiation, where the radiation amplitude vanishes and the polarization direction becomes undefined [7,10,11]. When the exact decoupling condition is relaxed, for example by weak symmetry breaking or structural detuning, a BIC can evolve into a quasi-BIC with finite radiative leakage while retaining a high quality factor [8,9]. More generally, symmetry breaking and radiation-channel engineering can redistribute the leakage of a guided resonance between the two sides of a photonic structure, leading to unidirectional guided resonances (UGRs) [17–21].

UGRs are guided resonances that radiate predominantly or exclusively toward one side of a photonic structure. Unlike conventional directional emitters or grating couplers that rely on bottom mirrors, metal reflectors, or multilayer interference, UGRs can realize mirror-free directional radiation by engineering the far-field radiation channels of resonant modes [17]. In the polarization-topology picture, a UGR is associated with an undefined far-field polarization on the suppressed-radiation side, while the radiation channel on the opposite side remains finite [17]. One important route to such a condition is the approach or merging of paired circular-polarization points in the suppressed-side radiation channel [17,22]. When two C points with opposite helicities meet at the same momentum, a nonzero field would have to be simultaneously left- and right-circularly polarized, which is not possible; the corresponding outgoing field is therefore strongly suppressed or vanishes [17]. This mechanism makes UGRs promising for efficient grating couplers, directional antennas, and surface-emitting photonic devices [17,19,21].

Despite these advantages, most reported UGRs are tied to finely tuned structural parameters. Since perfect or near-perfect suppression of one radiation channel is sensitive to the momentum-space position of polarization singularities, small variations in geometry or material parameters can shift the system away from the UGR condition [17,18,21]. This fine-tuning requirement limits the flexibility of UGR-based devices. Moreover, a static UGR generally provides directional radiation at a fixed resonance wavelength and momentum point, whereas practical photonic systems often require post-fabrication tunability, multi-state operation, and nonvolatile retention.

Phase-change materials offer an effective route to address this limitation. $\text{Ge}_2\text{Sb}_2\text{Se}_4\text{Te}_1$ (GSST), $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST), and related chalcogenide phase-change materials exhibit large, reversible, and nonvolatile changes in optical constants between amorphous, crystalline, and intermediate phase states [23,24]. Because the phase state can be retained without static holding power, these phase-change materials have been widely used in reconfigurable metasurfaces, tunable absorbers, optical switches, beam-steering devices, and nonvolatile photonic memories [25–32]. Incorporating phase-change materials into resonant metasurfaces allows the eigenfrequency, linewidth, modal overlap, and radiation channels of guided resonances to be modified after fabrication [23,24,26,28].

Previous GSST-based metasurfaces have demonstrated nonvolatile spectral and wavefront reconfiguration [33]. A closely related phase-change UGR study employed GST and associated the ideal UGR with the fully amorphous endpoint, while intermediate states

were used to examine the accompanying evolution of radiation asymmetry and optimum momentum toward this endpoint condition [34]. The present work addresses a different design objective: the strongest-directionality region is located within the crystallization range rather than at a phase endpoint, allowing UGR-like high directionality to be retained as the phase state varies on either side of the optimum.

Here, we propose a GSST-based phase-change metasurface that realizes this objective through the controlled momentum-space evolution of a symmetry-related pair of air-side C points. The pair is engineered to remain close to the $k_y = 0$ line over the tuning range, with its closest sampled approach occurring near an intermediate crystallization state. Using eigenfrequency simulations, we continuously track the same TE-like guided-resonance branch across 11 crystallization states. At the high-directionality operating point selected for each state, the eigenwavelength shifts by 202.2 nm, while $\eta = \gamma_{\text{down}}/\gamma_{\text{up}} > 10^2$ is maintained throughout the full crystallization range. The design therefore enables multistate nonvolatile spectral tuning with persistent UGR-like directionality.

2. Structure Design and Numerical Methods

Figure 1 shows the unit cell of the proposed one-dimensional phase-change metasurface. The structure consists of a Si/GSST ridge directly placed on a SiO₂ substrate. The grating is periodic along the x direction with a period of $a_0 = \Lambda = 2.3 \mu\text{m}$ and is invariant along the y direction. Each unit cell contains a 0.1 μm -thick Ge₂Sb₂Se₄Te₁ (GSST) layer and a 1.4 μm -thick Si layer, giving a total patterned-layer height of 1.5 μm . The patterned ridge has a width of 1.3 μm at the mid-height plane. One sidewall of the ridge is tilted by $\theta = 18^\circ$ with respect to the z axis, while the opposite sidewall is kept vertical. The substrate breaks the up–down symmetry of the radiation environment, while the tilted sidewall serves as a geometric perturbation and the GSST layer provides a nonvolatile material tuning degree of freedom for engineering asymmetric leakage channels.

One possible fabrication route for the proposed metasurface would begin with room-temperature RF magnetron sputtering of a 100 nm GSST film on SiO₂, followed by low-temperature PECVD deposition of a 1.4 μm -thick Si layer. Dose-modulated grayscale electron-beam lithography in HSQ could define an asymmetric mask with one graded edge and one abrupt edge. A calibrated ICP-RIE step, using timed or endpoint-controlled termination at the Si/GSST interface, could then transfer this profile through the Si layer. The exposed GSST could subsequently be patterned by a separate short, material-selective plasma-etch step down to the SiO₂ substrate. The GSST state could then be programmed optically using crystallization and melt–quench pulses, with the pulse conditions calibrated for the actual thermal stack.

