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ABSTRACT
Two ultrabroadband and omnidirectional perfect absorbers based on transversely symmetrical multilayer structures are presented, which are achieved by four absorptive metal chromium (Cr) layers, antireflection coatings, and the substrates, glass and PMMA, in the middle. At the initial step, the proposed planar structure shows an average absorption of $\sim 93\%$ over the visible (VIS) and near-infrared range from 400 to 2500 nm and 98% in the VIS range. The optimum flat is optically characterized by the transfer matrix method and local metal-insulator-metal resonance under illumination with transverse-electric and transverse-magnetic polarization waves. The multilayer materials, which are deposited on an intermediate substrate by e-beam evaporation, outperform the previously reported absorbers in the fabrication process and exhibit a great angular tolerance of up to 60°. Afterward, we present a novel symmetrical flexible absorber with the PMMA substrate, which shows not only perfect absorption but also the effect of stress equilibrium. The presented devices are expected to pave the way for practical use of solar-thermal energy harvesting.

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I. INTRODUCTION
Optical absorbers based on nanostructures and electromagnetic (EM) metamaterials (MMs) have been considered as an indispensable optical component in diverse applications including sensing and spectroscopy for ultranarrow band absorbers,1–7 thermophotovoltaics,7,8 thermal-emitting devices,8–10 and solar–thermal harvesting devices.7,8 In the last few decades, MMs have attracted considerable attention with these special properties and unprecedented EM phenomena, such as negative effective permeability, cloaking behavior, and backward propagation,11,12 which cannot be gathered from nature. MM absorbers have widely been investigated with a variety of artificial metatoms and characteristic of block transmission and have also been recognized to have many potential applications.13–15 However, the development and practical application of MM absorbers are greatly limited due to their less lattice constant16 and complex technological process and being easily interfered with environmental factors.17 Most recently, planar nanostructures that can provide high-efficiency functionality in much smaller volumes have been focused on intensive investigations. In most of the absorber research studies, narrow-band absorbers play an important role in high sensitivity sensor systems based on Tamm surface plasmon structures18 and special 2D materials, such as graphene and transition metal dichalcogenides (TMDCs),19–22 while these narrowband absorbers are limited to extend photovoltaics (PV) and thermophotovoltaic applications.23 Consequently, it is extremely necessary to develop the novel absorber scheme from narrowband to broadband absorption that can address the aforementioned limitations and promote the applications of solar-thermal energy simultaneously.
Most of the existing perfect planar absorbers exploit absorptive metals or semiconductors with optical thickness to block trans-
mission and reduce reflection to achieve the desired unilateral and omnidirectional absorption characteristic.\textsuperscript{12}--\textsuperscript{15} Perhaps, it is a major obstacle to improving the efficiency of solar-thermal energy absorption. In addition, compared with the devices using non-
flexible substrates, such as glass and ceramics, it is found that flexible devices have many very practical and unique features—
light weight, conformal ability, suitable for mass production, and shipment.\textsuperscript{24,25} It is noteworthy that the flexible substrates are
highly vulnerable to strain and stress action of multilayers naturally owing to these extremely thin thicknesses, resulting in a signifi-
cantly downgraded performance. To this regard, one of the solu-
tions is to deposit a balanced film system on the other side of
the substrate to counteract the compressive and tensile stresses. However, there is also a defect of limited adaptability to achieve
complete stress balance for each layer, especially for thin metal
layer. Therefore, sufficiently depositing the multilayer films with
bilateral-symmetric structure is a prerequisite for its widespread
applications.

