Active Tuning from Narrowband to Broadband Absorbers Using a Sub-wavelength VO₂ Embedded Layer

Ataollah Kalantari Osgouei^{1,2} · Hodjat Hajian² · Bahram Khalichi^{2,3} · Andriy E. Serebryannikov^{2,4} · Amir Ghobadi^{2,3} · Ekmel Ozbay^{1,2,3,5}

Received: 17 November 2020 / Accepted: 29 December 2020 / Published online: 18 January 2021

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC part of Springer Nature 2021, corrected publication 2021

Abstract

Metamaterial perfect absorbers (MPAs) with dynamic thermal tuning features are able to control the absorption performance of the resonances, providing diverse applications spanning from optical switches and filters to modulators. In this paper, we propose an MPA with diverse functionalities enabled by vanadium dioxide (VO₂) embedded in a metal-dielectric plasmonic structure. For the initial design purpose, a silicon (Si) nanograting on a silver (Ag) mirror is proposed to have multiple resonant responses in the near infrared (NIR) region. Then, the insertion of a thin VO₂ layer at the right position enables the design to act as an on/off switch and resonance tuner. In the insulator phase of VO₂, in which the permittivity data of VO₂ is similar to that of Si, a double strong resonant behavior is achieved within the NIR region. By increasing the temperature, the state of VO₂ transforms from insulator to metallic so that the absorption bands turn into three distinct resonant peaks with close spectral positions. Upon this transformation, a new resonance emerges and the existing resonance features experience blue/red shifts in the spectral domain. The superposition of these peaks makes the overall absorption bandwidth broad. Although Si has a small thermo-optic coefficient, owing to strong light confinement in the ultrasmall gaps, a substantial tuning can be achieved within the Si nanogratings. Therefore, the proposed hybrid design can provide multi-resonance tunable features to cover a broad range and can be a promising strategy for the design of linearly thermal-tunable and broadband MPAs. Owing to the proposed double tuning feature, the resonance wavelengths exhibits great sensitivity to temperature, covering a broad wavelength range. Overall, the proposed design strategy demonstrates diverse functionalities enabled by the integration of a thin VO₂ layer with plasmonic absorbers.

Keywords Vanadium dioxide · Plasmonics · Perfect absorber · Active tunable metamaterial · Localized surface plasmon

Introduction

Metamaterials are a periodic array of subwavelength structures, which can be artificially engineered to achieve exotic properties not available in nature [1, 2]. These characteristics

make metamaterials a promising technology for a wide variety of applications, such as light harvesting [3, 4], invisible cloaks [5], asymmetric light transmission [6, 7], lasing [8], and negative refractive index [9, 10]. Among them, manipulating and controlling the absorption properties of optical metamaterials have gained a lot of attention over the last decades. In particular, metamaterials with nearly perfect absorption features are called metamaterial perfect absorbers (MPAs). MPAs have been demonstrated to realize either narrow or broadband absorptions depending on the geometry and the material type being used in the design. The former resonant response may have applications in sensing [11], imaging [12], and color filtering [13], while the latter correspondent is promising in the areas of solar cells [14], photochemical devices [15], hot-electron-based photodetectors [16], and radiative cooling [17]. Such MPAs have been developed from visible [18, 19] to terahertz [20, 21] and the microwave regions [22, 23]. MPAs can be physically realized

✉ Ataollah Kalantari Osgouei
akalantari@bilkent.edu.tr

¹ Department of Physics, Bilkent University, Ankara 06800, Turkey

² NANOTAM- Nanotechnology Research Center, Bilkent University, Ankara 06800, Turkey

³ Department of Electrical and Electronics Engineering, Bilkent University, Ankara 06800, Turkey