In the wavelength range considered here, Si is modeled as a nondispersive dielectric with refractive index $n_{\text{Si}} = 3.43$. The SiO₂ substrate is described by $n_{\text{SiO}_2} = 1.37$ with a small extinction coefficient of $k_{\text{SiO}_2} \approx 1.5 \times 10^{-4}$. The optical constants of GSST are taken from the reported data in the Supplementary Information of Ref. [33]. In the amorphous state, GSST is modeled with $n_a = 3.2$ and $k_a = 0$. In the crystalline state, GSST is approximated by $n_c = 4.7$ and $k_c \approx 0.057$ over the spectral range of interest. Intermediate crystallization states of GSST are described using the Lorentz–Lorenz effective-medium relation [33],

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

where ξ denotes the crystallization fraction of GSST, and ε_a and ε_c are the complex permittivities of the amorphous and crystalline states, respectively. The endpoints $\xi = 0$ and $\xi = 1$ correspond to amorphous and crystalline GSST, respectively, whereas intermediate values represent effective partially crystallized optical states. The Lorentz–Lorenz relation

provides an isotropic homogenized description of partially crystallized GSST. It assumes that the characteristic amorphous and crystalline domains remain much smaller than the local optical wavelength and the modal field-variation scale within the GSST layer, and that their spatial distribution does not produce a resolved macroscopic anisotropy. Accordingly, it does not resolve morphology-specific effects such as nucleation, domain connectivity, percolation, oriented crystallites, or spatially nonuniform crystallization.

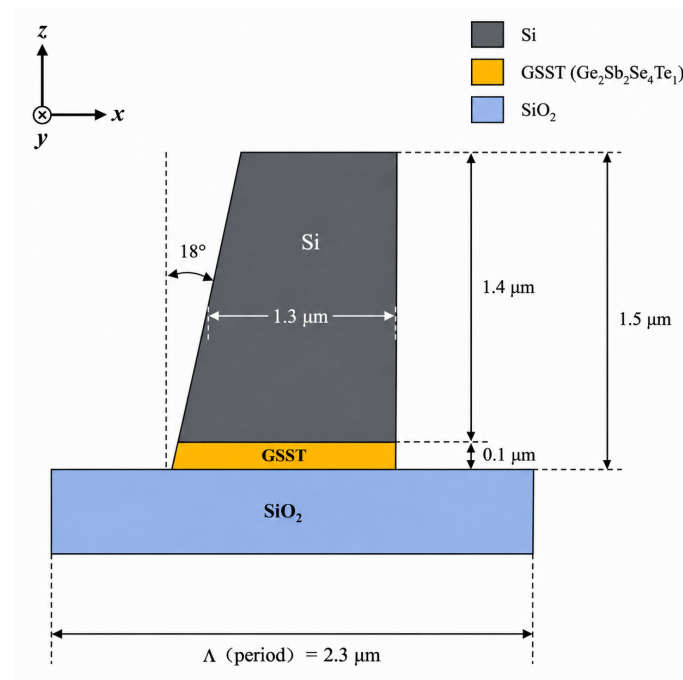


Figure 1. Schematic of the one-dimensional Si/GSST metasurface unit cell in the x - z plane. The structure consists of a Si/GSST ridge on a SiO_2 substrate and is invariant along the y direction. The period is $a_0 = \Lambda = 2.3 \mu\text{m}$, and the ridge width is $1.3 \mu\text{m}$ at the mid-height plane of the patterned layer. The GSST and Si layers have thicknesses of $0.1 \mu\text{m}$ and $1.4 \mu\text{m}$, respectively, resulting in a total patterned-layer height of $1.5 \mu\text{m}$. One sidewall of the ridge is tilted by $\theta = 18^\circ$ with respect to the z axis.

All numerical simulations in this work were performed using the finite-element method. Bloch periodic boundary conditions are applied along the x direction, and perfectly matched layers are used along the z direction. The structure is assumed to be uniform along the y direction. The maximum mesh-element size in every material domain was kept below one twelfth of the corresponding local material wavelength, with additional refinement in the GSST layer to ensure accurate extraction of the nonradiative loss. The upward and downward radiative decay rates were obtained from Poynting-flux line integrals in homogeneous air and substrate regions positioned sufficiently far from both the metasurface and the PML boundaries to suppress evanescent-field and boundary effects.

To clarify the design principle and the topological origin of the UGR-like resonances, two reference structures are also considered. Unless otherwise specified, the reference structures retain the same period, patterned-layer height, and nominal ridge width as the final metasurface, with $a_0 = \Lambda = 2.3 \mu\text{m}$, a patterned-layer height of $1.5 \mu\text{m}$, and a nominal ridge width of $1.3 \mu\text{m}$. In the air-reference structure, the SiO_2 substrate is removed, the sidewalls are kept vertical, and the GSST sublayer is retained geometrically but assigned the same lossless refractive index as Si. The internal Si/GSST optical interface therefore disappears and the patterned region behaves as a single Si ridge. In the glass-substrate reference structure, the same vertical, optically merged ridge is placed on a SiO_2 substrate. These reference structures are used below to identify the topological parent mode and to

reveal how substrate-induced up–down asymmetry converts the parent BIC into paired C points.

3. Results

3.1. Topological Parent Mode in the Reference Structures

We first examine the two reference structures to identify the topological origin of the UGR-like response. In the air-reference structure, the GSST layer is optically merged with the Si layer because $n_{\text{GSST}} = n_{\text{Si}}$, and the radiation environment is up–down symmetric. In the glass-substrate reference structure, the substrate breaks the up–down symmetry of the radiation environment while all other index-matched conditions are retained. Therefore, the comparison between these two reference systems isolates the effect of substrate-induced symmetry breaking.