Here, we propose two novel transversely symmetrical mul-
tilayer absorbers based on the antireflection (AR) coatings, the
metal-insulator-metal (MIM) resonator, a substrate, MIM res-
onator and AR coatings (AMSMA) that could enable omnidirec-
tional, ultrabroadband response with nearly perfect absorption and
polarization-independence across the entire VIS and near-infrared
(NIR) spectra. Among them, Cr is chosen as the bimetallic layers
in the MIM structure and the graded refractive index dielectrics are
exploited as the AR coatings to enhance transmission, which are
explained in more detail in subsequent work. First, the optimum
configuration with glass-substack is investigated using numerical
simulations, and the design is fabricated and characterized. The proposed planar stack displays an average absorption of ~93% over
the visible (VIS) and NIR range from 400 to 2500 nm and 98% in
the VIS range. On the basis of saving metal greatly, the inter-
action of Cr layers at different locations can be fully utilized to
achieve the ultrabroadband absorption effect to a large extent. Con-
currently, angle-invariant performance can be maintained up to
±60° for Transverse-Electric (TE) and Transverse-Magnetic (TM)
polarization waves from both bilateral illumination directions; thus,
the proposed planar stack can equate to a spherical absorber. Fur-
thermore, in order to potentially extend the viability of devices to various application fields over a large area, the flexible material
PMMA with a modest high temperature resistance is involved for
the structural substrate fabrication, which forms an important part
of flexible absorption devices with bending deformation on the opti-
cal properties. The described concept holds great promise in a broad
range of applications such as flexible electronics, optical lithography,
and solar panels.

II. RESULTS AND DISCUSSIONS

Figure 1(a) shows a schematic diagram of the proposed ultrabroadband absorber that is made of a glass substrate and AM-MA
multilayers, where SiO$_2$ ($d_{11}$) and TiO$_2$ ($d_{l}$) with a refractive index gradient act as the AR layers and Cr ($d_{21}$), SiO$_2$ ($d_{2}$), and Cr ($d_{22}$) as the MIM layers are deposited on top of the optically thick glass sub-
strate. The bottom layers of the glass are symmetrically distributed with the upper films. The four Cr layers from the bottom up are
defined as $#1$ to $#4$, respectively. To achieve high-efficiency broad-
band absorption behavior, the dimension parameters of the config-
uration can be analyzed theoretically by using the transfer matrix
method (TMM) and optimized based on the optical film design
tool—TFCalc. The thickness of each film is set as $d_{11} = 99$ nm, $d_{l} = 60$ nm, $d_{21} = 7$ nm, $d_{2} = 104$ nm, and $d_{22} = 10$ nm, and the thin glass substrate has a negligible effect on absorption charac-
teristics. Considering the antireflection effect, the reflectance and
transmission are greatly reduced by lossy metallic films so that our
transversely symmetrical multilayer system can be seen as a perfect
absorber under the TM and TE waves. An optical photograph of the
fabricated sample is given in Fig. 1(b) which is totally black since the
omnidirectional incidence in natural light is completely absorbed.
Plotted in Fig. 1(c) are the simulated absorption spectra (blue lines)
of the whole configuration over the full range, displaying an excel-
 lent agreement with measured inset illustration (orange line) in the
VIS range. The proposed planar stack shows an average absorp-
ton of ~93% over the VIS and NIR range from 400 to 2500 nm in the simulation results and 98% in the VIS range. The device

![FIG. 1](https://example.com/figure1.png)

(a) Schematic diagram of the proposed ultrabroadband visible-NIR absorber with a glass substrate. (b) Photo of the fabricated absorber on the glass substrate under normal incidence. (c) Simulated and measured absorption spectra for the full range and visible range. Simulation whole and simulation half represent the absorption of the whole structure and the structure on one side of the glass substrate, respectively.
fabrication is carried out using electron beam evaporation on the
substrate, in which the Cr evaporation rate is 0.5 Å/s. The home-
made spectral measurement setup with a fiber spectrophotometer
(USB 2000+VIS-NIR-ES) is used to measure the VIS absorbance
spectra. It is not necessary to consider the slight differences in par-
tial segments because of the tiny change in the permittivity of Cr
with chamber pressure, evaporation temperature, and rate, which
can be neglected. Moreover, in order to correspond to the char-
acteristics and absorption contribution of Cr in each layer in the
follow-up work and highlight the broadband and high-intensity
absorption characteristics of the transversely symmetrical structure,
we also simulated the absorption spectrum of the structure on the
side of the glass substrate (green line). It can be seen that in the
whole research wave band, the absorptivity decreases obviously and
is weaker than that of the whole structure. Multiple resonances
in each MIM stack at different absorptive ranges are established,
and the broadband absorption range can reach more than 2 μm,
which is far exceed other research, the metasurfaces and the stack
absorbers.

