Broadband and Polarization-Insensitive Coherent Perfect Absorption by Black Phosphorus Metasurfaces

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Abstract: Black phosphorus (BP), a relative new plasmonic two-dimensional (2D) material, offers unique photonic and electronic properties. In this work, we propose a new broadband and polarization-independent ultrathin coherent perfect absorber (CPA) operating in the terahertz (THz) frequency range. It is based on a bifacial metasurface made of BP patch periodic arrays separated by a thin dielectric layer. Broadband CPA bandwidth is realized due to the ultrathin thickness of the proposed device and the extraordinary properties of BP. In addition, a substantial modulation between CPA and complete transparency is achieved by adjusting the phase difference between the two counter-propagating incident waves. The CPA performance can be tuned by dynamically changing the electron doping level of BP. The CPA response under normal and oblique transverse magnetic (TM) and electric (TE) polarized incident waves is investigated. It is derived that CPA can be achieved independent of the incident polarization and for a broad range of incident angles. The presented CPA device can be used in the design of tunable planar THz modulators, all-optical switches, detectors, and signal processors.

1. Introduction

The absorption of electromagnetic energy by a conductive material can be greatly enhanced due to interference between the incident and reflected waves [1], [2]. The recently proposed concept of coherent perfect absorption (CPA) [3]–[6] has generalized this feature to free-standing structures based on the destructive interference of two input waves interacting inside their lossy materials. It can lead to total absorption in a flexible and controllable way by efficiently manipulating the interference effect via varying the incident waves’ intensities or phases. Recently, the CPA concept has attracted increased research interest [7]–[13] because of its potential use in nanophotonic applications, such as optical modulators, optical switches, and sensors. Moreover, CPA devices have been realized with different versatile geometries. The use of metamaterials or metasurfaces has opened new possibilities in the efficient CPA control through the incorporation of additional robust system parameters and artificial engineered materials. Moreover, two-dimensional (2D) materials [14], such as graphene, promise to provide further tunability in the CPA response through dynamically controlling their doping level by using appropriate gating voltage configurations [12]. This dynamic feature cannot be achieved with other systems based on conventional bulky materials.

CPA consists the time-reversed analog of laser, inevitably leading to narrow bandwidth operation [3]. However, it has been reported that the CPA bandwidth can be improved by substantially decreasing the size of the absorbing medium [15], i.e., making the CPA structure much smaller than the incident wave wavelength. This effect is impossible to be achieved by using conventional lossy materials because enormous loss coefficients will be required to attain CPA that are difficult to be realized in practice [10]. 2D materials provide a practical alternative to design ultrathin CPA devices (much smaller than the operation wavelength), because they can sustain strongly confined subwavelength plasmonic waves along their surfaces [16]–[21]. The resulted compactness of the CPA devices based on 2D materials is another significant advantage, besides their unique tunability feature.

Graphene is the most widely investigated 2D material due to its outstanding optical (plasmonic), mechanical, and electronic properties [22]–[24]. As an alternative to graphene,
recently, black phosphorus (BP) demonstrated prominent potential to a variety of applications including photodetectors, phase shifters, absorbers, and field effect transistors [25]–[27]. It can be manufactured either by using exfoliation or other mechanical/chemical deposition techniques [28]–[30]. By patterning the monolayer BP to circular or rectangular patches, we can design plasmonic metasurfaces operating at THz frequencies [31]–[33]. In addition, unlike graphene and other 2D materials, BP exhibits a strong anisotropic plasmonic response because of the puckered honeycomb lattice structure formed by its atoms [34], [35]. Another difference compared to graphene is that BP has a thickness-dependent direct bandgap, ranging from \( \sim 0.3 \text{eV} \) (bulk BP) to \( \sim 2 \text{eV} \) (monolayer BP) [36]–[38]. This characteristic property makes BP a prominent material to enable tunable optical response over a broad wavelength range [39]. Note that 2D BP monolayers have already been used as conventional THz absorbers [32], [40]–[43] under single wave illumination.