Figure 2 shows the eigenwavelength and quality factor of the target TE-like branch along the $k_y = 0$ line. For the air-reference structure, the quality factor exhibits a pronounced divergence at a finite in-plane momentum, indicating the formation of an off- Γ BIC. The corresponding eigenwavelength branch varies smoothly with k_x , confirming that the BIC belongs to the same continuously tracked guided-resonance branch. After introducing the glass substrate, the ideal divergence of the quality factor disappears, and the resonance becomes leaky. This behavior indicates that the substrate breaks the up–down symmetry of the radiation environment and converts the parent BIC into a finite- Q guided resonance.

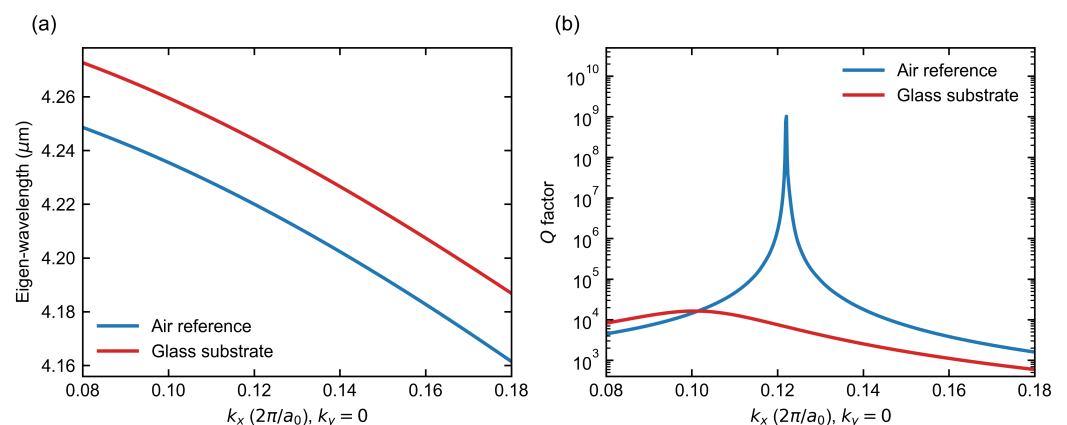


Figure 2. Eigenwavelength and quality factor of the target TE-like branch for the air-reference and glass-substrate reference structures. (a) Eigenwavelength as a function of k_x along the $k_y = 0$ line. (b) Corresponding quality factor. The air-reference structure exhibits a pronounced Q divergence at a finite in-plane momentum, indicating an off- Γ BIC. Introducing the glass substrate breaks the up–down radiation symmetry and converts the ideal BIC into a finite- Q leaky guided resonance.

The far-field polarization maps in Figure 3 further confirm the topological nature of the parent BIC. At each in-plane wave vector $\mathbf{k}$, the radiated far field is projected onto the local TE/TM transverse plane-wave basis associated with the same radiated wave vector. The polarization-ellipse orientation in this smoothly defined local basis is

$$\psi(\mathbf{k}) = \frac{1}{2} \arg(S_1 + iS_2),$$

and the polarization charge is evaluated as

$$q = \frac{1}{2\pi} \oint_C \nabla_{\mathbf{k}} \psi(\mathbf{k}) \cdot d\mathbf{k}.$$

Along a closed loop enclosing the parent V point, the unwrapped orientation angle undergoes one complete turn, $|\Delta\psi| = 2\pi$, yielding the integer charge magnitude $|q| = 1$. The short black segments in Figure 3 visualize this major-axis orientation in the local TE/TM basis. When the glass substrate is introduced, the ideal BIC is lifted and the parent singularity resolves into a pair of circular-polarization singularities of half-integer charge magnitude $|q| = 1/2$, identified from the extrema of S_3/S_0 with opposite helicities. This analysis establishes that the final UGR-like resonances originate from a charged parent BIC that evolves into paired C points after up–down symmetry is broken.

