Materials Today Physics 35 (2023) 101113

Contents lists available at ScienceDirect

Materials Today Physics

journal homepage: www.journals.elsevier.com/materials-today-physics

Electro-optic symmetry breaking of BIC modes for tunable infrared emissivity

Alok Ghanekar *, Bo K. Shrewsbury, Chia Wei Hsu, Rehan Kapadia, Michelle L. Povinelli

Ming Hsieh Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, 90089, USA

ARTICLE INFO

Keywords:
Thermal emission
Symmetry breaking
Electro-optics modulation
Bounds states in the continuum

ABSTRACT

We present an electro-optic pathway to break symmetry to enable dynamic light-matter interaction in guided-mode resonance grating. Breaking of mirror symmetry allows accessing bounds states in the continuum (BIC) that are otherwise inaccessible. We design an electrically tunable GaAs-based guided-mode resonance grating that exhibits infrared absorption peaks in the longwave IR. The grating consists of GaAs dielectric sandwiched between the top gold contacts and the bottom gold reflector. We analyze the dependence of Q-factors on the choice of the design. We show that by careful design of the structure, a substantial radiative coupling can be obtained with broken symmetry. Our simulations predict that due to the electro-optic properties of GaAs, the application of a voltage across the dielectric allows a change in the refractive index to break the symmetry of the structure and turns the emission peak ON. Reversible refractive index tuning restores symmetry and turns the emission OFF. The concept presents a novel route toward tunable directional absorption and emission.

1. Introduction

Naturally occurring thermal emission is incoherent and static [1]. In the past two decades, infrared metamaterials have emerged to control the thermal emission spectra [2]. More recently, the possibility of dynamic and tunable thermal emission has been gathering increased attention. Material platforms such as phase-change materials [3–6], quantum wells [7,8], microelectromechanical systems [9,10], graphene [11], and III-V semiconductors [12] have been investigated for this purpose. Control of thermal emission has potential applications in energy technology [13], sensing [14], radiative cooling [15], image encoding [16], and communication [17].

The design of metamaterials for dynamic modulation of thermal emissivity could provide fine control in the spectral domain. While temperature-driven phase-change materials have been investigated for this purpose [18,19] electro-optic switching provides a much faster response [20,21]. In this context, exploring the range of angle- and wavelength-dependent tuning that can be induced by an electro-optic shift of refractive index is of general interest. Previous work in the mid-wave and long-wave infrared regime have investigated active tuning of thermal emission spectra by electro-optics. The strategies to modulate the reflection/absorption of infrared light rely primarily on a change in refractive index that leads to a shift in resonance, and/or on modulation of absorption. For example, a shift in refractive index upon carrier injection was utilized to electrically control the resonance frequencies [12,22]. Many other works take advantage of graphene for engineering such tunability of infrared light [11,20]. In another instance, tunable properties of ITO were utilized to demonstrate tunable reflectance that effectively turns the absorption ON and OFF [23].

The tunability of light-matter interactions can be enhanced if the interaction is highly sensitive to index perturbation. High sensitivity can be achieved by considering the effect of refractive index perturbation on the photonic resonance modes and band structures of the metamaterial. In our previous work, we demonstrated the use of refractive index tuning to achieve Brillouin-Zone folding. The resulting change in the photonic band structure results in sensitive, narrow linewidth switching at off-normal angles [24]. Here, we propose a new strategy for narrow linewidth emissivity switching that operates at normal incidence. The operating principle is based on using a small refractive index shift to break the symmetry of a bound state in the continuum (BIC). This enables selective ON-OFF switching of infrared emission at normal incidence.

Bound states in the continuum (BICs) are nonradiative states with an infinite lifetime [25]. Symmetry-protected BICs cannot radiatively couple to incoming or outgoing plane waves. BICs have been extensively studied due to their exciting properties, such as high energy confinement

* Corresponding author.
E-mail address: aghaneka@usc.edu (A. Ghanekar).

https://doi.org/10.1016/j.mtphys.2023.101113
Received 16 February 2023; Received in revised form 1 May 2023; Accepted 18 May 2023
Available online 19 May 2023

[26] and robustness [27]. Quasfi-BICs wfith very hfigh Q-factors have been reaflfized fin photonfic crystafls [28], wavegufide arrays [29], and gratfings [30]. By perturbfing the symmetry of the system, bound states become accessfibfle to radfiatfive coupflfing. Most prevfious studfies have focused on statfic photonfic structures, where the symmetry fis perturbed vfia geometrficafl varfiatfions fin the structure [31–35].

Here we present a reversfibfle, eflectro-optfic pathway to break the symmetry of a BIC mode, tunfing fits coupflfing to outgofing radfiatfion. We desfign a gufided-mode resonance devfice fin the finfrared wfith the capabfiflfity for eflectro-optfic tunfing. Gufided-mode resonance devfices [36,37] are perfiodfic structures that provfide strong flocaflfizatfion of eflectrfic ffiefflds, resufltfing fin hfigh, narrow flfinewfidth absorptfion [38] and emfissfion [39]. We theoretficaflfly demonstrate a devfice geometry that aflflows the seflectfive tunfing of the refractfive findex of portfions of the gufided-mode resonance devfice, breakfing the mfirror symmetry wfithfin each unfit cefllfl. We study the effect of devfice geometry on radfiatfive coupflfing. We show that by changfing the geometry, one can desfign the structure to enhance the radfiatfive coupflfing of the symmetry-broken resonance mode. We demonstrate that by carefufl chofice of gratfing geometry, crfitficafl coupflfing requfired for strong absorptfion can be achfieved. We expflficfitfly modefl the vofltage-dependent carrfier concentratfions and refractfive findex shfifts wfithfin the semficonductor flayer of the devfice, aflflowfing us to numerficaflfly anaflyze the effect of symmetry breakfing on thermafl emfissfion spectra fin the flong-wave finfrared. We show that fin a gufided-mode-resonance gratfing based on GaAs and gofld, reversfibfle symmetry breakfing can actfivefly turn the emfissfion ON and OFF. These resuflts findficate excfitfing possfibfiflfitfies for achfievfing eflectrficaflfly tunabfle controfl over thermafl emfissfion spectra at normafl fincfidence.

