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Article type: Communication**Ge₂Sb₂Te₅-Based Tunable Perfect Absorber Cavity with Phase Singularity at Visible Frequencies***Kandammathe Valiyaveedu Sreekanth, Song Han and Ranjan Singh**

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E-mail: ranjans@ntu.edu.sg**Keywords:** Perfect absorbers, Lithography-free, Flat-optics, Visible frequencies, Phase change materials, Active photonic devices, Fabry-Perot cavity

The metal-dielectric stacks-based asymmetric Fabry-Perot (F-P) cavity systems have recently attracted much interest from the scientific community for realizing perfect absorption over the spectral bands from visible to infrared since they possess a lithography-free design that is cost-effective and scalable. Here, we experimentally demonstrate an asymmetric F-P cavity system for achieving tunable wide angle perfect absorption and phase singularity. The proposed system shows tunable multiband perfect absorption in the visible spectral region by incorporating an ultra-thin layer of phase change material such as Ge₂Sb₂Te₅ (GST) in the stack. The system shows multi-narrowband perfect absorption with a maximum of 99.8% at a specific incident angle and polarization state when the GST is in amorphous phase, however, the absorption bands blue shift and broaden after switching to the crystalline phase. More importantly, the proposed scheme shows tunable phase singularity at the reflection-less point. The obtained tunable perfect absorption and abrupt phase change are solely due the presence of a highly absorbing ultra-thin layer of GST in the stack. Experimental results are validated using an analytical simulation model based on transfer matrix method. The proposed scheme could find potential active photonic device applications, especially for phase-sensitive biosensors and absorption filters.

Signal modulation, storage, and transmission are the cornerstone functionalities of the modern information revolution. Electronics and photonics compete to realize these functionalities most efficiently. While photonics is the preferred choice when it comes to data transport due to its low losses and high bandwidth, electronics dominate manipulating and storing information, even substituting traditional domains of photonics such as compact disks and camera films. The integration and miniaturization of electronic devices makes them the major contender for data storage. However, the discovery of the interesting optical properties of phase change materials ^[1] (PCM) may open the door for photonic data storage again. These materials modify their optical constants which can be rapidly activated thermally, optically, or electronically. The versatile and rapid modulation of such materials makes them suitable for a wide range of optoelectronic devices and for data storage. However, in order to properly compete with electronic storage, miniaturized optical devices with strong response are required. Amplifying the optical response of materials is realized when light is critically coupled to a resonator ^[2]. Critical light coupling is associated with perfect light absorption due to the existence of non-zero losses in optical resonators. Light is critically coupled when reflection and absorption rates of a resonator are equal.

Metamaterials and plasmonic nanostructures-based absorbers ^[3-12] enabled controlled light absorption and achieved near-to-perfect absorption (<99%). Most of the works on metamaterial perfect absorbers focused on broadening the absorption band using different strategies ^[13-15], especially overlapping multi-resonant impedance matching absorbers. Introducing tunable materials enabled active plasmonic and metamaterial designs with tunable absorption. A number of active plasmonic absorbers have been demonstrated by incorporating tunable materials such as graphene ^[16, 17], liquid crystals ^[18, 19] and phase change materials ^[20-23] (VO₂ and chalcogenides) into plasmonic systems. The tunability is commonly achieved in such systems by external stimulus such as thermal, electrical and optical. The graphene, microelectromechanical systems ^[24] (MEMS) and liquid crystal-based absorbers are usually

tuned electrically, whereas phase change material-based systems can be tuned by electrically [25], thermally [26] and optically [27]. However, most of these systems are lithographically intense, and lithography free perfect absorbers were not demonstrated in the visible. Thus, this emerging research field is currently facing many technological challenges that has hindered the development of practical active photonic device applications in the visible spectrum regime. Realizing perfect light absorption using phase change materials in the visible is crucial as higher frequencies provide larger modulation bandwidth.