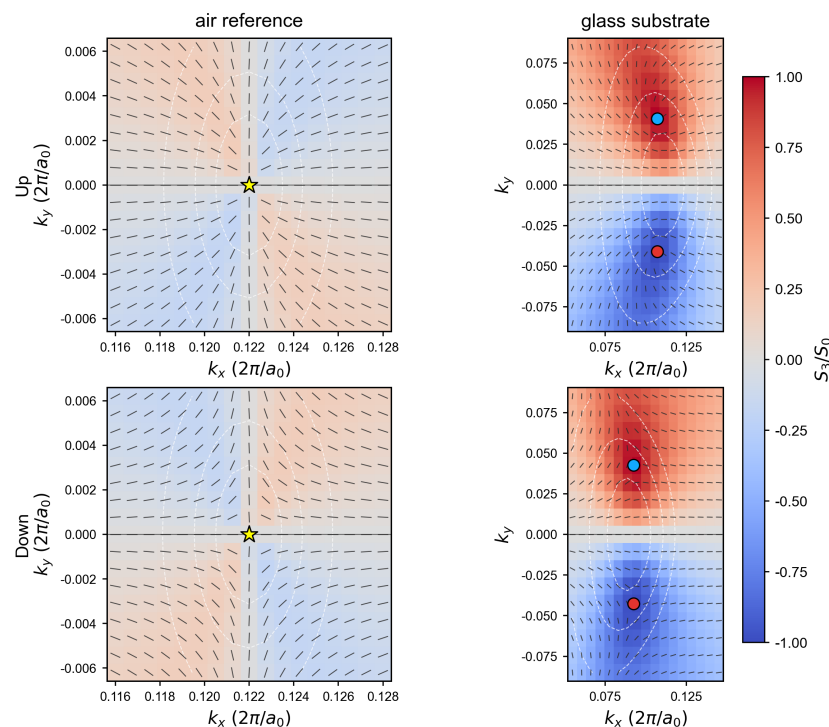


Figure 3. Far-field polarization maps of the reference structures. For the air-reference structure, the upward and downward radiation channels show polarization vortices centered at the BIC position, corresponding to V points with an integer charge magnitude $|q| = 1$. The yellow stars mark the V points at the BIC momentum. For the glass-substrate reference structure, the substrate-induced up–down symmetry breaking lifts the ideal BIC and resolves the parent integer singularity into a pair of C points of $|q| = 1/2$ in momentum space. The color map represents the normalized Stokes parameter S_3/S_0 , and the short black segments visualize the major-axis orientation of the far-field polarization ellipse in the local TE/TM transverse basis associated with each radiated wave vector. The blue and red circles indicate the locations of the C points identified from the extrema of S_3/S_0 .

3.2. Nonvolatile Spectral Tuning of UGR-like Resonances

We next investigate the phase-change response of the final Si/GSST metasurface along the $k_y = 0$ line, which corresponds to the designed out-coupling plane of the one-dimensional grating. For each crystallization fraction ζ , the same TE-like guided-resonance branch is tracked by eigenfrequency calculations. Here and in the following, $a_0 \equiv \Lambda = 2.3 \mu\text{m}$ is used to normalize the in-plane momentum. Figure 4 summarizes the evolution of the eigenwavelength, quality factor, and directional radiation asymmetry as functions of k_x .

As shown in Figure 4a, the eigenwavelength of the target branch shifts continuously as the crystallization fraction increases. The selected UGR-like operating points are summarized in Table 1, where k_x^* is selected near the strongest downward-to-upward radiation asymmetry for each crystallization state. At these selected operating points, the eigenwavelength shifts from $4.1780 \mu\text{m}$ to $4.3802 \mu\text{m}$, corresponding to a total tuning range of

202.2 nm. This wavelength shift indicates that the nonvolatile GSST phase states provide spectrally resolvable tuning while the same TE-like branch remains in the UGR-like regime.

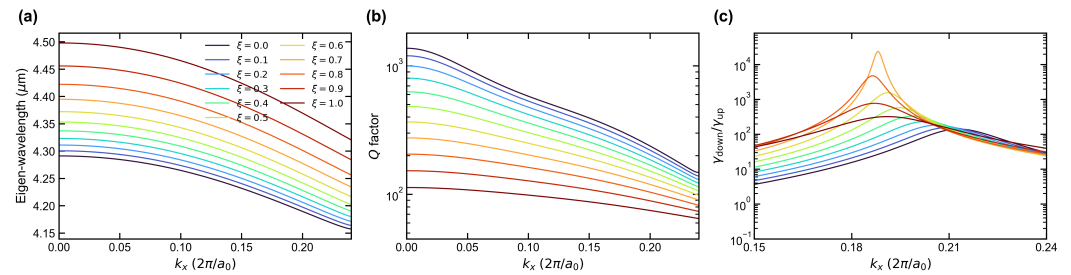


Figure 4. Nonvolatile spectral tuning and directional radiation of the UGR-like resonance. (a) Eigenwavelength of the target TE-like branch as a function of k_x for different GSST crystallization fractions ξ . (b) Corresponding quality factor. (c) Downward-to-upward radiation asymmetry ratio $\eta = \gamma_{down}/\gamma_{up}$. The asymmetry ratio remains above the 10^2 level over the investigated phase states and reaches approximately 2.4×10^4 near $\xi = 0.7$, indicating the strongest UGR-like response.

The corresponding quality factors are shown in Figure 4b. At the selected operating points, Q decreases from 202.8 at $\xi = 0$ to 77.2 at $\xi = 1$. The associated eigenmode linewidth $\Delta\lambda = \lambda/Q$ therefore broadens from 20.6 to 56.7 nm. Even in the fully crystalline state, the 202.2 nm tuning range is approximately 3.56 times the largest linewidth. The smooth evolution of the eigenwavelength and Q also confirms continuous tracking of the same guided-resonance branch rather than switching between unrelated modes.

Figure 4c shows the downward-to-upward radiation asymmetry ratio,

$$\eta = \frac{\gamma_{down}}{\gamma_{up}}, \quad (2)$$

where γ_{down} and γ_{up} denote the radiative decay rates toward the substrate and air sides, respectively. An ideal merged UGR requires $k_y^C = 0$ and $\gamma_{up} = 0$. For the finite-asymmetry states studied here, we use the operational criterion $\eta \geq 10^2$ for the UGR-like near-merging regime; this corresponds to an air-side fraction of the total radiative decay $f_{up} = 1/(1 + \eta) \leq 0.99\%$. The selected amorphous state gives $\eta = 1.41 \times 10^2$, and the maximum reaches 2.39×10^4 near $\xi = 0.7$, for which $f_{up} \approx 0.0042\%$. Although η decreases after the optimum, it remains above 10^2 at all 11 investigated phase states. Thus, the structure maintains UGR-like directional radiation throughout the nonvolatile spectral-tuning trajectory rather than only at one isolated phase state.