In this paper, a new tunable, broadband, and polarization-independent THz CPA device based on two bifacial BP-based metasurfaces separated by a thin dielectric spacer layer is designed. We provide the theoretical analysis of the proposed planar and compact CPA device by using the transfer matrix and equivalent circuit models. Numerical simulations are used to verify the accuracy of the theoretical models. Thanks to the properties of the BP patches, the CPA resonance can be dynamically tuned by changing the electron doping level of BP. The CPA effect can be realized for both transverse magnetic (TM) and electric (TE) polarized incident waves. Furthermore, a CPA angular tolerance as high as 60° is achieved. Finally, we compare the CPA performance of the proposed structure with a similar graphene-based device and find that the broad bandwidth feature is a unique advantage of the presented BP-based device. The flexible tunability and wide bandwidth operation imply the great potential of the proposed device to be used in the design of tunable compact planar THz modulators, detectors, switches, and signal processors.

2. Theoretical analysis and design of coherent perfect absorber

Fig. 1(a) demonstrates the schematic of the proposed CPA device, which is composed of two BP monolayers structured in a patch array (metasurface) formation and separated by a thin dielectric spacer layer. The geometrical parameters of the unit cell are shown in Fig. 1(b). The transfer matrix \( S \) formalism is used to theoretically analyze the propagation of the two incident waves and their interactions with the proposed BP-based CPA device. Thus, the output waves \( (O) \) can be expressed as:

\[
\begin{bmatrix}
O_x \\
O_y
\end{bmatrix} = S \begin{bmatrix}
I_x \\
I_y
\end{bmatrix} = \begin{bmatrix}
r_x & t_x \\
t_x & r_x
\end{bmatrix} \begin{bmatrix}
I_x \\
I_y
\end{bmatrix},
\]

(1)

where \( r_x, r_y \) and \( t_x, t_y \) are the reflection and transmission coefficients at the forward and backward direction, respectively. To quantitatively investigate the CPA effect, we define the output coefficient variable \( \Theta \) as the ratio of the output waves intensities to that of the input waves [44][45]:

\[
\Theta = \frac{|O_x|^2 + |O_y|^2}{|I_x|^2 + |I_y|^2} = \frac{|r + t e^{i \lambda p}|^2 + |t + r e^{i \lambda p}|^2}{2},
\]

(2)

where we utilized \( r_x = r \) and \( t_x = t \) due to symmetry and reciprocity. Furthermore, we assume that the amplitude of the forward and backward waves are always equal throughout this work, which means that one input source can be used that can be split in two counter-propagating
waves with different phases by using a beam splitter and phase delay configuration. Hence, the relation between the two counter-propagating incident beams is: \( I = e^{i\omega t}I \), where \( \Delta \phi \) is the phase difference introduced by the different propagation distance between the incident waves or another phase delay configuration. CPA can be achieved when the output coefficient becomes \( \Theta = 0 \), which means that there will be no outgoing waves \( (O_r = 0) \) and the total incident energy will be fully absorbed by the device. Quasi-CPA has been reported in the THz regime in the case of suspending BP [46] and graphene [47] monolayers, but this response was not broadband, polarization-insensitive, and omnidirectional. It was concluded that \( |r| = |t| \) under single wave incidence is the necessary condition to achieve the CPA performance. We derive a more precise CPA condition that also takes into account the phase difference of the two incident waves. By rearranging the output coefficient formula, we obtain \( \Theta = r^2 + t^2 + 2rt \cos \Delta \phi \). In this case, CPA \( (\Theta = 0) \) can be achieved if \( r = -t \) and \( \cos \Delta \phi = 1 \) \( (\Delta \phi = 2n\pi) \) or if \( r = t \) and \( \cos \Delta \phi = -1 \) \( (\Delta \phi = (2n+1)\pi) \), with \( n \) being an arbitrary integer number. Note that \( r = -t \) implies that the amplitude of reflection and transmission coefficients are the same and their phase difference \( \Delta \theta \) (not to be confused with the phase difference \( \Delta \phi \) between the two counter-propagating waves) is \( \pi \), i.e., \( |r| = |t| \) and \( \Delta \theta = \pi \). Similarly, \( r = t \) means that \( |r| = |t| \) and \( \Delta \theta = 0 \).