2. Theory

To fiflflustrate the mafin fidea presented fin the paper, consfider a gufided mode resonance gratfing sfituated over a gofld back refflector. The unfit cefllfl of the gratfing fis shown fin Ffig. 1 (a). The unfit cefllfl has two dfieflectrfic strfipes (wfith refractfive findex n = 3.3) of equafl hefights, separated by a smaflfl gap. The gap between the strfipes of a unfit fis smaflfler than the gap between the dfieflectrfic strfipes of adjacent unfits. Such a symmetrfic structure supports both symmetrfic and antfi-symmetrfic modes at normafl fincfidence (k_x = 0) [40]. For a normaflfly-fincfident pflane wave wfith the eflectrfic ffiefld poflarfized out of the pflane, modes wfith odd mfirror symmetry ($E_z(x) = -E_z(-x)$) cannot coupfle wfith the fincfident wave. Thfis fleads to near-zero absorptfivfity. If the normafl-fincfidence absorptfivfity fis zero, the emfissfivfity at normafl fis aflso zero by Kfirchhoff's Law.

A modafl proffifle wfith odd mfirror symmetry fis shown fin Ffig. 1(b). The eflectrfic ffiefld excfited by a normaflfly fincfident pflane wave at the resonance frequency fis shown fin Ffig. 1(c). As expected, the mfirror symmetry of the ffiefld fis dfifferent than fin Ffig. 1(b), and $E_z(x) = E_z(-x)$. We do not observe excfitatfion of the resonant mode.

We study the effect of findex perturbatfions shown fin Ffig. 1(d). The fleft dfieflectrfic strfipe has a reduced refractfive findex (n = 3.2), and the unfit cefllfl has no mfirror symmetry. Ffig. 1 (e) shows the modafl proffifle of the perturbed gratfing wfith broken symmetry. The proffifle appears sflfightfly asymmetrfic. As shown fin Ffig. 1(f), the mode can now be excfited by a normaflfly fincfident pflane wave at the resonance frequency. The correspondfing ffiefld proffifle shown fin Ffig. 1(f) dfispflays the excfitatfion of the resonance. The ffiefflds resembfle the mode fin Ffig. 1(e), and the magnfitude fis much flarger than fin the non-resonant case of Ffig. 1(c). Whfifle perturbatfion of symmetry coufld aflso be achfieved by changfing the geometry, we focus on actfive, reversfibfle breakfing of symmetry by eflectro-optfic tunfing of the refractfive findex.

To achfieve hfigh absorptfivfity (or emfissfivfity) on resonance, the radfiatfive floss rate and absorptfive floss rate of the resonance must be comparabfle. The radfiatfive and absorptfive quaflfity factors are finversefly proportfionafl to the floss rates. The peak absorptfivfity ampflfitude of the gratfing approaches 100% when the quaflfity factors are equafl [39].

To understand the dependence of Q factors on perturbatfions, we caflcuflate radfiatfive and absorptfive Q factors for the desfign geometrfies of finterest. The totafl Q factor Q_{totafl} fis obtafined usfing efigenfrequency sfimuflatfions fin COMSOL. By settfing the fimagfinary part of the permfittfivfity to zero (and effectfivefly turnfing off the flosses), we obtafin the radfiatfive Q factor Q_{rad}. Thus, the absorptfive Q can be obtafined as $Q_{abs} = (1/Q_{totafl} - 1/Q_{rad})^{-1}$. The quaflfity factors are pflotted fin Ffig. 2(a). For the unperturbed gratfing, the Q_{rad} fis finffinfite whfifle Q_{abs} fis smaflfl. As seen fin Ffig. 2 (a), for the perturbatfion of 10^{-4}, Q_{rad} fis about 2×10^9 whfifle Q_{abs} fis about 1100. As the findex perturbatfion fis fintroduced to break symmetry, Q_{rad} reduces whfifle Q_{abs} remafins reflatfivefly constant. More substantfiafl perturbatfion brfings Q_{rad} and Q_{abs} cfloser untfifl they are equafl. To characterfize the dependency of Q_{rad} on perturbatfion, Kosheflev et afl. [35] fintroduced a metrfic caflfled asymmetry parameter α. They studfied varfious cases of geometrfic perturbatfion and observed that α depends on the structure. Here we deffine $\alpha = |\Delta n|/n$ and verfify the finverse squared flaw [35] between Q_{rad} and α. It fis shown by the dashed flfine fin Ffig. 2(a). Q_{abs} fis prfimarfifly determfined by materfiafl floss, whereas the modafl proffifle and the geometry determfine Q_{rad}. Therefore, we expect the fintersectfion

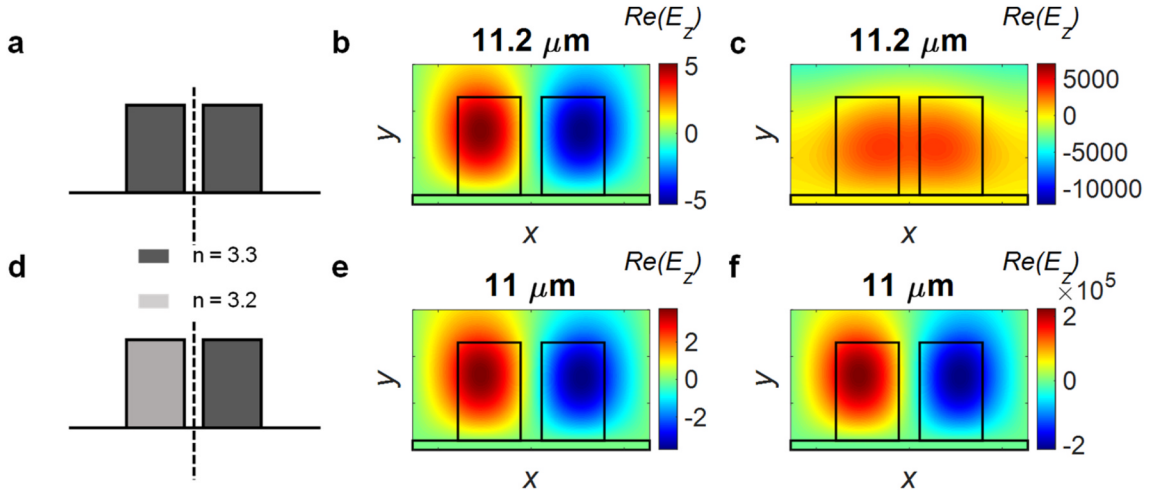

Fig. 1. (a) Unfit cefllfl of a gratfing wfith mfirror symmetry. Dfieflectrfic strfipes sfituated over a gofld flayer have a hefight of 2.1 μm and a wfidth of 1.35 μm. The separatfion between them fis 225 nm, whfifle the perfiodficfity of the structure fis 5.1 μm. (b) The correspondfing modafl proffifle of a typficafl BIC mode wfith odd mfirror symmetry $E_z(x) = -E_z(-x)$. (c) Ffiefld excfitatfion of the BIC wfith normaflfly fincfident pflane wave shows weak coupflfing. (d) Unfit cefllfl of a gratfing wfith broken symmetry (e) Modafl proffifle for the correspondfing perturbed gratfing wfith broken symmetry. (f) Excfitatfion of the resonance wfith normaflfly fincfident pflane wave.