⁴ Faculty of Physics, Adam Mickiewicz University, 61-614 Poznan, Poland

⁵ UNAM-Institute of Materials Science and Nanotechnology, Bilkent University, Ankara, Turkey

by suppressing both the transmission and reflection of the incident electromagnetic (EM) waves, simultaneously. The transmission can be eliminated by using an optically thick metallic layer as a mirror, and the reflection may be blocked by matching the impedance of the structure with the surrounding medium. Therefore, metal–insulator pair-based configurations such as metal-insulator-metal (MIM) cavity designs have been proposed and widely used in the literature [24, 25]. Generally, in these structures, a dielectric film is sandwiched by a patterned top metal film and a flat bottom reflector mirror layer. However, the resonant properties of MPAs are almost fixed, which greatly reduce their practical applications. Therefore, to fully exploit the optical properties and to extend the functionality of MPAs, dynamically tunable control over resonances such as electrical [26], optical [27], and thermal [28] tuning have been studied to realize actively tunable metamaterials. Recently, the thermal tunable narrowband MPAs are emerging with possible applications such as optical modulator [29], optical switches [30], and infrared (IR) camouflage [31]. Certain mediums known as phase-change materials (PCM) like GeSbTe (germanium-antimony-tellurium or GST) and vanadium dioxide (VO_2) are the most prominent substances for active MPA designs. Their optical properties show a large change when undergoing a phase transition. The temperature required for GST crystallization is around 160°C . Moreover, the amorphization of GST is only obtained at the temperature above 640°C , which is required by very fast cooling. In contrast, VO_2 is a volatile PCM, and the insulator-to-metal transition occurs at a much lower temperature of 68°C . During this transition, the lattice of the structure is transformed from a monoclinic to tetragonal one as the temperature increases well above the critical point. At the same time, the conductivity of VO_2 rises by several orders, leading to sudden change in the optical and electrical properties of the material [32–34]. It is also important to discuss here that the insulator-to-metal transition of VO_2 can be perfectly reversible when the temperature of the material drops below the critical transition temperature, which provides a great power in memory storage. However, the bandwidth of MPAs based on GST and VO_2 are very small, usually around hundreds of nanometers [35, 36] at the near-infrared ranges (NIR) because of the inherent absorption and ohmic loss of metallic resonators. On the other hand, Mie theory predicts that it is possible to design narrowband MPAs based on employing high-refractive index dielectric materials like silicon (Si) and germanium (Ge), since they strongly support magnetic and electric dipoles at the resonance wavelengths [37, 38]. Nevertheless, the thermo-optic coefficient of these materials is rather low and cannot provide a dynamic tuning. In a recent work, Zhaol et al. proposed a linearly thermal-tunable narrowband MPA using four-nanorod amorphous Si (a-Si) with the sensitivity of 0.08nmC^{-1} . They reported that the resonances can

be tuned from 1164 to 1172 nm by increasing the temperature of a-Si from 20 to 120°C [39]. Taking everything into account, in an ideal scheme, a hybrid design that can couple dielectric based Mie resonators with PCMs can provide a strong thermal tunability and diverse functionalities. As a result, an elegant design based on PCM VO_2 embedded in a-Si nanograting resonator is proposed in the present paper. The bottom layer of the structure is chosen to be silver (Ag) with a sufficient thickness to block transmission leading to high absorptivity and narrow-band perfect absorption at the NIR region. Specifically, double narrowband perfect absorptions are successfully achieved at the resonant wavelengths of 1077 nm and 1314 nm under the insulator VO_2 state. Under the metallic VO_2 phase, the proposed design demonstrates triple spectrally adjacent perfect absorptions at the wavelength peaks of 1064 nm, 1166 nm, and 1323 nm, which leads to a broadband light absorption. The obtained electric field distributions near the resonance wavelengths, calculated via the eigenvalue solution of Maxwell's equation in the region of interest, besides the numerical simulation of the proposed structure based on the commercial finite-difference time-domain solver, indicate that the first and second resonant peaks are Fabry-Perot (FP) like resonances, while the third peak is due to the excitation of localized surface plasmon resonances (LSPRs) in metal-dielectric interface. From the obtained results, it is also seen that, upon insulator-metal transformation, the first resonance experiences a blue shift due to change in the phase of reflected wave. The second resonance is due to formation of a virtual MIM design, due to the lossy nature of VO_2 in metal phase. Finally, the third LSPR mode experiences a slight red-shift due to increase in the effective refractive index of the grating design. In the last section, the thermal tunability of a-Si itself is studied. It is shown that, due to strong field confinement in the grating gaps, a new dynamic tuning is added to the structure due to change in the thermo-optic coefficient of a-Si. This paper numerically demonstrates the possibility of the realization of multiple functionalities using a hybrid plasmonic-PCM design.