A closely related phenomenon to perfect light absorption is the notion of point-of-darkness. Achieving point-of-darkness and abrupt phase change at the reflection-less point at a specific incident angle, frequency and polarization state is known in the case of ideal optical systems such as prism coupled surface plasmon resonance [28], coherent absorption [29], and parity-time metamaterial [30]. However, in practice, it is only demonstrated through the concept of topological darkness [31]. Topological darkness is a generalized Brewster angle concept in the complex refractive index ($n_{eff}(\lambda)$, $k_{eff}(\lambda)$) plane. Various subwavelength nanostructures [31-35] have been proposed for realizing abrupt phase change (difference in phase, Δ) at the point of darkness. This finds an immediate application in label-free phase-sensitive optical biosensing [31, 35] because a singular behavior of phase in Fourier space is possible at the point-of-darkness. This singular phase behavior has only been demonstrated based on the concept of topological darkness which demands complex lithography techniques to fabricate nanostructures to engineer their effective refractive index.

Visible frequency near-perfect absorption has been experimentally [36-46] and theoretically [47-49] demonstrated using lithography-free planar multilayer thin-film stacks. Furthermore, tunable planar multilayer thin-film-based perfect absorbers using phase change materials such as VO_2 and $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) have been demonstrated [50-56]. However, VO_2 -based systems [50-52] provide perfect absorption at infrared frequencies, whereas GST-based systems only provide near-perfect absorption at visible and near infrared frequencies [53, 54].

Another major issue with GST-based systems is the drastic reduction in resonant absorption after switching the GST phase from amorphous to crystalline state ^[54].

To address the challenges associated with visible frequency tunable perfect absorbers, here we propose and experimentally demonstrate a novel lithography-free planar multilayer thin-film stack to achieve tunable resonant perfect absorption and phase singularity at visible frequencies. The proposed stack is a four-layered metal-dielectric-dielectric-metal (MDDM) thin film with one of the dielectric layers as an ultra-thin layer (8 nm) of the phase change material GST. The proposed asymmetric F-P cavity exhibits perfect light absorption and singular phase behavior at the point-of-darkness which are dependent on the existence of strong optical losses in GST amplified by the cavity resonance. The absorption and phase singularity are, accordingly, highly sensitive to changes in the optical properties of GST which are activated by switching GST phase from amorphous to crystalline.

The proposed active asymmetric F-P cavity is shown in **Figure 1a**, which consists of a silicon substrate, a top (18 nm) and bottom (50 nm) Ag layer forming the cavity mirrors. An ultra-thin layer of Ge₂Sb₂Te₅ (8 nm) was deposited on the bottom Ag film, on to which, a lossless methyl methacrylate (MMA) (8.5MMAEL 11, MICROCHEM) film (522 nm) was spin coated. The Ag layers were deposited by thermal evaporation (Oerlikon Leybold vacuum system) of Ag pellets at a deposition rate of 0.2 Å/s and base pressure of $<5 \times 10^{-6}$ mbar. GST layer was grown using radio frequency (RF) sputtering of Ge₂Sb₂Te₅ alloy target at a deposition rate of 0.2 Å/s with a base pressure of $<5 \times 10^{-6}$ mbar (Oerlikon Leybold vacuum system). The optical constants and thickness of all films were determined using spectroscopic ellipsometry (J. A. Woollam Co., Inc, V-VASE). The ellipsometrically acquired and fitted optical constants of thin films are shown in **Figure 1b**, **Figure 1c**, and **Figure 1d**. To obtain the optical constants of GST in both amorphous and crystalline phases, initially 20 nm GST thin film was deposited on a silicon substrate and a Tauc-Lorentz model was used to fit the measured ellipsometry data. Since as deposited GST sample was in amorphous phase, we

annealed the GST sample at 160°C for 60 min to switch the phase of the GST from amorphous to crystalline. The crystalline GST sample was fitted using a Tauc-Lorentz oscillator model. The obtained optical constants (n and k) of GST in both phases are shown in **Figure 1b**. It is evident that there is a significant variation in both n and k values (especially with increasing wavelength) when the phase of the GST is switched between amorphous and crystalline state, which is consistent with previously reported values ^[55]. In the case of MMA, MMA copolymer was spin coated at 3000 r.p.m. on a silicon substrate and a Cauchy model was used to obtain the n values of MMA (**Figure 1c**). The experimentally determined optical constants of 50 nm thick Ag film are shown in **Figure 1d**.