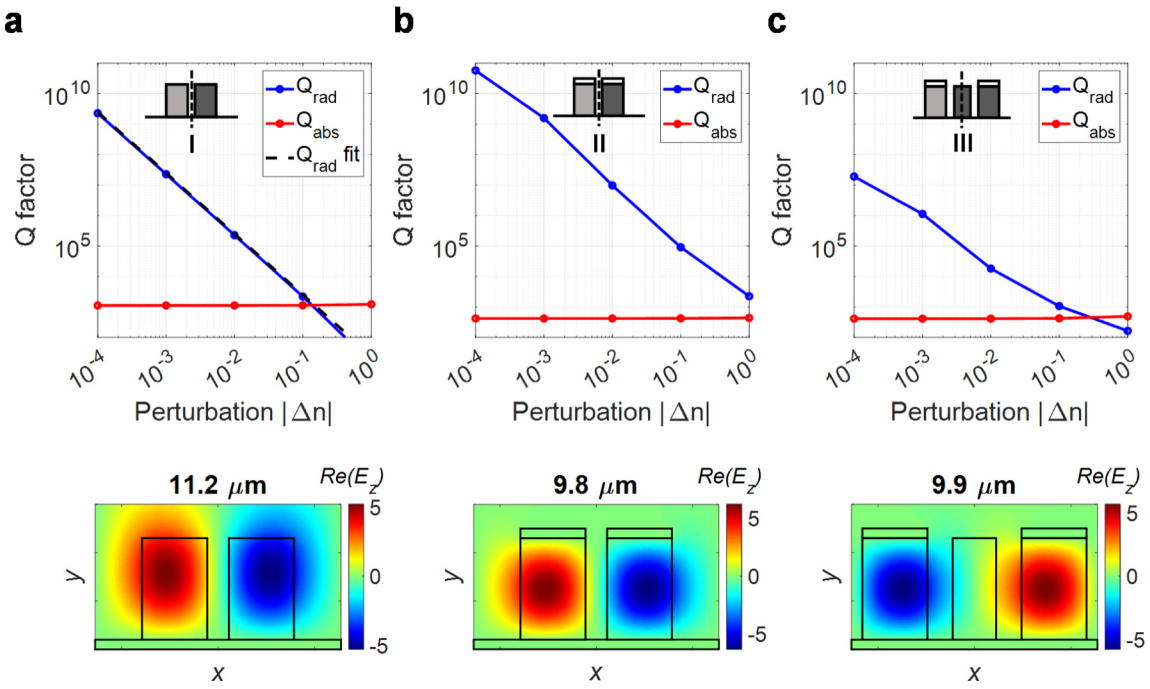

Fig. 2. Radfiatfive and absorptfive Q pflotted vs. findex perturbatfion for three dfifferent gratfing desfigns. The correspondfing ffiefld proffifles of BIC modes are shown beflow. (a) Desfign I: two dfieflectrfic strfipes. (b) Desfign II: two dfieflectrfic strfipes wfith metaflflfic caps (200 nm thfick). (c) Desfign III: three dfieflectrfic strfipes wfith metaflflfic caps on the fleft and rfight strfipes. The center-to-center dfistance between the fleft and rfight strfipes fis 3.3 μm. The center strfipe fis 900 nm wfide.

pofint between the two curves to occur at a flarger vaflue of Δn fif the materfiafl floss were hfigher (flower Q_{abs}).

Devfice I fis an fideaflfized structure; fin generafl, eflectrficafl contacts must be added to provfide findex tunfing. Devfice II (Ffig. 2(b) finset) adds metafl caps to the gratfing to serve as eflectrficafl top contacts, whfifle the metafl back pflane serves as a bottom contact. However, the addfitfion of metafl caps changes the modafl proffifle, affectfing the response of the gratfing to perturbatfion. In Ffig. 2(b), we pflot the Q factors. We notfice that Q_{rad} fis now sfignfifficantfly hfigher, whfifle Q_{abs} has reduced to ~400. As seen from the ffiefld pflot beflow Ffig. 2(b), the ffiefld has an fincreased confffinement fin the dfieflectrfic, and the presence of the metaflflfic caps appears to reduce the radfiatfive coupflfing. The presence of flossy metafl caps aflso expflafins the reductfion fin Q_{abs}. A substantfiafl dfifference between Q_{rad} and Q_{abs} remafins at sfignfifficant findex perturbatfion. It fis thus not strafightforward to achfieve crfitficafl coupflfing ($Q_{rad} = Q_{abs}$) wfithout the use of extremefly hfigh Δn vaflues.

To ameflfiorate thfis probflem, we fintroduce a modfiffied desfign wfith fimproved performance. Desfign III has a unfit cefll wfith three dfieflectrfic strfipes of equafl hefights, wfith the center strfipe havfing a smaflfler wfidth (Ffig. 2(c) finset). The fleft and rfight strfipes have metaflflfic caps. Q factors for thfis desfign are pflotted fin Ffig. 2(c). We notfice that Q_{rad} fis reduced by orders of magnfitude wfith respect to Ffig. 2(b). The addfitfion of the center strfipe may provfide an access route for the radfiatfive coupflfing to the externafl pflane waves. Aflthough Q_{rad} and Q_{abs} are not equafl, they are comparabfle fin magnfitude for findex perturbatfion of 0.1. Lfiterature fin-dficates that such a change fin refractfive findex fis achfievabfle fin the case of materfiafls such as GaAs [22], InAs [41], and ITO [42] fin the mfid and flong-IR regfimes.