Structure and Simulation Setup

The schematic diagram of thermal tunable narrowband metamaterial absorber is shown in Fig. 1. The structure is composed of a VO_2 layer sandwiched between a-Si and a continuous Ag bottom reflector. Due to the resonating nature of the structure [40–42], CST Microwave Studio Eigen-solver is utilized to have an initial guess regarding the dimension of the parameters of the structure and the resonance wavelengths in the NIR region which are useful for the future optimization. Accordingly, the bottom layer is chosen to be 100 nm, with no transmission in our desired range. The thickness of the VO_2

Fig. 1 Geometry and schematic of the VO₂-based metamaterial absorber. The absorber consists of VO₂ in **a** the insulating phase and **b** the metallic phase sandwiched between layers of a-Si and continuous film of Ag as the bottom layer of the structure

layer is 5 nm. The distance from the top surface of Ag to VO₂ layer is d , as shown in Fig. 1. The thickness of the nanorating structure Si/VO₂/Si is t while its width is w . The period of the unit cell is fixed at P in the x -direction. The numerical calculations based on commercial finite-difference time-domain (FDTD) software package Lumerical FDTD solutions [43] are used to obtain the optical properties of the proposed absorber. The periodic boundary condition is applied only in the x -direction and the perfectly matched layer (PML) boundary condition is used in the z -direction in order to avoid the boundary scattering. The reflection spectrum is recorded by putting a 2D frequency-domain power monitor, which is placed behind the incident source monitor. Since the bottom metallic layer is chosen to be thick enough to suppress the transmission, the transmission is nearly zero and absorption can be calculated from the formula $A = 1 - R$. The frequency profile monitors are used to obtain electric and magnetic fields at the resonances. The optical properties of the silver film follow the common Palik model and the optical constant of VO₂ in both the insulator and metallic phases is reported in [44], where the permittivity of the material in the NIR region is experimentally measured by variable angle spectroscopic ellipsometry and then fitted by the Tauc-Lorentz model [VO₂ (insulator)] and Drude model [VO₂ (metal)]. The VO₂ in

the insulator phase acts like a spacer at a room temperature of 25°C as presented in Fig. 1a, while the transition to the metallic phase can be accomplished in a hot environment at 80°C as illustrated in Fig. 1b. From now on, we specifically refer to these different phases as VO₂ (I) and VO₂ (M). As for the a-Si, we use a linear relationship with the temperature dependence limited by the thermal-optical coefficient given by $3.25 \times 10^{-4}/^{\circ}\text{C}(n(T)) = 3.42 + 3.25 \times 10^{-4} \times (T - 20)$. According to the relationship, the refractive index of a-Si at the room temperature of 25°C is 3.42 [45, 46]. To get proper physical insight into the absorption resonances of the proposed design, we replaced a collection of scattering object materials by a homogeneous medium, whose properties result from the averaging of local EM fields. The procedure of modeling a composite environment and replacing it with a homogeneous medium is defined as the effective medium theory. It is better to be noted that the equivalent problem can be defined when the applied electric fields are static or have spatial variations on a large scale. Therefore, it is possible to replace the inhomogeneous materials by an effective medium [47, 48] where the electromagnetic properties of the inhomogeneous materials can be obtained from solving the Maxwell's equations inside the effective medium. Accordingly, we exploit the effective medium theory to describe the

impedance amplitude of the absorption resonances for both insulator and metallic phases. Meanwhile, the effective and impedance parameters of the proposed metamaterial absorber are extracted using the S-parameter calculation embedded in FDTD Lumerical solver.

Results and Discussions

In this section, we are going to study the impact of periodicity, thickness, and width of a-Si in the overall absorption spectra of the proposed design. It is crucial to be mentioned here that the real part of the permittivity of a-Si and VO₂ (I) is almost equal to each other at the room temperature of 25°C. Therefore, we can simplify the design to a straightforward simulation route of Ag-Si to study the overall absorption response of the proposed structure. As a first step, the absorption spectra of the structure as a function of periodicity differing from 750 to 1000 nm at different operating wavelengths is considered in Fig. 2a, while the other material dimensions of the structure are kept unchanged. The result represents a double resonance response for all P values, where both resonances experience a red shift as the periodicity increases. Moreover, larger P values broaden the absorption peak (see Fig. 2a for the bandwidth of the resonances) and reduce the strength of the longer wavelength resonance. In other words, the absorption spectra experience a sharp reduction for the second resonance once the periodicity of the design is increased from 750 to 1000 nm. Keeping in mind that the perfect absorption threshold is considered as 0.9, the optimal periodicity is chosen as 770 nm. The next step is sweeping a-Si layer thickness from 150 to 350 nm as the result is presented in Fig. 2b. It can be observed that both resonances red-shift, and the second resonance has more-pronounced change with a semi-linear trend. Again, taking the strength and bandwidth of the resonances into consideration, the optimized thickness value that retains both the narrowband peaks in the structure is 240 nm. At the final step, a-Si width

is swept from 400 to 750 nm where both the periodicity and the thickness of a-Si are kept at their optimal values.