To investigate the effect of the multiple resonances and top
metallic layers, which involves the reasonable range of the refractive
indices (both real and imaginary parts), as well as the determina-
tion of materials in different bands for outer metal layers (#1 and
#4), several 3D contour plots are presented in Fig. 2. With this sim-
ulation, the permittivity values of intermediate double layer Cr (#2
and #3) and the optical constants of SiO₂ are obtained from the data
of Palik, and the refractive index of TiO₂ is set as 2.3, in order for
the broadband absorption to reach above 0.9, which means that the
refractive indices of outer metal layers should stay inside the inner-
most circle of the horizontal contour. We can see from the contour
analysis diagrams that the four wavelengths selected can basically
cover the VIS to NIR bands what we concerned. Ordinarily, there
are many metals, semiconductors, or their alloys that can be used as
absorptive layers to achieve high-efficiency absorption, such as tita-
nium (Ti), germanium (Ge), and nickel (Ni). In contrast to these
cases, absorption was eventually identified using thin Cr to serve as
the outer absorptive metal based on its optically lossy characteristics
and weak dispersion, which can satisfy our research requirement.

Figures 3(a) and 3(b) display normalized electric-field distribu-
tion and absorption profile, which as a function of incidence wave-
length, into the proposed multilayer structural broadband absorbers.
As can be seen from Fig. 3(a), it is apparent that there are several regions
where the electric field is intensively focused on the top AR coatings over the whole wave range and SiO₂ layers over the VIS range
with different performance. The E-field is shown to be highly con-
ﬁned by double absorptive metals (#3 and #4) and trapped in the
dielectric layers of the upper portion of the structure not only at
resonance wavelength but across the entire investigated range with
TM wave incidence. Obviously, the phenomenon can be easily con-
sidered by examining the frequency response of the MIM structure
at various research areas. The simple Cr-SiO₂-Cr model resembles
a Fabry-Perot-like (FP-like) nanocavity within a short wavelength
range due to several lossy metallic boundaries outside of the cav-
ity construction. While the light intensity is localized to a greater
greater extent above the upper layer of Cr (#4), the extinction coefficient
increases gradually in the long-wave band. The calculated full
optical absorption diagram shown in Fig. 3(b) further unveils the
reason for the contribution of thin Cr films at different positions
as the optical absorption (P_{abs}) is directly proportional to the whole
E-field intensity (|E|^2). It can be expressed as

![Figure 2](image-url)
FIG. 3. (a) Electric field distribution within the whole structure at all wavelengths and (b) calculated full optical absorption diagram according to the electric field distribution. (c) Optical absorption spectrum corresponding to different layers of Cr; other layers are considered as nonabsorptive hypothetic materials. (d) The electric field distribution within the whole layers and normalized optical absorption with increasing wavelength.

\[ P_{\text{abs}} = \frac{1}{2} \omega \varepsilon_0 n k |E|^2, \]  

where \( \omega \) is the angular frequency, \( \varepsilon_0 \) is the permittivity of free space, and \( n \) and \( k \) are the real and imaginary part of the refractive index.\(^{23,35} \) In addition to the normal attenuation of light waves, four-layer Cr exhibits different physical performance, in which the absorption inside the top Cr films is probably wavelength sensitive. The electric field can only be considered as the traveling wave type because there are only ultrathin loss layers without a thick reflector.

On the basis of the descriptions containing the field intensity distribution in Fig. 3(a) and the absorptivity aimed for Cr in different layers in Fig. 3(b), the clustering physical principle of Cr thin films is further elaborated in Fig. 3(c), where the extinction coefficients of the unconsidered Cr layers are assumed to be zero, while the optical constants of other dielectrics remain invariant. For the red curve, only the bottom Cr (#1) layer plays an absorptive role, while the extinction coefficients of the other Cr layers are considered to be set as nonabsorptive hypothetic materials in the simulation of this section. Note that the absorption of the whole structure is significantly improved compared with the less Cr layer situation by adjusting the quantity of Cr layers. Simultaneously, the absorption of the full film stack is much higher than other cases, which corresponds to the phenomenon in Fig. 3(b). To better illustrate the relationship of the electromagnetic energy and absorption characteristics with the width of the absorber layer, the curves of \( |E|^2 \) and the normalized absorption based on the TMM along the z axis at different incidence wavelengths are shown in Fig. 3(d). We can see from the full range figures that the E-field intensity \( |E|^2 \) in Cr is less than that in SiO\(_2\) in the short wavelength range. In contrast to these cases, with the increase in wavelength, \( |E|^2 \) shows an exponential decay trend. According to the propagation characteristics of the electromagnetic wave between interfaces toward the shorter wavelength regime, the E-field is continuous in the tangential direction of the interface, while a mutation occurs in the normal direction, which makes \( |E_{\text{out}}| > |E_{\text{in}}| \). Furthermore, if \( \varepsilon_1 > \varepsilon_2 \), \( |E_{\text{out}}| > |E_{\text{in}}| \). Thus, when the electromagnetic wave enters Cr from SiO\(_2\), \( |E|^2 \) in the Cr is always less than that in SiO\(_2\) because \( \varepsilon_{\text{Cr}} > \varepsilon_{\text{SiO2}} \), which is consistent with the simulation results. However, for the long wavelength incidence, the wavelength is much larger than the thickness of Cr, indicating that the influence of Cr on electromagnetic field propagation is almost negligible, which is equivalent to
the propagation of electromagnetic wave in a uniform attenuation medium, thus showing an exponential attenuation curve.