The angular reflection measurements were performed using a variable angle high resolution spectroscopic ellipsometer. Reflectance spectra as a function of wavelength (400 nm to 1000 nm) were acquired for different angles of incidence (20° to 80°). The absorbance spectra were then obtained from the reflectance data ($A = 1 - R - T$ with $T=0$). The absorbance spectra of the samples are shown in **Figure 2a**. The system supports two cavity modes for both p - and s -polarization. However, the maximum absorbance was recorded for p -polarization at a specific wavelength and angle of incidence. When GST is in the amorphous phase (black curve), the maximum resonant absorbance was obtained at 62°, with absorbance reaching 99.7% and 99.8% at 520 nm and 782 nm, respectively. The absorbance spectrum of the stack after switching the phase of the GST into crystalline state (baked at 160°C for 60 min) is shown as red curve. We observed a blue shift and broadening of resonant absorbance with a maximum value of 97.7 % and 99.7% at 500 nm and 750 nm, respectively. It shows that a slight decrease in absorbance is obtained at the same incident angle (62°). This is due to the change in the effective index of the stack. However, the stack with GST in crystalline phase provides slightly increased absorbance at a different angle of incidence. In fact, maximum absorbance was recorded at 736 nm and 66°, which is 99.97% (see

Supporting Figure 1). Unlike existing thin-film based-tunable absorbers^[54], our system realizes perfect absorption at visible frequencies when the GST is in both phases. In addition, we observed a blue shift in resonant absorptance after crystallization. Note that similar modes are supported by the asymmetric F-P cavity when the GST layer was removed from the stack (see Supporting Figure 2 and 3). The stack without GST layer provides narrow absorption bands and reduced maximum resonant absorptance for *p*-polarization at a higher wavelength and lower incident angle (99.6% at 825 nm and 55°). Therefore, it is clear that the broadening of absorption bands with increased absorptance is possible by introducing a highly absorbing dielectric such as GST in the stack. More importantly, tunable perfect absorption is realized using the system.

We further corroborated the experimental results using a numerical model based on transfer matrix method (TMM)^[56]. In the calculations, the Fresnel's reflection coefficients ($r_{p,s}$) for an *N*-layer model was solved, which are a serial product of the interface matrix I_{jk} ($j = 0, 1, 2, 3 \dots$ and $k = j+1$), and the layer matrix L_j . The reflectance was calculated as, $R_{p,s} = |r_{p,s}|^2$. The simulated absorptance for both polarizations when GST is in amorphous and crystalline phase is shown in **Figure 2b** (also see Supporting Figure 1). The simulation results accurately reproduce the key spectral features including the blue-shifted absorptance peak wavelength upon crystallization as well as the increased *p*-polarized absorptance as compared to *s*-polarized absorptance. In the simulations, the experimentally obtained *n* and *k* values of thin films were used, however, the thickness of the top Ag and MMA layers were slightly varied (16 nm for Ag and 525 nm for MMA) from the measured values. The main physical reason behind the tunable perfect absorption of this multilayer film is due to the presence of a highly absorbing ultra-thin GST film in the stack because an ultra-thin layer of GST heavily attenuates the incident light⁴⁰. This absorption resonance gets enhanced with

increasing complex refractive index of ultra-thin dielectric. This is the reason why stack with crystalline GST layer provided a slightly higher absorptance.