We employ the transmission-line method [48], appropriately modified to model the current BP-based design, to compute the reflection, transmission, and absorption coefficients when a single incident wave illuminates the proposed device. The complex anisotropic conductivity of a BP monolayer can be described by the semi-classical Drude model [31]:

\[
\sigma_j = iD_j/\pi(\omega + i\eta/h),
\]

where \( D_j = \pi n_e e^2/m_j \) is the Drude weight, \( j = x, y \) represents each in-plane direction, \( n_e \) is the electron doping level, \( e \) is the electron charge, \( \omega \) is the incident radial frequency, \( h \) is the reduced Planck’s constant, and \( \eta = 10\,meV \) is a typical relaxation rate value for BP [31]. The electron mass of BP along the \( x \)- (armchair) and \( y \)- (zig-zag) direction can be expressed as:

\[
m_{x} = \hbar^2/(2\gamma^2/\Delta + \eta) \quad \text{and} \quad m_{y} = \hbar^2/2\nu_{e},
\]

where \( \gamma = 4a_0/\pi \,eV \text{m} \), \( \Delta = 2\,eV \), \( \eta = \hbar^2/(0.4n_0) \), and \( \nu_{e} = \hbar^2/(1.4m_0) \) [34]. Here, the thickness of the BP monolayer \( a \) is set equal to 0.223 nm. The surface impedance of the proposed metasurface based on an array of periodic BP patches can be expressed as: [49]–[51]

\[
Z_j = \left( \frac{P}{L_j \sigma_j} \right) - \frac{i}{\omega \varepsilon_j (\varepsilon_{d} + 1)}P \ln \{\csc(\pi(P-L_j)/2P)\} \frac{L_j}{L_i},
\]

where \( j \) represents the \( x \)- (or \( y \)-) in-plane direction, and \( i \) represents the \( y \)- (or \( x \)-) direction, respectively, \( P \) is the period of the patch array, and \( \varepsilon_j \) is the relative permittivity of the dielectric spacer layer. Eq. (3) can be rearranged as:

\[
Z_j = \frac{(\eta/h)\pi P}{L_j D_j} + \frac{i}{\omega \varepsilon_j (\varepsilon_{d} + 1)}P \ln \{\csc(\pi(P-L_j)/2P)\},
\]

where \( C_j \) is the effective capacitances in the \( j \) direction, which is determined by the dielectric spacer layer and the geometrical parameters of the BP patch array:

\[
C_j = \left( \frac{L_j}{L_i} \right) (\varepsilon_{d} + 1) P \ln \{\csc(\pi(P-L_j)/2P)\}.
\]
Eq. (4) demonstrates that the surface impedance of the BP patch array is anisotropic. In addition, it can be derived that the BP patch array can be modeled by an effective resistor (R), inductor (L), and capacitor (C) in series, as shown in Fig. 2(a). The wave impedance of the dielectric spacer layer for normal incidence illumination is equal to:
\[ Z_d = \eta_d \tan(k_d d) = 1/(i\omega C_d) \]
where \( \eta_d = \sqrt{\mu_0/\varepsilon_0} e_d \) and \( k_d = \alpha_0 \sqrt{\varepsilon_0} e_d \mu_0 \) are the characteristic impedance and wave number, respectively, and \( C_d \) is the effective capacitance that can be calculated by the \( Z_d \) formula.