The corresponding result is presented in Fig. 2c, and it demonstrates that the absorption response versus the width of an a-Si layer can take a wider bandwidth due to the excitation of both resonances, while the first resonant peak completely disappears by moving toward a narrower Si width. Moreover, in comparison with the width changes (as illustrated in Fig. 2b), the thickness variations cause weaker shifts in the shorter resonance wavelengths. Accordingly, the origin of the first and second resonances depends on the thickness and width of the grating, respectively. All in all, the optimal obtained values are considered for the design of the proposed narrowband NIR MPA. As presented in Fig. 3a, b, the effects of changing the locations of VO₂ layer (at two different phases) on the overall absorption spectra of the proposed structure are studied. In the figure, d denotes the distance of VO₂ film from the bottom metallic layer. Figure 3a demonstrates that the overall spectral response for VO₂ (I) is somehow insensitive to the variation of d , in spite of slight changes in the strength of the resonances, which agrees with our expectation based on similar permittivity values for both a-Si and VO₂ (I). On the contrary, variation of d has a significant impact on the absorption response of the structure as well as strength of the resonances when VO₂ layer at the metallic phase is used. In this case, at two different values of d (75 nm and 235 nm), a second weak resonance gets stronger with a peak amplitude above 0.9. Therefore, in the metallic phase, the position of VO₂ layer can be manipulated to efficiently excite another resonance with a slight effect in the first and third resonance values. As d increases, the first resonance experiences a blue-shift, while the third resonance shows a red-shift which will be discussed later. Taking all into account, the optimal position of VO₂ layer is considered to be 75 nm to have a broad and nearly flat absorption response in the metallic phase. To have a better qualitative comparison, the absorption response of the MPA absorber with (both metallic and insulator phases)

Fig. 2 Color plots of the absorption spectra at different operating wavelengths versus **a** periodicity of the grating, **b** the thickness of the a-Si layer, and **c** the width of the a-Si layer

Fig. 3 The calculated absorption spectra of the proposed absorber based on distances of VO₂ film mid plane from the bottom metallic layer **a** in the insulator phase, **b** in the metallic phase, and **c** the

obtained optimized distances of VO₂ layer in the insulator and metallic phases compared with absorption spectra without VO₂ layer

and without a VO₂ embedded layer is plotted in Fig. 3c. The figure implies that upon a thermally induced phase change, a distinct transformation from a narrowband absorber to a broadband one is achieved using an ultrathin VO₂ interlayer. To gain an insight on the origin of these resonance modes, CST Microwave Studio Eigen-solver together with FDTD commercial software are utilized to determine the supported modes by the MPA with and without considering the VO₂ layer. Therefore, we can interpret the coupling among these modes and VO₂ interlayer. The vector electric-field distributions across the x - z plane, at three wavelength values of 1048 nm, 1181 nm, and 1294 nm, are depicted in Fig. 4a-c. Formation of standing wave interference patterns within the Si grating shows that the first and second resonance modes are dominantly FP-like modes. However, the third mode originates from the excitation of LSPRs in Ag-Si interface. This is in agreement with the obtained results in Fig. 2. The strong dependence of the first peak position to the grating thickness (Fig. 2b) is due to the change in the optical path length of the FP resonator, while the third resonance is tailored by the grating width (Fig. 2c) which is a major factor defining the resonance position of the LSPR mode. To analyze the coupling of these modes to metal and insulator phase VO₂ layer, electric-field distributions