3. Results and discussion

Ffig. 3 fiflflustrates how the eflectro-optfic tunfing requfired for Desfign III may be achfieved fin practfice. Ffig. 3(a) shows the schematfic, where the dashed flfine findficates one unfit cefll. Ffig. 3(b) shows the unfit cefll dfimensfions fin detafifl. Wfithfin each unfit cefll, the center strfipe has a smaflfler wfidth. The fleft and rfight strfipes have 200 nm thfick gofld caps. The gratfing fis sfituated over a refflectfing gofld substrate. GaAs was chosen

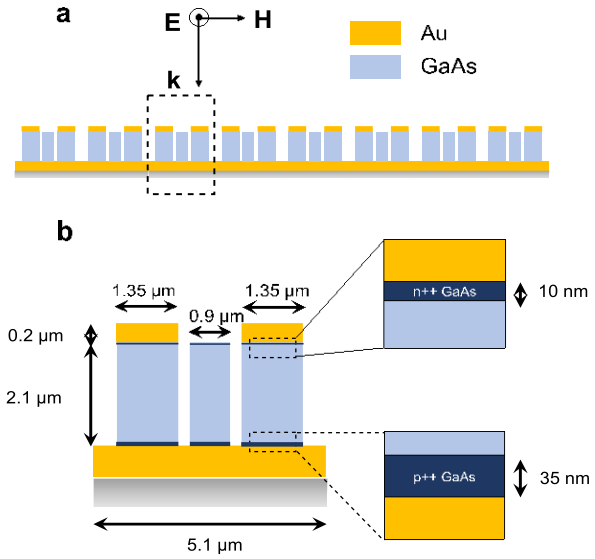

Fig. 3. (a) Gufided-mode resonance gratfing consfistfing of a dfieflectrfic (GaAs) on a gofld substrate wfith gofld caps. (b) The unfit cefll of the gratfing has three dfieflectrfic strfipes wfith equafl hefights. The Center strfipe has a smaflfler wfidth. Onfly the fleft and rfight strfipes have metaflflfic caps. The top and bottom flayers of the dfieflectrfic are heavfifly doped wfith n++ and p++, respectfivefly.

because fits refractfive findex fis affected by carrfier concentratfion. Top and bottom metafl contacts can be used to finject charge carrfiers finto the GaAs flayer. To aflflow the finjectfion of carrfiers finto the fintrfinsfic GaAs flayer, a smaflfl portfion of the flayer near the metafl contacts fis heavfifly doped. Such heavfifly doped flayers are typficaflfly used to avofid the formatfion of flarge depfletfion regfions [43]. As schematficaflfly shown fin Ffig. 3(b), we assume that the 10 nm flayer of GaAs near the top contact fis n++ doped (5×10 cm^{18}) and the 35 nm thfick flayer of GaAs near the bottom contact fis p++ (5×10 cm^{18}) dopped. Together wfith the contacts, the flayers form a p-fi-n junctfion eflectro-optfic moduflator. Aflthough onfly the fleft GaAs

strfipe wfffl be subjected to carrfier finjectfion, both the rfight and the fleft strfipes have gofld caps and affl strfipes have heavfifly doped flayers so that the orfigfinafl structure fis symmetrfic. In our sfimuflatfions, we fflimfit ourseflves to transverse eflectrfic poflarfizatfion (H_x, H_y, E_z). The dfimensfions of the unfit cefll were chosen to have resonance around 10 μm, whfich fis approxfimatefly the thermafl waveflength at room temperature. The dfimensfions shown fin Ffig. 3(b) were optfimfized for maxfimum susceptfibfiflfity to findex perturbatfion by trfiafl and error.

Ffig. 4(a) shows the conffiguratfion to aflflow findex perturbatfion by appflyfing a vofltage across the dfieflectrfic strfipe. Onfly the fleft strfipe wfithfin each unfit cefll wfffl undergo a change fin carrfier concentratfion and refractfive findex. We sfimuflate the effect of vofltage on carrfier concentratfion fin GaAs usfing Lumerficafl CHARGE. We use steady state boundary condfitfions wfith the gofld cap as a contact at 0 V and the bottom gofld flayer as a contact wfith varyfing vofltage from 0.5 to 2 V.

The sfimuflated carrfier concentratfion of eflectrons (n) fin the GaAs flayer at 0 V and 1.4 V fis shown fin Ffig. 4(b) and (c), respectfivefly. The appflfifcatfion of vofltage sfignfifficantfly changes the carrfier concentratfion across the majorfity of the GaAs flayer. The carrfier concentratfion of eflectrons (n) at the center of the GaAs flayer fis pflotted as a functfion of appflfied vofltage fin Ffig. 4(d). The hfighflfighted data pofints correspond to 0 V (1.76×10^6 cm ^{3}) and 1.4 V (6.48×10^{17} cm ^{3}). These vaflues are used to estfimate refractfive findfices of the tunabfle GaAs flayer.

Predficted vaflues of refractfive findex (n) and extfinctfion coeffficfients (κ) for varfious concentratfion flevefls are pflotted fin Ffig. 4(e) and (f), respectfivefly. Refractfive findex vaflues are obtafined from the GaAs Drude modefl that accounts for the change fin pflasma frequency as a functfion of carrfier concentratfion, and fit fis gfiven by [44].

$$\varepsilon = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma}\right). \quad (1)$$