To experimentally investigate the influence of incident angle and GST layer thickness on tunable perfect absorption, in **Figure 3**, we plot the absorptance of *p*-polarized light as a function of the incident angle (20° to 80°) and wavelength (400 nm to 1000 nm) for different thicknesses of GST layer (8 nm, 20 nm and 30 nm). The resonant absorption bands broaden and blue shift when the GST layer was switched from amorphous crystalline state for all three thicknesses of GST. However, all angle and multiband perfect absorptance is only observed for the stack with ultra-thin layer of GST (8 nm). In particular, a thick GST alter the conditions for critical light coupling to the resonator which minimizes the light trapped inside the cavity. Since longer wavelength perfect absorption band (above 700 nm) is only visible by varying the GST layer thickness, we focus on this band. One can see that wide angle maximum absorptance feature decreases with increasing GST thickness for amorphous GST stack (**Figure 3a, 3d and 3g**), whereas all angle maximum absorptance is possible at the same band for crystalline GST stack, with increasing GST thickness (**Figure 3b, 3e and 3h**). In addition, broadening of the absorption band is observed by increasing GST layer thickness. We further simulated 2D map of *p*-polarized absorptance spectra of 8 nm thick GST layer for both phases, which is in agreement with experimental results (see Supporting Figure 5). Since maximum absorptance was observed for the stack with GST in crystalline phase, the recorded maximum absorptance for the thickness 8 nm, 20 nm and 30 nm are 99.97% at 736 nm and 66°, 99.8% at 820 nm and 64°, and 99.6% at 840 nm and 61°, respectively. Accordingly, maximum absorptance decreases with increasing GST layer thickness due to losing the critical coupling condition. The measured percentage absorptance change upon crystallization

$$^{[25]}, \left(\Delta A(\%) = \frac{A_{Cry} - A_{Amp}}{A_{Amp}} \times 100 \right), \text{ as a function of incident angle and wavelength for 8 nm,}$$

20 nm and 30 nm thick GST sample is shown in **Figure 3c**, **Figure 3f** and **Figure 3i**,

respectively. For all incident angles, maximum percentage absorptance change was observed for 8 nm thick GST sample, which is nearly 8 times higher than 30 nm thick GST sample. It is important to note that *s*-polarized percentage absorption change measured for 8 nm thick GST sample is even higher than *p*-polarized percentage absorption change (see Supporting Figure 6). It implies that ultra-thin layer of GST (<10 nm) is required for the proposed lithography-free geometry to achieve efficient tunable perfect absorption at visible spectral region.

An important and promising feature of the proposed planar multilayer film is that it shows tunable singular phase behavior at the maximum absorption point (point-of-darkness) due to ultra-thin GST layer. In order to experimentally investigate this, we record a pair of ellipsometric parameters such as ψ (ellipsometric reflection) and Δ (phase shift), as a function of wavelength (400 nm to 1000 nm) and angle of incidence (20° to 90°). Since maximum absorptance for *p*-polarized light was obtained at 62° and 66° respectively for amorphous and crystalline GST stack, the abrupt phase change is expected at these incident angles. The recorded ψ and Δ spectrum as a function of wavelength for amorphous and crystalline GST stack at 62° and 66° are shown in **Figure 4a** and **Figure 4b**, respectively. As expected, singular phase behavior for longer wavelength mode at minimum ψ (ψ_{min}) value was obtained at 782 nm and 736 nm for amorphous and crystalline GST stack, respectively. Then, the pair of ellipsometry parameters were recorded as a function of incident angle by selecting the point-of-darkness wavelength as 782 nm and 736 nm for amorphous and crystalline GST stack, which are shown in **Figure 4c** and **Figure 4d**, respectively. It is evident that ψ_{min} and the phase singularity are exactly obtained at 62° and 66° for amorphous and crystalline GST stack, respectively. The recorded ψ_{min} value and phase change at ψ_{min} for amorphous and crystalline GST stack are 1.05° & 40° and 0.82° & 89°, respectively. It is evident that the abrupt phase change increases with decreasing ψ_{min} value. The observed higher phase jump for crystalline GST stack in both wavelength and angular scan is due to the increase of *p*-polarized absorptance as compared to amorphous GST stack. In addition, ψ spectra broaden

after crystallization of the GST stack, which is consistent with absorptance spectra. Even though perfect absorption is possible without a GST layer, the singular phase behavior is only possible after introducing a GST ultra-thin film in the stack (see Supporting Figure 8 and 9). More importantly, abrupt phase change, and ψ_{min} wavelength and angle can be tuned by switching the phase of the GST between amorphous and crystalline states.