in the x - z plane are recorded and illustrated in Fig. 5. As is apparently displayed in this figure, the field distributions are quite similar for both metallic and insulator phase designs. The first resonance is a hybrid mode with FP resonance dominancy that is formed due to the interference of incoming and reflected waves with the cavity. When PCM material changes its phase to lossy metallic one, due to its larger permittivity values, its optical path length increases and, therefore, the impedance matching condition is blue-shifted. The second resonance is also a FP mode with hot spots formed within the a-Si grating. Placing VO₂ in a high-field region will make its absorption maximized. This is the case when d equals to 75 nm and 235 nm, see Fig. 3. In fact, in this situation, Ag-Si-VO₂ forms a virtual MIM cavity design. When VO₂ transforms from a low loss to lossy phase, the cavity is activated and a new resonance starts to appear. The last mode, which is the LSPR mode, shows the field localization patterns in the Ag-Si interface. In this case, the change in permittivity of the PCM will change the effective refractive index of the grating, and therefore, this leads to a red-shift in the resonance wavelength of the LSPR. All these results show that, upon use of right geometries and design, an ultrathin PCM can diversely modulate the optical absorption response of an MPA. In addition to mode

Fig. 4 Vector electric-field distributions of the proposed MPA with VO₂ layer under the insulating state at the resonant wavelengths of **a-c** 1048 nm, 1181 nm, and 1294 nm

Fig. 5 Magnitude of electric field distributions including VO2 layer in the **a–c** insulator phase at the resonant wavelengths of 1048 nm, 1181 nm, and 1294 nm and **d–f** in the metallic phase at the resonant wavelengths of 1035 nm, 1137 nm, and 1307 nm

profile analysis, the absorption properties of the proposed design can be fully explained by the equivalent media and impedance matching theories. Since the element size of the metamaterial absorber is much smaller than the operation wavelength, the effect of the internal microscope atoms and molecules of the EM field can be easily ignored. Therefore, the whole metamaterial structure can be regarded as a uniform and equivalent medium. At the same time, the input impedance of the entire structure, which is normalized to the free space impedance, can be analytically calculated by the following formula:

$$Z_{in} = \frac{\sqrt{(1 + S_{11}(w))^2 - S_{21}(w)^2}}{\sqrt{(1 - S_{11}(w))^2 - S_{21}(w)^2}} \quad (1)$$

where $S_{11}(w)$ and $S_{21}(w)$ are the reflection and transmission coefficients obtained by the S -parameter method. When the impedance matching condition is satisfied, the EM wave incident on the surface of the metamaterial can enter the structure without reflection and be directly converted into heating energy and absorbed in the structure. Therefore, the value of the equivalent

Fig. 6 Calculated the impedance amplitude of the absorber based on VO2 under the **a** insulating phase and **b** metallic phase

Fig. 7 Spectra absorptivity, peak absorptivity of the third resonant peak as functions of the temperature **a** varying from 25 to 250 °C. **b** The variation of resonance wavelengths corresponding to the estimated thermal-optical sensitivity through the linear fitting of the data of the proposed structure with respect to the temperature

complex impedance must be equal to 1. The equivalent impedance of the metamaterial absorber is also affected by the permittivity and permeability of the material. Here, we use the impedance theory technique to describe the perfect absorber of the structure as shown in Fig. 6. The results of the impedance amplitude for the VO₂ (I) is shown in Fig. 6a. In order to have perfect matching with free space, the real part of the normalized input impedance of the design must be close to 1, and its imaginary part should be near zero. Therefore, the impedance amplitude of the absorber at the desired perfect absorption peaks should be 1. For instance, the impedance amplitude for the spectra position of the first peak at 1077 nm is the order of magnitude 1, causing the strong narrowband perfect absorption. The same statement can also be applied to the second resonant peak as well as for the case of VO₂ (M) structure, which is shown in Fig. 6b, once more, the results of the impedance amplitude are completely in agreement with the theoretical conceptions. A good agreement between the impedance theory and actual MPA structures proves that the impedance theory is a common approach to investigate the physical mechanism of the EM waves of the structure. Up to this point, we showed how an ultrathin PCM can strongly change the optical absorption response of a MPA design in cold and hot states. In general, the active tuning optical absorption of MPA is achieved by modulating the refractive index of the material. However, in PCM materials, this change is rather abrupt and linear tuning is not possible with these designs. However, in reality, all types of materials have thermo-optic coefficients but these values are quite small. For instance, the refractive index of a-Si has a linear relationship with the temperature change (ΔT) with a thermo-optic coefficient of $3.25 \times 10^{-4} \text{C}^{-1}$. Therefore, for a bulk a-Si, the change in temperature causes a negligible change in the material index and, therefore, it cannot be used for active tuning scenarios. However, if we can design a structure with strong field localization in sub-wavelength geometry units, we can intensify this behavior. As in our case, we have strong field confinement in the gap regions, as shown in Fig. 5. Therefore, in such hot spots, the MPA design can show a