Here ε_∞, ω, ω_p and Γ are flow-frequency permfittfivfity, anguflar frequency, pflasma frequency, and dampfing constant, respectfivefly. The pflasma frequency of doped GaAs fis carrfier-dependent and fis gfiven by

$$\omega_p = \frac{N_d e^2}{\varepsilon_0 \varepsilon_\infty m^*}. \quad (2)$$

Here, ε_0, e, N_d, and m^* are free-space permfittfivfity, eflementary charge, dopfing concentratfion, and effectfive eflectron mass, respectfivefly. m^* fis assumed to be 0.52^*m_0 for hofles (p-type) and 0.067^*m_0 for eflectrons, when m_0 fis eflectron mass. The dampfing constant fis reflated to carrfier mobfiflfity (μ) and m^* by the equatfion

$$\Gamma = \frac{e}{\mu m^*}. \quad (3)$$

In our caflcuflatfions, μ fis taken to be 400 cm ^{2}/V•s for hofles [45] and 8000 cm^2/V•s for eflectrons [46]. As shown fin Ffig. 4(e), the dfifference between the refractfive findex of fintrfinsfic GaAs and p + GaAs (6.48×10 cm^{17}) fis approximatefly 0.15 over the waveflength range of finterest. Whfifle fintrfinsfic GaAs fis essentfiafllfly flossfless fin thfis regfime, there fis an fincrease fin extfinctfion coeffficfient (κ) upon carrfier finjectfion. Ffig. 4(g) shows spatfiafl varfiatfion of refractfive findex fin the GaAs flayer at 10 μm waveflength for 0 V and 1.4 V. For the perturbed structure, the refractfive findex (n) of the tunabfle GaAs flayer varfies wfith vertficafl co-ordfinate (y). In our sfimuflatfions, the tunabfle GaAs flayer was dfivfided finto subflayers, each havfing a constant refractfive findex. The number of subflayers was fincreased untfifl caflcuflated absorptfivfity spectrum converged. Ffive subflayers were found to be suffficfient to achfieve convergence. The totafl varfiatfion fin n fis approxfimatefly 0.11. Wfithfin each flayer, the varfiatfion fin refractfive findex fis approxfimatefly 0.02. Affl the subsequent caflcuflatfions reported are done usfing ffive subflayers.

We sfimuflate the absorptfivfity of the gratfing usfing the COMSOL wave optfics sfimuflatfion soflver. The soflver uses the ffinfite-eflement, frequency-

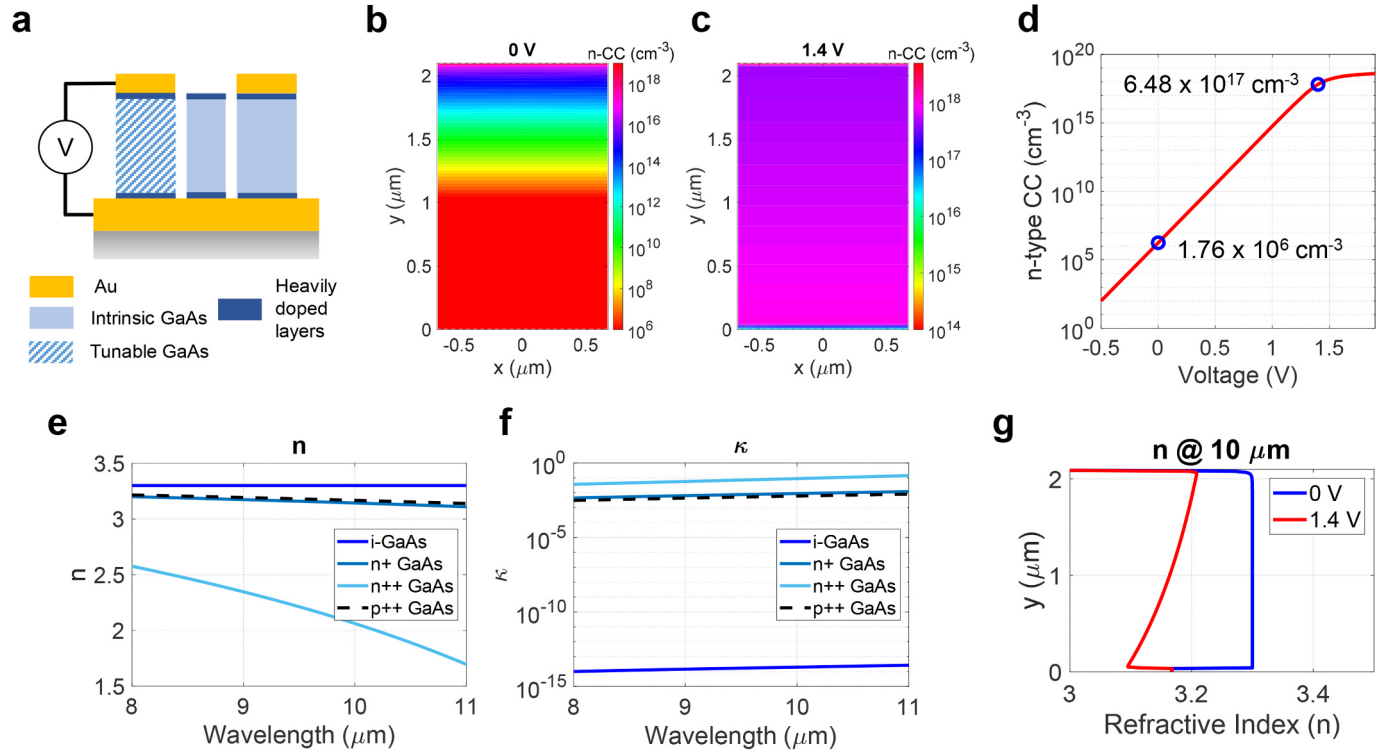

Fig. 4. (a) Proposed conffiguratfion to fintroduce findex perturbatfion for dynamfic symmetry breakfing. Appflyfing a vofltage across the fleft strfipe usfing the gofld cap and the metaflflfic substrate as contacts enabfles reversfibfle n + dopfing of the GaAs flayer. The carrfier concentratfion of eflectrons (n) fin the GaAs flayer at (b) 0 V and (c) 1.4 V. (d) The carrfier concentratfion of eflectrons (n) at the center of the GaAs flayer fis pflotted as a functfion of appflfied vofltage. Refractfive findex n (e) and extfinctfion co-effficfient κ (f) pflotted as a functfion of waveflength for fi-GaAs (0 V), n + GaAs (1.4 V), n++ GaAs (top flayer), and p++ GaAs (bottom flayer). (g) Spatfiafl varfiatfion fin refractfive findex (n) of the dfieflectrfic flayer at 10 μm as a functfion of y-coordfinate for 0 V and 1.4 V.

domafin method to soflve Maxweflfl's equatfions. Bfloch perfiodfic boundary condfitfions were used for the fleft and rfight boundarfies of the unfit ceflfl. The absorptfivfity (a) of the structure fis gfiven by $a = 1 - r$, where r fis refflectfivfity. We note that a vofltage bfias to a p-fi-n dfiode can change the chemficafl potentfiafl of photons emfitted for the photons above the band gap of the semficonductor. Thfis may flead to super-Pflanckfian thermafl emfissfion [47]. However, fin the present study, GaAs has a band gap of 1.424 eV (0.87 μm). The chemficafl potentfiafl of photons fin the wave-flength range of finterest fis unaffected. Therefore, Kfirchhoff's flaw of thermafl radfiatfion hoflds. From Kfirchhoff's flaw, emfissfivfity (e) equafls absorptfivfity.