Although k_x^* is selected separately for each crystallization fraction, the corresponding peak-direction angles vary from about 20.4° to 22.7° in air and from 14.8° to 16.3° in the SiO_2 substrate, according to

$$\sin \alpha = \frac{k_x}{nk_0} = \frac{[k_x/(2\pi/a_0)]\lambda}{na_0}.$$

These phase-dependent peak positions do not imply that the collection direction must be readjusted for every GSST state. Analysis of the same k_x -resolved eigenmode branches identifies a common air-side angle interval of 22.89° – 22.98° , over which all 11 phase states retain $\gamma_{down}/\gamma_{up} > 100$. Direct eigenfrequency calculations were then performed at the self-consistent momenta corresponding to the representative fixed direction $\theta_{air} = 22.93^\circ$, equivalent to 16.52° inside the SiO_2 substrate. The recalculated results give $119.60 \leq \gamma_{down}/\gamma_{up} \leq 191.30$, while the eigenwavelength shifts from 4.1766 to 4.3632 μm , providing a fixed-direction tuning range of 186.6 nm. Meanwhile, $\gamma_{nr}/\gamma_{rad} \leq 0.2812$, and the intrinsic substrate-side modal branching fraction remains above 77.6%. Thus, phase-dependent angular realignment is not required at the eigenmode level, although the

common fixed-angle window is narrow and the absolute coupling efficiency into a specific finite receiver remains dependent on its angular and spatial mode acceptance.

Table 1. UGR-like operating points extracted from the tracked TE-like resonance branch for different GSST crystallization fractions. For each ξ , k_x^* is selected near the strongest downward-to-upward radiation asymmetry along the $k_y = 0$ line. Here, $a_0 = \Lambda = 2.3 \mu\text{m}$ is used to normalize the in-plane momentum. The asymmetry ratio is defined as $\eta = \gamma_{\text{down}}/\gamma_{\text{up}}$.

ξ	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$k_x^*/(2\pi/a_0)$	0.213	0.210	0.206	0.202	0.198	0.195	0.191	0.188	0.186	0.187	0.191
λ^* (μm)	4.1780	4.1883	4.2002	4.2141	4.2296	4.2469	4.2673	4.2903	4.3161	4.3460	4.3802
Q	202.8	196.4	189.3	181.3	171.1	158.5	144.9	129.0	111.8	94.3	77.2
η	1.41×10^2	1.57×10^2	1.84×10^2	2.33×10^2	3.31×10^2	5.79×10^2	1.55×10^3	2.39×10^4	4.78×10^3	7.73×10^2	3.22×10^2

To visualize the directional leakage of the selected UGR-like states, Figure 5 shows representative normalized E_y field profiles at $\xi = 0, 0.3, 0.7$, and 1.0 . In all cases, the air-side field is strongly suppressed, whereas visible outgoing radiation remains on the substrate side. Here, γ_{nr} denotes the total material-absorption decay rate obtained from the dissipated power over all lossy material domains included in the eigenmode model. The radiative-to-nonradiative ratio $R_{\text{rad/nr}} = (\gamma_{\text{up}} + \gamma_{\text{down}})/\gamma_{\text{nr}}$ decreases from 84.3 in the amorphous state to 3.16 in the fully crystalline state, corresponding to a total nonradiative fraction of approximately 24.0% at $\xi = 1$. The intrinsic substrate-side modal branching fraction is

$$\beta_{\text{down}} = \frac{\gamma_{\text{down}}}{\gamma_{\text{up}} + \gamma_{\text{down}} + \gamma_{\text{nr}}} = \frac{\eta}{1 + \eta} \frac{R_{\text{rad/nr}}}{1 + R_{\text{rad/nr}}}. \quad (3)$$

It is approximately 98.1% at $\xi = 0$ and 75.7% at $\xi = 1$. This quantity describes the branching of the eigenmode decay rather than a complete source-to-receiver efficiency, which additionally depends on the excitation and collection configuration. The result confirms that the large asymmetry originates primarily from selective air-side leakage suppression rather than suppression of all radiation by material absorption.

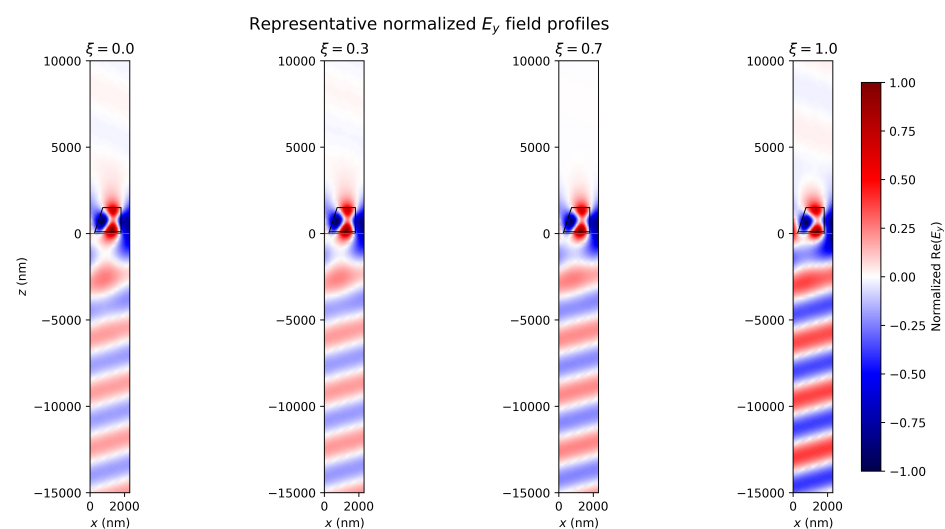


Figure 5. Representative normalized E_y field profiles of the selected UGR-like operating points at $\xi = 0, 0.3, 0.7$, and 1.0 . The four states correspond to the amorphous endpoint, an intermediate crystallization state, the optimal high-asymmetry state, and the crystalline endpoint, respectively. Each field profile is normalized independently. The air-side leakage is strongly suppressed, while visible outgoing radiation remains on the substrate side. The strongest air-side suppression occurs near $\xi = 0.7$, consistent with the maximum downward-to-upward radiation asymmetry shown in Figure 4c.