strong response to any changes in the refractive index of the grating. In the previous section, we showed that the third resonance is red-shifted upon transformation from cold to hot state. This was due to change in the effective refractive index of the grating. Now, a new mechanism can be added to the structure, which is the thermal tunability of a-Si index. By this way, we can design a linear-thermal tunable modulator. Figure 7 shows the absorption response of the MPA design at different temperatures. In the studied range, the refractive index of the a-Si increases linearly from 3.54 to 3.59 when the temperature of the absorber increases from 25 to 250°C. At the lower range, when the temperature increases from 25 to 100°C, the PCM materials take the main role in the absorption peak tuning. After this temperature, the change in a-Si index becomes the dominant mechanism for thermal tunability function of the MPA. As extracted from Fig. 7b, the overall sensitivity of the design reaches to a value as high as $S = \frac{\Delta\lambda}{\Delta T} \simeq 0.09 \text{nm}^\circ\text{C}^{-1}$. Beyond the simple wavelength tuning of the structure at NIR, the development of thermo-optic filters opens a new type of dynamic functionality, such as switching between the reflection and transmission at the specific wavelength channel. Such a linear thermal-tunable metamaterial absorber is a promising device in the applications of optical modulator and infrared (IR) camouflage.

Conclusion

In summary, we proposed MPA with diverse functionalities enabled by inserting of a thin VO₂ layer into the plasmonic a-Si nanograting resonator in the NIR region. Double narrowband perfect absorptions are achieved under the insulator VO₂ state. Upon phase transformation from insulator to metallic, the proposed design undergoes from double to triple spectrally adjacent perfect absorptions that results in a broadband light absorption. Our numerical analysis demonstrates that the first resonance peak experiences a blue shift because of changing in the phase of the reflected incident waves. The second resonance is due to the formation of a virtual MIM configuration and finally the third mode is red-shifted

because of increasing in the effective refractive index of the nanograting. In addition to the mode profiles, the impedance matching theory is used as the common method to physically analyze the EM waves of the structure at the resonances. In the last part of the paper, the linearly thermal tunability of Si is studied. It is shown that, owing to the strong light confinement in the ultrasmall gaps of the structure, a thermal tuning is achieved within the Si nanograting, which is sufficient enough to design multi-resonance tunable features to cover a broad range spectrum. Therefore, the proposed hybrid design can provide multi-resonances tunable features for designing linearly thermal-tunable and broadband MPAs. Apart from the traditional applications, such as optical switches and filters, this design shows great prospects in the development of novel optical modulators and infrared (IR) camouflages.

Authors' Contributions First author (A.K.O.) carried out the modeling, design, and simulations. H.H. and B.K. and A.E.S. and A.G. assisted in theoretical review and simulations. E.O. supervised the study. All the authors contributed in the results, discussions, and paper writing.

Funding One of the authors (A.E.S.) received partial financial support by Narodowe Centrum Nauki, Grant No. ~2015/17/B/ST3/00118 and TUBITAK under program 2221.