We further calculated the pair of ellipsometry parameter ψ and Δ using a TMM simulation model. The ψ spectra was obtained using, $\tan \Psi = \left| \frac{r_p}{r_s} \right|$, where r_p & r_s are the Fresnel's reflection coefficient for p - and s -polarization, respectively. Since Δ is the phase difference between s - and p -polarization, $\Delta = \phi_s - \phi_p$ with values of ϕ_s and ϕ_p are extracted from the Fresnel's reflection coefficients, $r_s = |r_s| \exp(i\phi_s)$ and $r_p = |r_p| \exp(i\phi_p)$. For both phases of GST, the calculated ψ and Δ values as a function of wavelength are shown in Supporting Figure 10. The simulated and measured spectra match very well with each other, including ψ_{min} spectral position, abrupt phase change and ψ spectrum broadening. The best fit was obtained for this thickness combination for top Ag, MMA, GST and bottom Ag: 17 nm, 525 nm, 8 nm, and 50 nm for amorphous GST stack and 15 nm, 525 nm, 8 nm, and 50 nm for crystalline GST stack. In addition, the TMM simulation model was further used to show the confined electric field distribution along the planar multilayer stack. We simulated the electric field distribution of the two modes when GST is in both phases. In the case of amorphous GST stack, 2D field map and the corresponding line profile obtained at 62° for the first mode (520 nm) and the second mode (782 nm) are shown in **Figure 5 (a, b)** and **Figure 5 (c, d)**, respectively. The corresponding field distributions calculated at 66° for crystalline GST stack are shown in **Figure 5 (e, f)** for the first mode (480 nm) and in **Figure 5 (g, h)** for the second mode (736 nm). The field intensity is tightly confined in the ultra-thin GST layer for the two modes and both phases of GST. However, higher field confinement was obtained for the

second mode compared to the first mode when GST is in both amorphous and crystalline phases. In contrast to amorphous GST stack, crystalline GST stack shows reduced field confinement due to the broadening of absorption and ψ spectra after crystallization of the GST layer in the multilayer stack. Note, the mode profile of the first and the second mode for both phases of GST are the same. This is because both modes are the cavity modes of an Ag/MMA system (see Supporting Figure 11) and that their behavior can be altered by the deposition of bottom thin films of Ag and GST with appropriate thicknesses. In short, the simulation results demonstrate the important role of GST in the planar multilayer stack and support the conclusion of the experimental observations.

In summary, we designed and fabricated lithography-free planar multilayered GST-based stacks for tunable perfect absorption and phase singularity at visible frequency regime. We have experimentally demonstrated that resonant perfect absorption bands can be tuned without reducing the absorptance intensity, by switching the phase of an ultra-thin layer of GST between amorphous and crystalline state. More importantly, we showed that tunable singular phase behavior is achieved for this system due to the presence of ultra-thin layer of GST in the stack. The experimental findings were fully validated using TMM-based simulation model. The abrupt phase change observed at point-of-darkness could find a potential application for ultra-sensitive biosensing based on phase-sensitive detection. The lithography-free design of the proposed system could find various cost-effective active photonic device applications, including data storage, optoelectronic devices, multi-channel biosensors and absorption filters for display and adaptive camouflage techniques.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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References