The strongest directionality near $\xi = 0.7$ suggests that this phase state is closest to the underlying UGR condition. In the following subsection, we show that this behavior originates from the phase-change-controlled motion of paired C points in momentum space.

3.3. Momentum-Space Evolution of Near-Merging C-Point Pairs

To clarify the origin of the UGR-like radiation observed along $k_y = 0$, we analyze the momentum-space evolution of the air-side C points during the GSST phase transition. Figure 6 shows the air-side far-field polarization maps for different crystallization fractions. The color map represents the normalized Stokes parameter S_3/S_0 , and the short line segments indicate the far-field polarization orientation.

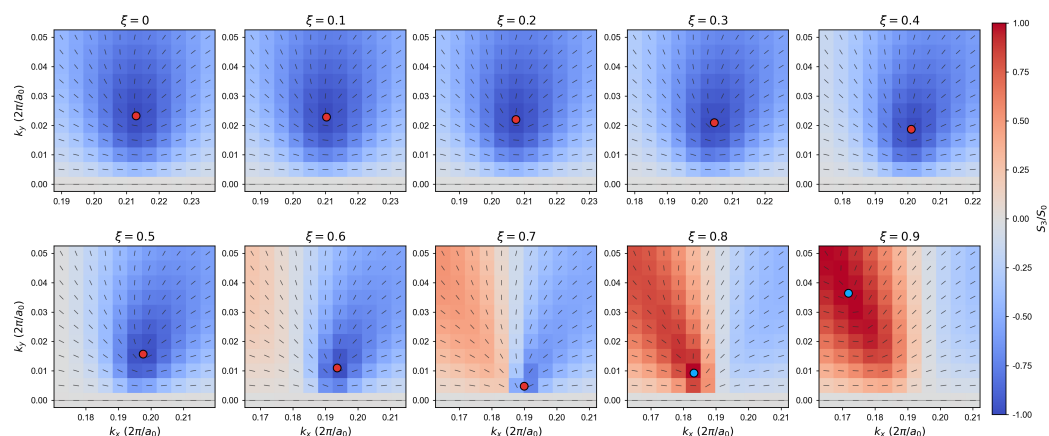


Figure 6. Air-side far-field polarization maps of the final GSST metasurface for different crystallization fractions ξ . The color map represents the normalized Stokes parameter S_3/S_0 , and the short black segments indicate the far-field polarization orientation. Due to the mirror symmetry with respect to the XOZ plane, the C points appear as symmetry-related pairs at (k_x, k_y) and $(k_x, -k_y)$. Only the upper half-plane is shown for this reason. The distance between the plotted C point and the $k_y = 0$ axis indicates how close the C-point pair is to merging. The closest approach occurs near $\xi \approx 0.7$, consistent with the strongest UGR-like radiation asymmetry observed along the $k_y = 0$ line shown in Figure 4. For clarity, the maps are shown for $\xi = 0$ – 0.9 ; at $\xi = 1$, the corresponding C point moves outside the selected small k_y window.

Because the structure is invariant along the y direction and is mirror symmetric with respect to the XOZ plane, the C points appear as symmetry-related pairs at (k_x, k_y) and $(k_x, -k_y)$. Therefore, only the upper half-plane with $k_y > 0$ is shown in Figure 6; the corresponding C point in the lower half-plane is determined by symmetry. Under this symmetry constraint, the distance of the plotted C point from the $k_y = 0$ axis provides a convenient measure of the geometric proximity of the pair to the merging condition. A smaller value of $|k_y^C|$ indicates that the two symmetry-related C points are closer to the $k_y = 0$ axis and hence closer to the UGR condition. It should be noted, however, that $|k_y^C|$ is a topological proximity indicator rather than a complete quantitative predictor of the radiation asymmetry. The absolute value of η also depends on the local radiation-coefficient gradients, the small offset between the selected operating momentum k_x^* and the C-point momentum, and the phase-dependent leakage into the substrate-side radiation channel.

As the crystallization fraction increases from $\xi = 0$, the C point gradually approaches the $k_y = 0$ axis. The minimum distance is reached near $\xi \approx 0.7$, indicating that the paired C points are closest to merging at this phase state. This behavior accounts for the pronounced enhancement of the radiation asymmetry and the peak value of η near $\xi = 0.7$. When the crystallization fraction is further increased, the C point moves away from the $k_y = 0$ axis and eventually leaves the selected momentum window near the crystalline side. Correspondingly, the directional asymmetry decreases from its peak value, although its

absolute magnitude is also influenced by the phase-dependent radiative coupling strength on both sides of the metasurface. Therefore, the observed evolution of the UGR-like response is directly correlated with the phase-change-controlled motion of the paired C points.