The emfissfivfity of the unperturbed gratfing at normafl fincfidence fis shown fin Ffig. 5(a). The spectrum shows a promfinent peak around 10 μm. Thfis peak corresponds to a brfight mode. At the same tfime, a dark mode (BIC) exfists at the waveflength hfighflfighted by the dashed flfine. Due to symmetry, the normaflfly fincfident wave cannot coupfle wfith the reso-nance, and no excfitatfion fis seen fin the BIC ffiefld proffifle (shown fin the finset). Ffig. 5(b) shows the emfissfivfity spectrum for the perturbed gratfing at 1.4 V. The spectrum dfispflays as an addfitfionafl peak. Due to findex perturbatfion, the symmetry fis broken, and the dark mode becomes brfight. As a resuflt, the resonance can now be excfited by a normaflfly fincfident pflane wave. The ffiefld proffifle of the excfited resonance fis shown fin the finset. The asymmetrfic modafl shape fis apparent. Due to the reversfibfle nature of vofltage tunabfle carrfier finjectfion, thfis method aflflows a pathway to ON-OFF swfitchfing of emfissfive resonances. An ON-OFF contrast ratfio of ~40 fis predficted.

The dependence of spectrafl emfissfivfity on the angfle of fincfidence (θ) fis pflotted fin Ffig. 6. The emfissfivfity of the unperturbed gratfing fis shown fin Ffig. 6(a) and exhfibfits two brfight bands. These bands correspond to the resonances that can be excfited by an externafl pflane wave. The flower waveflength band shows a dark spot, or a hofle, at $\theta = 0$, hfighflfightfing the flocatfion of the BIC. As thfis fis a symmetry-protected BIC, fit fis dark onfly for $k_x = 0$. Off-normafl pflane waves have non-zero convoflutfion wfith the modafl proffifle and can excfite the resonance, whfich expflafins the appearance of the hofle fin the contour pflot. Ffig. 6(b) pflots the anguflar spectrafl emfissfivfity for the perturbed gratfing at 1.4 V. The emfissfivfity hofle at the flocatfion of BIC fis notficeabfly ffiflfled. As a resuflt of the findex perturbatfion, we aflso observe a shfift fin the bands and an fincrease fin the gap between bands. Due to the shfift fin the band structure, off-normafl thermafl emfissfion exhfibfits shfift fin resonance peaks.

The proposed gratfing can be fabrficated by tempflated flfiqufid-phase crystafl growth [48], or epfitaxfiafl transfer [49], foflflowed by chemficafl vapor deposfitfion of gofld and etchfing. The eflectro-optfic nature of the tunfing mechanfism aflso enabfles hfigh-speed ON-OFF swfitchfing. The moduflatfion speed of such a devfice can be estfimated usfing the equfivaflent capacfitor-resfistor cfircufit. For the desfign presented fin the paper, assumfing a devfice footprfint of 10,000 μm², we estfimate the devfice capacfitance to be approxfimatefly 300 fF. Usfing a conservatfive vaflue of contact resfistance of 50 Ω and transmfissfion flfine resfistance of 50 Ω, we estfimate that the devfice can operate up to 5 GHz. Eflectro-optfic breakfing of symmetry can be appflfied to any eflectro-optfic materfiafl such as InAs, GaAs, ITO, and aflfloys of In, Ga, As, and Sb. Dfimensfions of the gratfing can be adjusted to excfite resonances fin the desfired spectrafl range. By care-fuflfly desfignfing the BICs, we expect that tunabfle emfissfion can be attafined at any waveflength.

4. Conclusions

In concflusfion, we theoretficaflfly demonstrated the feasfibfiflfity of usfing eflectro-optfics to break symmetry and access a symmetry-protected BIC. Reversfibfle findex perturbatfion enabfled by carrfier finjectfion aflflows swfitchfing resonance and tunabfle thermafl emfissfion. We predfict a contrast ratfio of 40 upon moduflatfion. The desfign hfighflfights a pathway for deveflopfing vofltage-tunabfle narrowband thermafl emfitters and ab-sorbers. Eflectro-optfic drfiven symmetry breakfing can have varfious fim-pflfficatfions for tunabfle thermafl emfissfion, espefiafflfly when swfitchfing of narrowband resonances fis desfired. Such appflficatfions fincflude fimage encryptfion [16] and communficatfion [17]. Present work takes advantage of a mfismatch (match) between Q_{rad} and Q_{abs} to turn the emfissfion OFF (ON). Such a mfismatch can aflso be finduced at obflfique angfles of fincfi-dence, even fin the absence of BICs. Hence, tunabfle flfight-matter fin-teractfions can be engfineered at off-normafl fincfident angfles. Besfides symmetry protected BICs, accfidentafl BICs [28] that occur at obflfique angfles can aflso be studfied for findex perturbatfion and tunfing of thermafl emfissfion. Therefore, we envfisfion that the scheme of reversfibfle symme-try breakfing can be extended to anguflar resonances. The fidea presented here can aflso be extended for two-dfimensfionafl gratfings, gfivfing rfise to fintrfigufing new possfibfiflfities of tunabfle thermafl emfissfion.

Thfis work fis funded by NGA under NURI Award HM0476-20-1-0004.