Effects of each coating layer on the optical performance of the absorber are studied by using an optical admittance figure that is a graphical technique showing the progression in the surface admittance through the full configuration from the symmetrical bottom material to the incident dielectric. The optical admittance $Y$ can be expressed initially as $Y = H/E$, where $H$ and $E$ mean the magnetic-field and the electric-field intensity, respectively. For a three-layer system, we first investigate the absorptance of the research film ($n_1$) on a substrate ($n_2$); the phase factor can be defined as

$$\delta_1 = \frac{2\pi n_1 d \cos \theta_1}{\lambda},$$

where $d$ denotes the thickness of the research film, $\theta_1$ denotes the incident angle, and $\lambda$ denotes the incident wavelength. In the TMM form,

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = \begin{bmatrix} \cos \delta_1 & i\sin \delta_1 \\ in_1 \sin \delta_1 & \cos \delta_1 \end{bmatrix} \begin{bmatrix} E_2 \\ H_2 \end{bmatrix}. \quad (3)$$

Consequently, the optical admittance $Y$ of a multilayer system can be simply expressed as

$$Y = \begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = \begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos \delta_1 & i\sin \delta_1 \\ in_1 \sin \delta_1 & \cos \delta_1 \end{bmatrix} \begin{bmatrix} 1 \\ n_{sub} \end{bmatrix}. \quad (4)$$

With this equivalent admittance, determining the optical absorptance of our proposed structure with symmetrical film distribution is similar to the three-layer system situation. Thus, the total characteristic matrix should be calculated as the superposition of several characteristic matrices for each film,

$$\begin{bmatrix} B \\ C \end{bmatrix} = \prod_{j=1}^{a} \begin{bmatrix} \cos \delta_j & i\sin \delta_j \\ in_1 \sin \delta_j & \cos \delta_j \end{bmatrix} \begin{bmatrix} 1 \\ n_{sub} \end{bmatrix}. \quad (5)$$

Moreover, the reflectance can be obtained based on the Fresnel reflection formula,

$$R = |r|^2 = \frac{(Y_1 - Y_2)(Y_1 + Y_2)}{(Y_1 + Y_2)^2}, \quad (6)$$

where $Y_1$ and $Y_2$ denote the admittance of the incident dielectric and the termination dot of the total film stack. Figure 4(a) uses the same medium parameter setting method as Fig. 3(c) and verifies that with the increase in the quantity of Cr layers in operation, the terminal point (orange dot) of admittance is finally closer to $(1,0)$, i.e., the index of the incident medium, air. We also note that reflectance marked in the figure is reduced gradually, and the perfect absorption is finally achieved at 2000 nm incidence by the entire film stack. Figure 4(b) presents the optical admittances of the entire configuration as the thicknesses of the each film increase. From the comparison results of admittance loci at different wavelengths, MIM resonance structure has the largest effective admittance, and it is noteworthy that the contribution of effective admittance of Cr in a short-wave band is much higher than that in a long-wave band.