- [1] M. Wuttig, H. Bhaskaran, T. Taubner, *Nat. Photon.* **2017**, 11, 465-476
- [2] M. A. Kats, R. Blanchard, P. Genevet, F. Capasso, *Nat. Mater.* **2013**, 12, 20-24
- [3] N. Landy, S. Sajuyigbe, J. Mock, D. Smith, D., W. Padilla, *Phys. Rev. Lett.* **2008**, 100, 207402
- [4] X. Liu, T. Starr, A. F. Starr, W. Padilla, *Phys. Rev. Lett.* **2010**, 104, 207403
- [5] J. Hao, J. Wang, X. Liu, W.J. Padilla, L. Zhou, M. Qiu, *Appl. Phys. Lett.* **2010**, 96, 251104
- [6] K. B. Alici, A. B. Turhan, C. M. Soukoulis, E. Ozbay, *Opt. Exp.* **2011**, 19, 14260
- [7] N. Liu, M. Mesch, T. Weiss, M. Hentschel, H. Giessen, *Nano Lett.* **2010**, 10, 2342-2348
- [8] L. Cong, S. Tan, R. Yahiaoui, F. Yan, W. Zhang, R. Singh, *Appl. Phys. Lett.* **2015**, 106, 031107
- [9] J. A. Mason, S. Smith, D. Wasserman, *Appl. Phys. Lett.* **2011**, 98, 241105
- [10] Y. Avitzour, Y. A. Urzhumov, G. Shvets, *Phys. Rev. B* **2009**, 79, 045131
- [11] H. Tao, N. I. Landy, C. M. Bingham, X. Zhang, R. D. Averitt, W. J. Padilla, *Opt. Exp.* **2008**, 16, 7181-7188
- [12] K. V. Sreekanth, M. Elkabbash, Y. Alapan, A. R. Rashed, U. A. Gurkan, G. Strangi, *Sci. Rep.* **2016**, 6, 26272
- [13] C. Gu, S. Qu, Z. Pei, H. Zhou, J. Wang, B. Lin, Z. Xu, P. Bai, W. Peng, *Progress In Electromagnetics Research Letters* **2010**, 17, 171-179
- [14] K. Aydin, V. E. Ferry, R. M. Briggs, H. A. Atwater, *Nat. Commun.* **2011**, 2, 517
- [15] Y. Yao, R. Shankar, M. A. Kats, Y. Song, J. Kong, M. Loncar, F. Capasso, *Nano Lett.*, **2014**, 14, 6526-6532
- [16] Z. Fang, Y. Wang, A. E. Schlather, Z. Liu, P. M. Ajayan, F. Javier García de Abajo, P. Nordlande, X. Zhu, N. J. Halas, *Nano Lett.*, **2014**, 14, 299-304
- [17] P. A. Kossyrev, A. Yin, S. G. Cloutier, D. A. Cardimona, D. Huang, P. M. Alsing, J. M. Xu, *Nano Lett.*, **2005**, 5, 1978-1981
- [18] Z. Su, J. Yin, X. Zhao, *Sci. Rep.* **2015**, 5, 16698