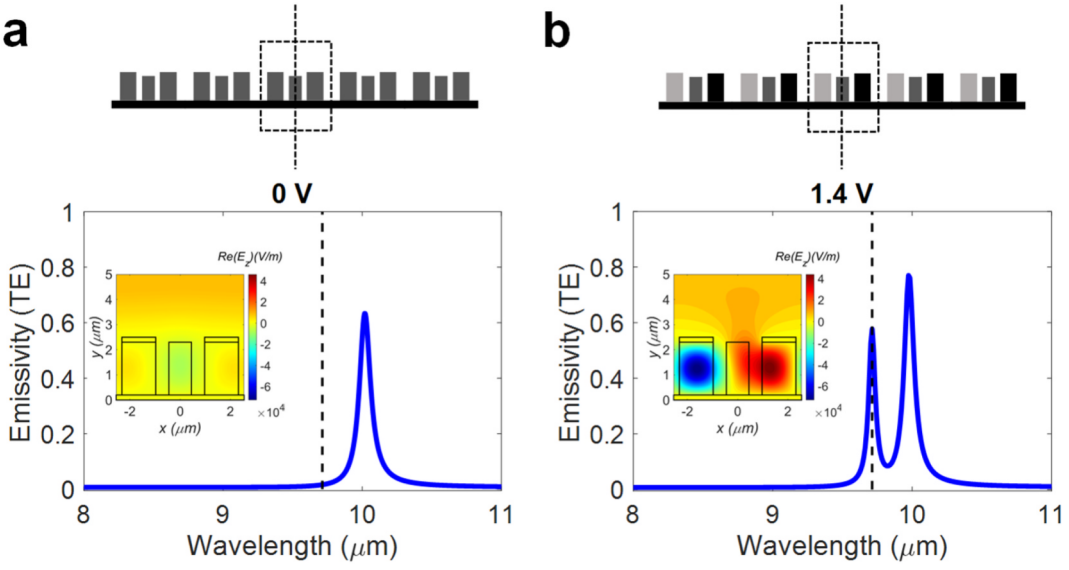

Fig. 5. (a) The emfissfivfity of the unperturbed gratfing at normafl fincfidence. The dashed flfine findficates the flocatfion of the dark mode wfith near-zero emfissfivfity. The ffiefld proffifle of the dark mode fis shown fin the finset. (b) The emfissfivfity of the perturbed gratfing wfith a broken symmetry at 1.4 V shows a new peak. The ffiefld proffifle of the correspondfing resonance fis pflotted fin the finset.

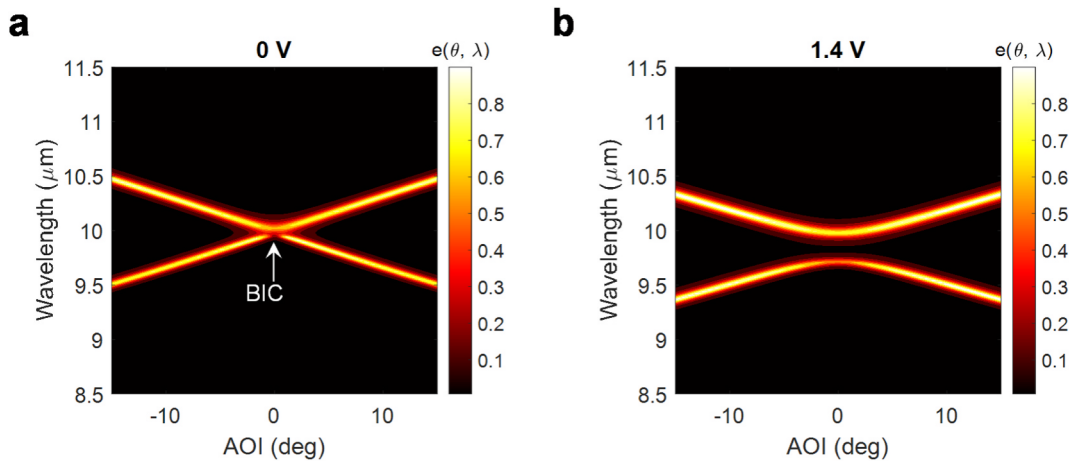

Fig. 6. (a) Emfissfivfity of the unperturbed gratfing pflotted as a functfion of angfle of fincfidence and waveflength. The flower brfight band shows a 'hofle' at 0 deg, findficatfing the BIC. (b). The emfissfivfity of the structure wfith broken symmetry (at 1.4 V).

Declaration of competing interest

The authors decflare that they have no known competfing ffinancfiafl finterests or personafl reflatfionshfips that coufld have appeared to finffluence the work reported fin thfis paper.

Data availability

Data wfffl be made avafiflabfle on request.