Previous descriptions of this work focus on the effects of TM waves on the proposed absorber. Next, we also simulated the

![Figure 4](image-url)
angular-dependence absorption spectra for TE and TM polarization waves, as shown in Figs. 5(a)–5(c). A highly efficient absorption performance encompassing the wavelengths from VIS to NIR is accomplished over a broad range of incident angles up to ±60°. In individual extreme cases, to clearly see that for TE, with long-band large-angle incidence, and for TM, with short-band large-angle incidence, the average absorption efficiency can still reach higher than 93%. Figure 5(d) exhibits photographs of the fabricated black absorbers taken at three different observing angles within indoor ambient illumination, showing an angle-polarization invariant even at large incident angles. On the basis of interaction between the gradient index AR coating layers and strong resonance effects of the MIM structure, the phase invalidation response between dielectrics and metal films interfaces is conducive to the angle-insensitivity performance. 38,39

In order to expand the wide application of absorbers in high ductility solar-thermal energy collectors, ultrabroadband absorbers based on flexible substrates were investigated. As the fabrication of the proposed structure just involves an uncomplicated evaporation process, the multilayer devices can be easily implemented on a flexible platform. Figure 6(a) shows a schematic diagram of the flexible absorber, in which the substrate is replaced by PMMA, and the rest is consistent with the composition of the planar absorber. The optical image of the fabricated flexible structural absorber is provided in Fig. 6(b). PMMA is chosen owing to its weak dispersion, similar refractive index to glass, high transmittance in the research band, and basically stable spectral characteristics. Subsequent work will show that the absorptivity can be maintained at a stable high efficiency at the same time of large deformation. As shown in Fig. 6(c), in comparison with previous planar absorbers, there is only a slight difference in the perfect absorption performance between the two structures. The main reason is that the selected PMMA sample material is a little bit thicker than glass and slightly different in the equivalence of transmission characteristics. Furthermore, considered that the thermal stability of flexible materials is weakened during vacuum evaporation, which affects the quality of films, the fabrication of them should strictly control the experimental indexes. From the inset of Fig. 6(c), it can be concluded that the absorption of the fabricated sample in the VIS band is roughly equal to that of the simulation.

To further explore the absorption performance of flexible devices, a bending coefficient is defined as $B = t/s$, where $t$ and $s$ denote the bending height and bending span of rectangular (aspect ratio = 5:3) absorber samples, respectively, and the schematic
FIG. 6. (a) Schematic diagram of the proposed ultrabroadband and flexible visible-NIR absorber with a PMMA substrate. (b) Photo of the fabricated flexible absorber under normal incidence. (c) Simulated and measured absorption spectra for the 400–2500 nm and visible range.

diagram is shown in Fig. 7(a). From Fig. 7(b), it is apparent that the $B$ is less than 1.497, that is, when the curvature of the half-edge absorber is about 70°, the absorption characteristics are almost unchanged, which can satisfy the near-perfect absorption effect under the normal incidence condition.

III. CONCLUSION

In summary, two high-efficiency and ultrabroadband multilayer absorbers based on the transversely symmetrical planar and flexible structure have been demonstrated. The proposed planar and flexible devices present the average absorption of ~93% over the visible (VIS) and near-infrared (NIR) range from 400 to 2500 nm and 98% in the VIS range. The greater angular-dependence can be simulated up to ±60°. The designed flexible device is simply composed of the AM-MA structure and PMMA substrate, which can perform nearly perfect absorption in the case of high bending. Both the double MIM resonator of the multilayer stack comprising economic absorptive materials and the AR property arising from the graded index profile structure contribute to the ultrabroadband absorption with high-efficiency of these planar and flexible devices. The ultra-thin symmetrical structure can significantly improve the bilateral absorption performance and is expected to play a more valuable role in various applications such as solar-thermal collectors, bolometers, and photodetection.

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REFERENCES

1. Z. Y. Fang, Y. M. Wang, A. E. Schlather, Z. Liu, P. M. Ajayan, F. J. G. de Abajo, P. Nordlander, X. Zhu, and N. J. Halas, “Active tunable absorption enhancement with graphene nanodisk arrays,” Nano Lett. 14(1), 299–304 (2014).
2. X. Lu, R. Wan, and T. Zhang, “Metal-dielectric-metal based narrow band absorber for sensing applications,” Opt. Express 23(22), 29242 (2015).
3. D. Wu, R. F. Li, Y. M. Liu, Z. Y. Yu, L. Yu, L. Chen, C. Liu, R. Ma, and H. Ye, “Ultra-narrow band perfect absorber and its application as plasmonic sensor in the visible region,” Nanoscale Res. Lett. 12(1), 427 (2017).
K. Aydin, V. E. Ferry, R. M. Briggs, and H. A. Atwater, "Broadband polarization-independent resonant light absorption using ultrathin plasmonic super absorbers," Nat. Commun. 2(1), 517 (2011).