References

- Boardman A (2010) Pioneers in metamaterials: John Pendry and Victor Veselago. *J Opt* 13(2):020401
- Tretyakov S, Urbas A, Zheludev N (2017) The century of metamaterials. *J Opt* 19(8):080404
- Guo CF, Sun T, Cao F, Liu Q, Ren Z (2014) Metallic nanostructures for light trapping in energy-harvesting devices. *Light: Science & Applications* 3(4)
- Zhu J, Zhang L, Jiang S, Ou J, Liu QH (2020) Selective light trapping of plasmonic stack metamaterials by circuit design. *Nanoscale* 12(3):2057–2062
- Schurig D, Mock JJ, Justice BJ, Cummer SA, Pendry JB, Starr AF, Smith DR (2006) Metamaterial electromagnetic cloak at microwave frequencies. *Science* 314(5801):977–980
- Li Z, Mutlu M, Ozbay E (2013) Chiral metamaterials: from optical activity and negative refractive index to asymmetric transmission. *J Opt* 15(2):023001
- Zhu R, Wu X, Hou Y, Zheng G, Zhu J, Gao F (2018) Broadband asymmetric light transmission at metal/dielectric composite grating. *Sci Rep* 8(1)
- Fang A, Koschny T, Soukoulis CM (2010) Lasing in metamaterial nanostructures. *J Opt* 12(2):024013
- Hoffman AJ, Alekseyev L, Howard SS, Franz KJ, Wasserman D, Podolskiy VA, Gmachl C (2007) Negative refraction in semiconductor metamaterials. *Nat Mater* 6(12):946–950
- Kraftermakher GA, Butylkin VS (2003) A composite medium with simultaneously negative permittivity and permeability. *Tech Phys Lett* 29(3):230–232
- Stewart ME, Anderton CR, Thompson LB, Maria J, Gray SK, Rogers JA, Nuzzo RG (2008) Nanostructured plasmonic sensors. *Chem Rev* 108(2):494–521
- Landy NI, Bingham CM, Tyler T, Jokerst N, Smith DR, Padilla WJ (2009) Design, theory, and measurement of a polarization-insensitive absorber for terahertz imaging. *Phys Rev B* 79(12)
- Ji C, Lee K, Xu T, Zhou J, Park HJ, Guo LJ (2017) Engineering light at the nanoscale: structural color filters and broadband perfect absorbers. *Adv Opt Mater* 5(20):1700368
- Khan AD, Khan AD, Khan SD, Noman M (2018) Light absorption enhancement in tri-layered composite metasurface absorber for solar cell applications. *Opt Mater* 84:195–198
- Khan SUM, Al-Shahry M, Ingler WB Jr (2002) Efficient photochemical water splitting by a chemically modified n-TiO₂. *Science* 297:2243–2245
- Arquer FP, Mihi A, Konstantatos G (2015) Large-area plasmonic-crystal-hot-electron-based photodetectors. *ACS Photonics* 2(7):950–957
- Kong A, Cai B, Shi P, Yuan X (2019) Ultra-broadband all-dielectric metamaterial thermal emitter for passive radiative cooling. *Opt Express* 27(21):30102
- Ghobadi A, Hajian H, Gokbayrak M, Dereshgi SA, Toprak A, Butun B, Ozbay E (2017) Visible light nearly perfect absorber: an optimum unit cell arrangement for near absolute polarization insensitivity. *Opt Express* 25(22):27624
- Lei L, Li S, Huang H, Tao K, Xu P (2018) Ultra-broadband absorber from visible to near-infrared using plasmonic metamaterial. *Opt Express* 26(5):5686
- Cheng Y, Zou H, Yang J, Mao X, Gong R (2018) Dual and broadband terahertz metamaterial absorber based on a compact resonator structure. *Opt Mater Express* 8(10):3104
- Wang B, Tang C, Niu Q, He Y, Chen R (2019) A broadband terahertz metamaterial absorber enabled by the simple design of a rectangular-shaped resonator with an elongated slot. *Nanoscale Advances* 1(9):3621–3625
- Zhang J, Wu X, Liu L, Huang C, Chen X, Tian Z, Zhang W (2019) Ultra-broadband microwave metamaterial absorber with tetramethylurea inclusion. *Opt Express* 27(18):25595
- Zhao J, Wei S, Wang C, Chen K, Zhu B, Jiang T, Feng Y (2018) Broadband microwave absorption utilizing water-based metamaterial structures. *Opt Express* 26(7):8522
- Fann C, Zhang J, Elkabbash M, Donaldson WR, Campbell EM, Guo C (2019) Broadband infrared plasmonic metamaterial absorber with multipronged absorption mechanisms. *Opt Express* 27(20):27917
- Ghobadi A, Hajian H, Rashed AR, Butun B, Ozbay E (2018) Tuning the metal filling fraction in metal-insulator-metal ultra-broadband perfect absorbers to maximize the absorption bandwidth. *Photonics Research* 6(3):168
- Zou Y, Cao J, Gong X, Qian R, An Z (2019) Ultrathin and electrically tunable metamaterial with nearly perfect absorption in mid-infrared. *Appl Sci* 9(16):3358
- Abb M, Albella P, Aizpurua J, Muskens OL (2011) All-optical control of a single plasmonic nanoantenna-ITO hybrid. *Nano Lett* 11(6):2457–2463
- Huang X, He W, Yang F, Ran J, Yang Q, Xie S (2019) Thermally tunable metamaterial absorber based on strontium titanate in the terahertz regime. *Opt Mater Express* 9(3):1377
- Chandra S, Franklin D, Cozart J, Safaei A, Chanda D (2018) Adaptive multispectral infrared camouflage. *ACS Photonics* 5(11):4513–4519
- Huang W, Yin X, Huang C, Wang Q, Miao T, Zhu Y (2010) Optical switching of a metamaterial by temperature controlling. *Appl Phys Lett* 96(26):261908
- Lee N, Kim T, Lim J, Chang I, Cho HH (2019) Metamaterial-selective emitter for maximizing infrared camouflage performance with energy dissipation. *ACS Appl Mater Interfaces* 11(23):21250–21257
- Liu H, Lu J, Wang XR (2017) Metamaterials based on the phase transition of VO₂. *Nanotechnology* 29(2):024002