- [19] A. Tittl, A.-K. U. Michel, M. Schäferling, X. Yin, B. Gholipour, L. Cui, M. Wuttig, T. Taubner, F. Neubrech, H. Giessen, *Adv. Mater.* **2015**, 27, 4597-4603
- [20] J. K. Pradhan, S. A. Ramakrishna, B. Rajeswaran, A. M. Umarji, V. G. Achanta, A. K. Agarwal, A. Ghosh, *Opt. Exp.* **2017**, 25, 9116
- [21] M. J. Dicken, K. Aydin, I. M. Pryce, L. A. Sweatlock, E. M. Boyd, S. Walavalkar, J. Ma, H. A. Atwater, *Opt. Exp.* **2009**, 17, 18330-18339
- [22] Z. Zhu, P. G. Evans, R. F. Haglund, Jr., J. G. Valentine, *Nano Lett.* **2017**, 17, 4881-4885
- [23] W. Dong, Y. Qiu, J. Yang, R. E. Simpson, T. Cao, *J. Phys. Chem. C* **2016**, 120, 12713-12722
- [24] P. Pitchappa, C. P. Ho, P. Kropelnicki, N. Singh, D.-L. Kwong, C. Lee, *Appl. Phys. Lett.* **2014**, 104, 201114
- [25] P. Hosseini, C. D. Wright, H. Bhaskaran, *Nature* **2014**, 511, 206-211
- [26] M. A. Kats, R. Blanchard, P. Genevet, Z. Yang, M. M. Qazilbash, D. N. Basov, S. Ramanathan, F. Capasso, *Opt. Lett.* **2013**, 38, 368-370
- [27] M. Rudé, V. Mkhitarian, A. E. Cetin, T. A. Miller, A. Carrilero, S. Wall, F. Javier García de Abajo, H. Altug, V. Pruneri, *Adv. Optical Mater.* **2016**, 4, 1060-1066
- [28] H. Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings: Index*; Springer: Berlin, Germany, 1988
- [29] W. Wan, Y. Chong, L. Ge, H. Noh, A. D. Stone, H. Cao, *Science* **2011**, 331, 889
- [30] L. Feng, Y.-L. Xu, W. S. Fegadolli, M.-H. Lu, J. E. B. Oliveira, V. R. Almeida, Y.-F. Chen, A. Scherer, *Nat. Mater.* **2013**, 12, 108
- [31] V. G. Kravets, F. Schedin, R. Jalil, L. Britnell, R. V. Gorbachev, D. Ansell, B. Thackray, K. S. Novoselov, A. K. Geim, A. V. Kabashin, A. N. Grigorenko, *Nat. Mater.* **2013**, 12, 304-309
- [32] L. Malassis, P. Massé, M. Tréguer-Delapierre, S. Mornet, P. Weisbecker, P. Barois, C. R. Simovski, V. G. Kravets, A. N. Grigorenko, *Adv. Mater.* **2014**, 26, 324-330
- [33] B. Vasic, R. Gagic, *J. Appl. Phys.* **2014**, 116, 023102
- [34] H. Song, N. Zhang, J. Duan, Z. Liu, J. Gao, M. H. Singer, D. Ji, A. R. Cheney, X. Zeng, B. Chen, S. Jiang, Q. Gan, *Adv. Optical Mater.* **2017**, 5, 1700166
- [35] M. Svedendahl, R. Verre, M. Kall, *Light: Science & Applications* **2014**, 3, e220
- [36] H. Kocer, S. Butun, Z. Li, K. Aydin, *Sci. Rep.* **2015**, 5, 8157
- [37] M. A. Kats, F. Capasso, *Laser & Photonics Reviews* **2016**, 10, 699