N. I. Landy, C. M. Bingham, T. Tyler, N. Jokerst, D. R. Smith, and W. J. Padilla, "Design, theory, and measurement of a polarization-insensitive absorber for terahertz imaging," Phys. Rev. B 79(12), 125104 (2009).

N. Liu, M. Mesch, T. Weiss, M. Hentschel, and H. Giessen, "Infrared perfect absorber and its application as plasmonic sensor," Nano Lett. 10(7), 2342–2348 (2010).

W. Streyer, S. Law, G. Rooney, T. Jacobs, and D. Wasserman, "Strong absorption and selective emission from engineered metals with dielectric coatings," Opt. Express 21(7), 9113–9112 (2013).

P. Li, B. Liu, Y. Xi, K. K. Liew, J. Sze, S. Chen, and S. Shen, "Large-scale nanoporous solar selective absorbers for high efficiency solar thermal energy conversion," Adv. Mater. 27(31), 4585–4591 (2015).

C. Y. Yang, C. G. Ji, W. D. Shen, K. T. Lee, Y. G. Zhang, X. Liu, and L. J. Guo, "Compact multilayer film structures for ultrabroadband, omnidirectional, and efficient absorption," ACS Photonics 3(4), 590–596 (2016).

Q. Liang, T. Wang, Z. Lu, Q. Sun, Y. Fu, and W. Yu, "Metamaterial-based two-dimensional plasmonic subwavelength structures offer the broadest bandwidth light harvesting," Adv. Opt. Mater. 1(1), 43–49 (2013).

P. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," Phys. Rev. Lett. 84(18), 4184–4187 (2000).

D. Schuri, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial electromagnetic cloak at microwave frequencies," Science 314(5801), 977–980 (2006).

S. L. Wu, Y. Gu, Y. Ye, H. Ye, and L. S. Chen, "Omnidirectional broadband metasurface absorber operating in visible to near-infrared regime," Opt. Express 26(17), 21479 (2018).

X. Huang, W. He, F. Yang, J. Ran, B. Gao, and W. L. Zhang, "Polarization-independent and angle-insensitive broadband absorber with a target-patterned graphene layer in the terahertz regime," Opt. Express 26(20), 25558–25566 (2018).

N. Mou, S. Sun, H. Dong, S. Dong, Q. He, L. Zhou, and L. Zhang, "Hybridization-induced broadband terahertz wave absorption with graphene metasurfaces," Opt. Express 26(9), 11728–11736 (2018).

Y. J. Yoo, H. Y. Zheng, Y. J. Kim, J. Y. Rhee, J. H. Kang, K. W. Kim, H. Cheong, Y. H. Kim, and Y. P. Lee, "Flexible and elastic metamaterial absorber for low frequency, based on small-size unit cell," Appl. Phys. Lett. 105(4), 041902 (2014).

T. Huang, D. R. Chowdhury, S. Ramani, M. T. Reiten, S. N. Luo, A. K. Azad, A. J. Taylor, and H. T. Chen, "Impact of resonator geometry and its coupling with ground plane on ultrathin metamaterial perfect absorbers," Appl. Phys. Lett. 101(10), 101102 (2012).

X. Wang, X. Jiang, Q. You, J. Guo, X. Dai, and Y. Xiang, "Tunable and multichannel terahertz perfect absorber due to Tamm surface plasmons with graphene," Photonics Res. 5(6), 536–542 (2017).

Q. Yang, C. Zhang, S. Wu, S. Li, Q. Bao, and V. Giannini, "Photonic surface waves enabled perfect infrared absorption by monolayer graphene," Nano Energy 48, 161–169 (2018).

K. Li, J. M. Fitzgerald, and X. F. Xiao, "Graphene plasmon cavities made with silicon carbide," ACS Omega 2, 3640–3646 (2017).

Y. Xu, N. M. Gabor, J. S. Alden, A. M. Van der Zande, and P. L. McEuen, "Photothermaloelectric effect at a graphene interface junction," Nano Lett., 10(2), 562–566 (2010).