This result shows that the GSST phase transition does not simply switch a UGR on or off at a single phase state. Instead, it continuously tunes the C-point pair in momentum space. Over a broad crystallization range, the pair remains sufficiently close to the $k_y = 0$ axis to suppress the upward radiation channel, thereby producing persistent UGR-like directional radiation. The near-merging trajectory should therefore be understood as the topological mechanism that suppresses the air-side radiation channel, while the absolute value of η is determined by the full radiative coupling of the specific structure. In the present design, eigenfrequency calculations confirm that this suppression is sufficient to keep η above the 10^2 level for all selected phase states.

4. Discussion

The results above indicate that the directional response of the proposed metasurface is governed by a combined spectral-topological tuning mechanism. The reference-structure analysis shows that the target resonance branch originates from a parent BIC carrying an integer polarization charge. After the up-down symmetry of the radiation environment is broken by the substrate, this parent singularity is no longer preserved as an ideal non-radiating state but is unfolded into a pair of circular-polarization singularities. In the final GSST metasurface, the role of the phase-change layer is therefore not limited to shifting the resonance wavelength. More importantly, it continuously changes the momentum-space position of the paired C points and thereby tunes the distance of the system from the UGR condition.

This viewpoint also explains the nonmonotonic evolution of the radiation asymmetry during crystallization. As the GSST crystallization fraction increases, the paired C points first move toward the $k_y = 0$ axis, which drives the suppressed-side radiation channel closer to the singular condition and enhances the downward-to-upward radiation asymmetry. Near $\xi \approx 0.7$, the two symmetry-related C points are closest to the merging condition, leading to the strongest UGR-like behavior. Further crystallization moves the C-point pair away from this condition, so the asymmetry decreases. Thus, the phase-change process does not simply increase or decrease the resonance leakage monotonically; instead, it tunes the relative position between the resonance branch and the polarization-singularity structure in momentum space.

As a sensitivity check, the tracked $k_y = 0$ branch was recalculated using the symmetric Bruggeman model. At the same nominal ξ , this model gives larger effective n and k in the intermediate states and shifts the strongest UGR-like condition from approximately $\xi = 0.7$ to $\xi = 0.6$, while the amorphous and crystalline endpoints remain unchanged. Both models preserve the same nonmonotonic approach-then-depart evolution, with $\gamma_{\text{down}}/\gamma_{\text{up}} > 10^2$ and $\gamma_{\text{rad}}/\gamma_{\text{nr}} > 1$ retained throughout all 11 investigated states. Thus, the nominal intermediate-state optimum is effective-medium-model dependent, whereas the all-state high-directionality tuning trend is preserved. Because this comparison is based on the $k_y = 0$ branch, it does not represent a full two-dimensional Bruggeman reconstruction of the C-point coordinates.

The use of a near-merging C-point trajectory rather than an exact merging point is important for practical tunable operation. An exact UGR corresponds to a singular point in parameter and momentum space and is therefore inherently sensitive to structural and material variations. By contrast, the present design operates in a UGR-like regime where the paired C points remain sufficiently close to the $k_y = 0$ axis over a broad phase-change

range. This produces strong directional suppression without requiring the singularities to remain exactly merged at every nonvolatile state. Such a near-singular regime offers a useful compromise between high radiation asymmetry, finite out-coupling through the dominant side, and continuous spectral tunability. The fixed-angle analysis further shows that this regime can be accessed throughout the phase transition at one physical radiation direction, although the common high-directionality angle interval is narrow and requires precise initial alignment.

To assess representative geometry sensitivity, we evaluated a full $3 \times 3 \times 3$ factorial set comprising ridge widths of 1280, 1300, and 1320 nm, GSST thicknesses of 95, 100, and 105 nm, and physical sidewall tilts of 17° , 18° , and 19° from the vertical for each of four representative phase states, $\xi = 0, 0.3, 0.7$, and 1. These ranges correspond to approximately $\pm 1.5\%$, $\pm 5\%$, and $\pm 1^\circ$, respectively, and are treated as representative parameter-sensitivity ranges rather than process-qualified fabrication tolerances. The same TE-like branch was tracked continuously in k_x for all 108 geometry–state cases, and every reported peak was located inside a verified scan interval rather than at its boundary. On the adopted fine k_x grid, the smallest extracted peak directional ratio is 80.85, while the largest sampled value is 3.30×10^5 . Ninety-eight of the 108 cases retain $\eta \geq 10^2$, while the remaining ten lie between 80.85 and 99.06. The radiative-to-nonradiative ratio remains above unity in every case, with a minimum value of 2.561. Thus, the high-directionality regime is largely retained under the tested joint variations, although the exact process-qualified window would need to be established for a specific fabrication route.

Within the present Bloch-eigenmode picture, fabrication-induced boundary-profile deviations that remain approximately uniform along the ridge direction can modify the modal dispersion and the far-field radiation coefficients. At a given crystallization fraction, these changes may shift the air-side C-point coordinates in momentum space. If the XOZ mirror symmetry is retained, the C points remain paired at $(k_x^C, \pm k_y^C)$. Their separation $2|k_y^C|$, the crystallization fraction at which the closest approach occurs, and the selected high-directionality momentum k_x^* may therefore change, together with the associated eigenwavelength, Q factor, and directional ratio η .

The present 108 geometry–state cases quantify the sensitivity of the $k_y = 0$ peak directionality to variations in ridge width, GSST thickness, and the designed inclined-wall angle. Finite-radius corner rounding, deviations of the nominally vertical wall, and nonuniform sidewall roughness were not varied independently. Genuinely three-dimensional nonuniform roughness also lies outside the present y -invariant periodic unit-cell model and would require measured profiles or a dedicated disorder analysis.