- [38] H. Song, L. Guo, Z. Liu, K. Liu, X. Zeng, D. Ji, N. Zhang, H. Hu, S. Jiang, Q. Gan, *Adv. Mater.* **2014**, 26, 2737
- [39] Z. Li, S. Butun, K. Aydin, *ACS Photonics* **2015**, 2, 183-188
- [40] K. V. Sreekanth, S. Sreejith, S. Han, A. Mishra, X. Chen, H. Sun, C. T. Lim, R. Singh, *Nat. Commun.* **2018**, 9, 369
- [41] G. Kenanakis, Ch. P. Mavidis, E. Vasilaki, N. Katsarakis, M. Kafesaki, E. N. Economou, C. M. Soukoulis, *Appl. Phys. A* **2017**, 123:77
- [42] A. Ghobadi, S.A. Dereshgi, H. Hajian, B. Bozok, B. Butun, E. Ozbay, *Sci. Rep.* **2017**, 7:4755
- [43] Y. Zhang, W. Liu, Z. Li, H. Cheng, Y. Zhang, G. Jia, S. Chen, J. Tian, *Appl. Phys. Lett.* **2017**, 111, 111109
- [44] J. Park, J.-H. Kang, A. P. Vasudev, D. T. Schoen, H. Kim, E. Hasman, M. L. Brongersma, *ACS Photonics* **2014**, 1, 812-821
- [45] J. Chen, J. Guo, L.-Y. Chen, *Opt. Mater. Exp.* **2016**, 6, 3804-3813
- [46] M. ElKabbash, E. Ilker, T. Letsou, N. Hoffman, A. Yaney, M. Hinczewski, G. Strangi, *Opt. Lett.* **2017**, 42, 3598-3601
- [47] G. Kajtár, M. Kafesaki, E. N. Economou, C. M. Soukoulis, *J. Phys. D: Appl. Phys.* **2016**, 49, 055104
- [48] J.-B. You, W.-J. Lee, D. Won, K. Yu, *Opt. Exp.* **2014**, 22, 8339-8348
- [49] S. Shu, Z. Li, Y. Y. Li, *Opt. Exp.* **2013**, 21, 25307-25315
- [50] M. A. Kats, D. Sharma, J. Lin, P. Genevet, R. Blanchard, Z. Yang, M. M. Qazilbash, D. N. Basov, S. Ramanathan, F. Capasso, *Appl. Phys. Lett.* **2012**, 101, 221101
- [51] J. Rensberg, Y. Zhou, S. Richter, C. Wan, S. Zhang, P. Schöppe, R. Schmidt-Grund, S. Ramanathan, F. Capasso, M. A. Kats, C. Ronning, *Phys. Rev. Appl.* **2017**, 8, 014009
- [52] J. Liang, L. Hou, J. J. Li, *Opt. Soc. Am. B* **2016**, 33, 1075-1080
- [53] E.-T. Hu, T. Gu, S. Guo, K.-Y. Zang, H.-T. Tu, K.-H. Yu, W. Wei, Y.-X. Zheng, S.-Y. Wang, R.-J. Zhang, Y.-P. Lee, L.-Y. Chen, *Opt. Commun.* **2017**, 403, 166-169
- [54] V. K. Mkhitarian, D. S. Ghosh, M. Rudé, J. Canet-Ferrer, R. A. Maniyara, K. K. Gopalan, V. Pruneri, *Adv. Optical Mater.* **2017**, 5, 1600452
- [55] X. Tian, Z.-Y. Li, *Photon. Res.* **2016**, 4, 146-152
- [56] K. V. Sreekanth, S. Zeng, K.-T. Yong, T. Yu, *Sensors and Actuators B* **2013**, 182, 424-428

Figure 1. (a) Proposed four-layered active perfect absorber geometry. The optimized thickness of Ag, MMA, GST and Ag layers are 18 nm, 522 nm, 8 nm and 50 nm, respectively. Ellipsometrically determined optical constants (n & k) of thin films (b) $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (in both phases), (c) MMA and (d) Ag. In figure 1b, Amp: amorphous and Cry: crystalline.

Figure 2. Absorption spectra as a function of wavelength for *p*- and *s*-polarization (a) Measured and (b) simulated. Angle of incidence is 62° . GST_Amp: GST in amorphous phase, GST_Cry: GST in crystalline phase, *p*-pol: *p*-polarization, and *s*-pol: *s*-polarization.

Figure 3. Experimental 2D map of absorption spectra and percentage absorption spectra for different thickness of GST layer. For stack with GST is in amorphous phase (a) 8 nm GST (d) 20 nm GST, and (g) 30 nm GST. For stack with GST is in crystalline phase (b) 8 nm GST (e) 20 nm GST, and (h) 30 nm GST. For percentage absorption change (c) 8 nm GST (f) 20 nm GST, and (i) 30 nm GST.

Figure 4. Experimental demonstration of singular phase. Measured pair of ellipsometry parameters as a function of wavelength for (a) amorphous GST stack at 62° and (b) crystalline GST stack at 66° . Measured pair of ellipsometry parameters as a function of incident angle for (a) amorphous GST stack at 782 nm and (b) crystalline GST stack at 736 nm.

Figure 5. Calculated field distribution along the four-layered system using TMM. For amorphous GST stack at 62°, (a, b) mode at 520 nm and (c, d) mode at 782 nm. For crystalline GST stack 66°, (e, f) mode at 480 nm and (g, h) mode at 736 nm.