X. Wang, J. Wang, Z. D. Hu, T. Sang, and Y. Feng, "Perfect absorption of modified-molybenum-disulphide-based Tamm plasmonic structures," Appl. Phys. Express 11(6), 062601 (2018).

K. T. Lee, C. Ji, and L. J. Guo, "Wide-angle, polarization-independent ultrathin broadband visible absorbers," Appl. Phys. Lett. 108(3), 031107 (2016).

L. Qin, S. Wu, C. Zhang, and X. Li, "Narrowband and full-angle refractive index sensor based on a planar multilayer structure," IEEE Sens. J. 19, 2924–2930 (2019).

J. L. Wang, B. Z. Zhang, X. Wang, and J. P. Duan, "Flexible dual-band band-gap metamaterials filter for the terahertz region," Opt. Mater. Express 7(5), 1656–1665 (2017).

H. Tao, C. M. Bingham, A. C. Strikwerda, D. Pilon, D. Shrekenhamer, N. I. Landy, K. Fan, X. Zhang, W. J. Padilla, and R. D. Averitt, "Highly flexible wide angle of incidence terahertz metamaterial absorber," Phys. Rev. B 78(24), 241103 (2008).

D. H. Kim, S. S. Kim, S. Hwang, and J. H. Jang, "Surface relief structures for a flexible broadband terahertz absorber," Opt. Express 20(15), 16815–16822 (2012).

K. T. Lee, Y. S. Han, and H. J. Park, "Omnidirectional flexible transmissive structural colors with high-color-purity and high-efficiency exploiting multicavity resonances," Adv. Opt. Mater. 5(14), 1702841 (2017).

K. T. Lee, Y. S. Lee, S. Seo, and L. J. Guo, "Colored ultrathin hybrid photovoltaics with high quantum efficiency," Light: Sci. Appl. 10(1), e215 (2014).

B. Zhang, Y. Zhao, Q. Hao, B. Kiraly, I. C. Khooh, S. Chen, and T. J. Huang, "Polarization-independent dual-band infrared perfect absorber based on a metal-dielectric-metal elliptical nanodisk array," Opt. Express 19(16), 15221–15228 (2011).

J. Park, J. H. Kang, A. P. Vasudev, D. T. Schoen, H. Kim, and E. Hasmann, "Omnidirectional near-unity absorption in an ultrathin planar semiconductor layer on a metal substrate," ACS Photonics 19, 812–821 (2014).

S. A. Dereshgi, A. Ghobadi, H. Hajian, B. Butun, and E. Ozbay, "Ultra-broadband, lithography-free, and large-scale compatible perfect absorbers: The optimum choice of metal layers in metal-insulator multilayer stacks," Sci. Rep. 7(1), 14872 (2017).

Z. Li, E. Palacios, S. Butun, H. Kocer, and K. Aydin, "Omnidirectional, broadband light absorption using large-area, ultrathin lossy metallic film coatings," Sci. Rep. 5, 15137 (2015).

M. A. Kats, R. Blanchard, P. Genevet, and F. Capasso, "Nanometre optical coatings based on strong interference effects in highly absorbing media," Nat. Mater. 12(1), 20–24 (2012).

H. Kocer, S. Butun, Z. Li, and K. Aydin, "Reduced near-infrared absorption using ultra-thin lossy metals in Fabry-Perot cavities," Sci. Rep. 5, 8157 (2015).

C. W. Lin, K. P. Chen, M. C. Su, T. C. Hsiao, S. S. Lee, and S. Lin, "Admittance loci design method for multilayer surface plasmon resonance devices," Sens. Actuators B, 117(1), 219–229 (2006).

Y. J. Jen, W. C. Liu, T. K. Chen, S. W. Lin, and Y. C. Jhang, "Design and deposition of a metal-like and admittance-matching metamaterial as an ultra-thin perfect absorber," Sci. Rep. 7(1), 3076 (2017).

C. W. Cheng, M. N. Abbas, C. W. Chiu, T. K. Lai, M. H. Shih, and Y. C. Chang, "Wide-angle polarization independent infrared broadband absorbers based on metallic multi-sized disk arrays," Opt. Express 20(9), 10376–10381 (2012).

J. Y. Lee, K. T. Lee, S. Seo, and L. J. Guo, "Decorative power generating panels creating angle insensitive transmissive colors," Sci. Rep. 4, 4192 (2014).