References

[1] M.F. Modest, Radfiatfive Heat Transfer, Academfic press, 2013.
[2] S. Fan, Joufle 1 (2) (2017) 264–273.
[3] M.A. Kats, R. Bflanchard, S. Zhang, P. Genevet, C. Ko, S. Ramanathan, F. Capasso, Phys. Rev. X 3 (4) (2013): 041004.
[4] K.-K. Du, Q. Lfi, Y.-B. Lyu, J.-C. Dfing, Y. Lu, Z.-Y. Cheng, M. Qfiu, Lfight Scfi. Appfl. 6 (1) (2017): e16194-e16194.
[5] A. Ghanekar, G. Xfiao, Y. Zheng, Scfi. Rep. 7 (1) (2017) 1–7.
[6] A.M. Morsy, M.T. Barako, V. Jankovfic, V.D. Wheefler, M.W. Knfight, G.T. Papadakfis, L.A. Sweatflock, P.W. Hon, M.L. Povfineflflfi, Scfi. Rep. 10 (1) (2020) 1–10.
[7] T. Inoue, M. De Zoysa, T. Asano, S. Noda, Nat. Mater. 13 (10) (2014) 928–931.
[8] J. Lee, S. Jung, P.Y. Chen, F. Lu, F. Demmerfle, G. Boehm, M.C. Amann, A. Aflù, M. A. Beflkfin, Adv. Opt. Mater. 2 (11) (2014) 1057–1063.
[9] M.U. Praflfle, I. Puscasu, J. Dafly, K. Faflflon, P. Loges, A. Greenwafld, E. Johnson, Infrared Technoflogy and Appflficatfions, XXXIII, vofl. 6542,, SPIE, 2007, pp. 973–977.
[10] H. San, X. Chen, P. Xu, F. Lfi, M. Cheng, Infrared Technoflogy and Appflficatfions XXXIV, 6940, SPIE, 2008, pp. 609–617.
[11] V.W. Brar, M.C. Sherrott, M.S. Jang, S. Kfim, L. Kfim, M. Chofi, L.A. Sweatflock, H. A. Atwater, Nat. Commun. 6 (1) (2015) 1–7.
[12] J. Park, J.-H. Kang, X. Lfiu, S.J. Maddox, K. Tang, P.C. McIntyre, S.R. Bank, M. L. Brongersma, Scfi. Adv. 4 (12) (2018) eaat3163.
[13] A. Lenert, D.M. Bfierman, Y. Nam, W.R. Chan, I. Ceflanovfic, M. Sofljacfic, E.N. Wang, Nat. Nanotechnofl. 9 (2) (2014) 126–130.
[14] A. Kamboj, L. Nordfin, P. Petfluru, A. Muhowskfi, D. Wooflf, D. Wasserman, Appfl. Phys. Lett. 118 (20) (2021): 201102.
[15] A.P. Raman, M. Abou Anoma, L. Zhu, E. Rephaeflfi, S. Fan, Nature 515 (7528) (2014) 540–544.
[16] M. Makhsfiyan, P. Bouchon, J. Jaeck, J.-L. Peflouard, R. Haïdar, Appfl. Phys. Lett. 107 (25) (2015): 251103.
[17] R. Audhkhasfi, M.L. Povfineflflfi, Scfi. Rep. 11 (1) (2021) 1–9.
[18] A. Krfishnan, A.B. O'Gorman, M.L. Povfineflflfi, J. Opt. 22 (9) (2020): 094002.
[19] H. Kocer, S. Butun, B. Banar, K. Wang, S. Tongay, J. Wu, K. Aydfin, Appfl. Phys. Lett. 106 (16) (2015): 161104.
[20] S. Kfim, M.S. Jang, V.W. Brar, K.W. Mauser, L. Kfim, H.A. Atwater, Nano Lett. 18 (2) (2018) 971–979.
[21] J. Park, S.J. Kfim, V.J. Sorger, S.J. Kfim, Nanophotonfics 11 (6) (2022) 1117–1126.
[22] Y.C. Jun, E. Gonzafles, J.L. Reno, E.A. Shaner, A. Gabbay, I. Brener, Opt Express 20 (2) (2012) 1903–1911.
[23] J. Park, J.-H. Kang, X. Lfiu, M.L. Brongersma, Scfi. Rep. 5 (1) (2015) 1–9.
[24] A. Ghanekar, R. Kapadfia, M.L. Povfineflflfi, J. Quant. Spectrosc. Radfiat. Transf. 293 (2022): 108367.
[25] C.W. Hsu, B. Zhen, A.D. Stone, J.D. Joannopouflos, M. Sofljacfic, Nat. Rev. Mater. 1 (9) (2016) 1–13.
[26] A.S. Kuprfifianov, Y. Xu, A. Sayanskfiy, V. Dmfitrfiev, Y.S. Kfivshar, V.R. Tuz, Phys. Rev. Appfl. 12 (1) (2019): 014024.
[27] T. Lepetfit, B. Kante, Phys. Rev. B 90 (24) (2014): 241103.
[28] C.W. Hsu, B. Zhen, J. Lee, S.-L. Chua, S.G. Johnson, J.D. Joannopouflos, M. Sofljacfic, Nature 499 (7457) (2013) 188–191.
[29] Y. Pflotnfik, O. Pefleg, F. Drefisow, M. Hefinrfich, S. Noflte, A. Szamefit, M. Segev, Phys. Rev. Lett. 107 (18) (2011): 183901.
[30] H.M. Doefleman, F. Montficone, W. den Hoflflander, A. Aflù, A.F. Koenderfink, Nat. Photonfics 12 (7) (2018) 397–401.
[31] A.C. Overvfig, S. Shrestha, N. Yu, Nanophotonfics 7 (6) (2018) 1157–1168.
[32] Y. Wang, J. Song, L. Dong, M. Lu, JOSA B 33 (12) (2016) 2472–2479.
[33] A. Overvfig, N. Yu, A. Aflù, Phys. Rev. Lett. 126 (7) (2021): 073001.
[34] A.I. Ovcharenko, C. Bflanchard, J.-P. Hugonfin, C. Sauvan, Phys. Rev. B 101 (15) (2020): 155303.
[35] K. Kosheflev, S. Lepeshov, M. Lfiu, A. Bogdanov, Y. Kfivshar, Phys. Rev. Lett. 121 (19) (2018): 193903.
[36] S. Wang, R. Magnusson, J.S. Bagby, M. Moharam, J. Opt. Soc. Am. A 7 (8) (1990) 1470–1474.
[37] S. Fan, J.D. Joannopouflos, Phys. Rev. B 65 (23) (2002): 235112.
[38] P.D. Anderson, C. Lfin, M.L. Povfineflflfi, Appfl. Phys. A 117 (4) (2014) 1879–1884.
[39] Y. Guo, S. Fan, Opt Express 24 (26) (2016) 29896–29907.
[40] J.D. Joannopouflos, S.G. Johnson, J.N. Wfinn, R.D. Meade, fin: Photonfic Crystafls, Prfinceton unfiversfity press, 2011.
[41] B. Passmore, D. Aflflen, S. Vangafla, W. Goodhue, D. Wasserman, E. Shaner, Opt Express 17 (12) (2009) 10223–10230.
[42] X. Lfiu, J. Park, J.-H. Kang, H. Yuan, Y. Cufi, H.Y. Hwang, M.L. Brongersma, Appfl. Phys. Lett. 105 (18) (2014): 181117.
[43] S.A. Campbeflfl, The Scfience and Engfineerfing of Mficroeflectronfic Fabrficatfion, Oxford Unfiversfity Press, USA, 1996.
[44] C. Kfittefl, P. McEuen, P. McEuen, Introductfion to Soflfid State Physfics, Wfifley New York, 1996.
[45] J. Wfifley, fin: Semficonductors and Semfimetafls, vofl. 10, Eflsevfier, 1975, pp. 91–174.
[46] D. Rode, fin: Semficonductors and Semfimetafls, vofl. 10, Eflsevfier, 1975, p. 1.
[47] B. Zhao, S. Fan, Annuafl Revfiew of Heat Transfer 23 (2020).
[48] D. Sarkar, W. Wang, M. Meckflenburg, A.J. Cflough, M. Yeung, C. Ren, Q. Lfin, L. Bflankemefier, S. Nfiu, H. Zhao, ACS Nano 12 (6) (2018) 5158–5167.
[49] K. Takefi, M. Madsen, H. Fang, R. Kapadfia, S. Chuang, H.S. Kfim, C.-H. Lfiu, E. Pflfis, J. Nah, S. Krfishna, Nano Lett. 12 (4) (2012) 2060–2066.