The GSST phase transition produces an application-dependent compromise between spectral displacement and resonance sharpness. The eigenmode linewidth, estimated as $\Delta\lambda_{\text{eig}} = \lambda/Q$, increases from 20.6 nm at $\xi = 0$ to 56.7 nm at $\xi = 1$, whereas the full nonvolatile wavelength shift is 202.2 nm, or 3.56 times the broadest linewidth. The strongest directional state occurs near $\xi = 0.7$, where $Q = 129.0$ and $\Delta\lambda_{\text{eig}} \approx 33.3$ nm, rather than at the broadest fully crystalline endpoint. The lower crystalline-state Q implies a broader filtering bandwidth and lower spectral selectivity. However, a device-level signal-to-noise ratio or filter contrast cannot be inferred from the eigenfrequency data alone because these quantities also depend on the driven line shape, background response, source, receiver, and detector noise.

Representative tunable directional metasurfaces are compared in Table 2. Liquid-crystal, graphene, and mechanically deformable platforms provide substantial beam steering, while electrically switched GSST meta-optics offer broad nonvolatile spectral reconfiguration [33,35–37]. The present work targets a different combined metric: a resolvable multistate spectral shift while preserving a large one-sided eigenmode leakage ratio, in-

cluding at one fixed physical radiation direction. The comparison explicitly distinguishes asymmetry ratio, deflection efficiency, emissivity, optical contrast, material-absorption fraction, and modal branching rather than treating them as interchangeable quantities.

Table 2. Representative comparison with tunable directional metasurface platforms. N/R denotes information not reported in a directly comparable form in the cited work. Because the cited studies employ different observables and device functions, the listed quantities should not be interpreted as equivalent efficiency metrics.

Platform	Control Mechanism	Spectral Control	Directional/Angular Response	Reported Loss, Efficiency, or Related Metric
Liquid-crystal dielectric metasurface [35]	Thermal switching between nematic and isotropic LC states	Fixed-wavelength beam-switching demonstration	Beam switched between 0° and 12°	Beam-switching FOM = 0.48; total transmitted power decreases by approximately 20%
Graphene thermal metasurface [36]	Electrostatic graphene Fermi-level tuning	Fixed at $6.61\ \mu\text{m}$	Continuous angular tuning of 16°	Peak emissivity > 0.9
Mechanically deformed LCE metasurface [37]	Infrared-pump-induced mechanical deformation	Useful operating band of $0.48\text{--}1.1\ \text{THz}$	Maximum output-angle change of 22° at $0.68\ \text{THz}$	Cross-polarized first-order amplitude decreases with increasing deformation owing to additional diffraction orders
Electrically reconfigurable GSST meta-optics [33]	Electrically driven nonvolatile GSST switching	Half-octave spectral tuning	Reconfigurable beam steering; UGR asymmetry N/R	Spectral optical contrast $> 400\%$
GST-enabled UGR [34]	Nonvolatile GST switching	Asymmetry tuning at fixed k_x or fixed $\lambda = 4.392\ \mu\text{m}$; directly comparable multistate wavelength shift N/R	Numerically resolved dominant-to-suppressed radiation ratio on the order of 10^4 at the amorphous UGR endpoint	GST treated as lossless in the model; phase-dependent physical out-coupling-angle drift N/R
This work	Nonvolatile GSST switching	$202.2\ \text{nm}$ at the state-selected high-directionality points; $186.6\ \text{nm}$ at one fixed physical direction	$\eta_{\text{max}} = 2.39 \times 10^4$ and $\eta > 10^2$ at all 11 selected points; $119.6 \leq \eta \leq 191.3$ at the fixed direction corresponding to 22.93° in air and 16.52° in SiO_2	Total nonradiative fraction 24.0% at $\xi = 1$; intrinsic $\beta_{\text{down}} = 75.7\%$ at the selected crystalline endpoint and $\beta_{\text{down}} \geq 77.6\%$ along the fixed-direction trajectory

Note: The radiation-asymmetry convention in Ref. [34] is opposite to that adopted in the present work. Its result is therefore reported as the magnitude of the dominant-to-suppressed radiation ratio rather than using the symbol η .

The present work therefore concerns UGR-like resonances rather than an ideal UGR at every phase state. The C points are generally near-merging, so the suppressed channel remains finite but below 0.99% of the total radiative decay under the adopted criterion. This finite-leakage regime avoids relying on an exact singular condition while retaining nonvolatile spectral programmability; process-specific optimization will still be required for a fabricated device.

5. Conclusions

In summary, the GSST phase transition tunes both the eigenfrequency of the target resonance and the momentum-space position of its paired C points. By engineering a near-merging trajectory rather than a single exact-merging state, the same TE-like branch remains UGR-like throughout all 11 investigated phase states, providing a $202.2\ \text{nm}$ nonvolatile wavelength shift while maintaining $\eta > 10^2$ and reaching 2.39×10^4 near the optimal state. The modes remain radiatively active despite the increased material absorption toward the crystalline state, and the geometry-sensitivity analysis shows that the high-directionality regime is largely retained under the tested joint parameter variations. These results show that exact C-point merging at every phase state is unnecessary; a controlled near-singular trajectory provides a practical route to spectrally programmable directional resonances.

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Abbreviations

The following abbreviations are used in this manuscript:

BIC	Bound state in the continuum
GSST	$\text{Ge}_2\text{Sb}_2\text{Se}_4\text{Te}_1$
UGR	Unidirectional Guided Resonance

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