33. Song Z, Wang K, Li J, Liu QH (2018) Broadband tunable terahertz absorber based on vanadium dioxide metamaterials. *Opt Express* 26(6):7148
34. Eaton M, Catellani A, Calzolari A (2018) VO₂ as a natural optical metamaterial. *Opt Express* 26(5):5342
35. Sharma Y, Tiruveedhula VA, Muth JF, Dhawan A (2015) VO₂ based waveguide-mode plasmonic nano-gratings for optical switching. *Opt Express* 23(5):5822
36. Zhu Z, Evans PG, Haglund RF, Valentine JG (2017) Dynamically reconfigurable metadvice employing nanostructured phase-change materials. *Nano Lett* 17(8):4881–4885
37. Withayachumnankul W, Shah CM, Fumeaux C, Ung BS, Padilla WJ, Bhaskaran M, Sriram S (2014) Plasmonic resonance toward terahertz perfect absorbers. *ACS Photonics* 1(7):625–630
38. Cai W, Fan Y, Huang X, Fu Q, Yang R, Zhu W, Zhang F (2019) Electromagnetically induced transparency in all-dielectric metamaterials: Coupling between magnetic Mie resonance and substrate resonance. *Phys Rev A* 100(5)
39. Zhao L, Yang X, Niu Q, He Z, Dong S (2019) Linearly thermal-tunable near-infrared ultra-narrowband metamaterial perfect absorber with low power and a large modulation depth based on a four-nanorod-coupled a-silicon resonator. *Opt Lett* 44(15):3885
40. Kehn MN, Lai WY (2020) Modal analysis of gratings with conducting strip-loaded bars and sandwiched between multiple dielectric layers. *IEEE Trans Antennas Propag* 68(6):5027–5032
41. Nasr MH, Othman MA, Eshrah IA, Abuelfadl TM (2017) Solution of cavity resonance and waveguide scattering problems using the eigenmode projection technique. *J Appl Phys* 121(14):143105
42. Rosenblatt D, Sharon A, Friesem A (1997) Resonant grating waveguide structures. *IEEE J Quantum Electron* 33(11):2038–2059
43. Lumerical F. Solutions (2016)
44. Dicken MJ, Aydin K, Pryce IM, Sweatlock LA, Boyd EM, Walavalkar S, Atwater HA (2009) Frequency tunable near-infrared metamaterials based on VO₂ phase transition. *Opt Express* 17(20):18330
45. Hohlfeld D, Zappe H (2004) An all-dielectric tunable optical filter based on the thermo-optic effect. *J Opt A: Pure Appl Opt* 6(6):504–511
46. Zhao L, Yang X, Niu Q, He Z, Dong S (2019) Linearly thermal-tunable near-infrared ultra-narrowband metamaterial perfect absorber with low power and a large modulation depth based on a four-nanorod-coupled a-silicon resonator. *Opt Lett* 44(15): 3885
47. Smith DR, Vier DC, Koschny T, Soukoulis CM (2005) Electromagnetic parameter retrieval from inhomogeneous metamaterials. *Phys Rev E* 71(3)
48. Bai Y, Zhao L, Ju D, Jiang Y, Liu L (2015) Wide angle, polarization-independent and dual-band infrared perfect absorber based on L-shaped metamaterial. *Opt Express* 23(7):8670

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.