First, we investigate the proposed device under TM-polarized incident wave illumination. In this case, the electric field is polarized along the x-direction and the transmission line equivalent circuit model is shown in Fig. 2(a). Both the top and bottom BP patch arrays form identical R-L-C series circuits with parameters shown in Fig. 2(a). The total impedance of the device can be computed by the parallel combination of the two R-L-C series circuits and the capacitive impedance of the dielectric layer and is equal to:
\[ Z = Z_d \parallel 0.5Z_{ss} \]
where \( Z_{ss} \) is the corresponding surface impedance of the BP patch array in the x-direction due to TM-polarized illumination. Then, the input impedance of the proposed device is given by:
\[ Z_{in} = Z_d \parallel 0.5Z_{ss} \parallel Z_0 \]
where \( Z_0 = 120\pi \Omega \) is characteristic impedance of the surrounding free space. As a result, the total reflection, transmission, and absorption coefficients [52]–[54] of the proposed CPA THz device can be computed by:
\[ r = (Z_{in} - Z_0)/(Z_{in} + Z_0) \]
\[ t = 2Z_{in}/(Z_{in} + Z_0) \]
and \( A = 1 - |r|^2 - |t|^2 \), respectively. Note that a relationship exists that connects the input and surrounding free space impedance to perfectly satisfy the CPA condition:
\[ Z_{in} = 0.5Z_0 \]
The proposed bifacial metasurface design can decrease the total input impedance due to mutual coupling between the BP patches and realize the aforementioned CPA impedance condition. This condition cannot be satisfied with a single metasurface and a more elaborate bifacial design is required.

The parameters used for the thin dielectric spacer layer are \( \varepsilon_d = 2.92 \) and \( d = 20\text{nm} \). The periodicity of the device is \( P=500\text{nm} \). The electron doping level of the BP monolayer is chosen to have a moderate value of \( n_i = 4 \times 10^{13} \text{cm}^{-2} \). The side lengths of each BP patch in the x- and y-directions are equal: \( L_x = L_y = 480\text{nm} \). The spectra of the computed reflection, transmission, and absorption coefficients by the equivalent circuit model are demonstrated in Fig. 2(b). It can be seen that \( |r| = |t| \) at the resonant frequency (8 THz). In addition, the absorption reaches 50% at this resonance point, which satisfies the necessary condition to achieve CPA. In order to quantitatively demonstrate the CPA effect, we analytically calculate the output coefficient \( \Theta \) by substituting the computed reflection and transmission coefficients into Eq. (2). Indeed, CPA can be achieved at the resonant frequency 8 THz when the phase difference between the counter-propagating incident waves is \( \Delta \phi = 2\pi \), as it is shown in Fig. 2(c). The absorption can reach to 90% values at the off-resonant frequencies of 7.2 THz and 8.8 THz, which implies broadband quasi-CPA performance. The pink dotted line in Fig. 2(c) demonstrate the performance of the proposed CPA device for higher frequencies (10 THz), where the CPA effect ceases to exist. Note that the CPA can be modulated from 0.01% to 99.98% at the resonant frequency (8 THz) just by varying the phase difference \( \Delta \phi \) between the counter-propagating incident waves. This means that the proposed planar compact device can be switched from perfect absorption to complete transparency.

3. Results and discussion

The proposed CPA device is further investigated and optimized by performing simulations with COMSOL Multiphysics [56], a commercial electromagnetic solver based on the finite element method (FEM). The use of a 3D simulation domain is necessary because the BP monolayer is
modeled as a boundary layer with an anisotropic surface current distribution. The BP optical conductivity was given in Section II and this formula is used in the simulations. Periodic boundary conditions (PBC) are set in the x- and y- directions to model the periodic BP patches and port boundaries are placed in the z- direction to create the incident plane waves. Considering that BP is highly reactive to the oxygen of the surrounding free space, it is essential to encapsulate the entire device inside an ultrathin dielectric sheet to protect the BP monolayers from degradation [57]. Thus, a 10 nm thick Al₂O₃ thin film is used on both sides of the device that now can be exposed to the surrounding air. In a potential experiment, the fabrication can start with the micromechanical cleavage of bulk BP crystals directly onto the Al₂O₃ substrate from both sides, which will form the dielectric spacer layer between the metasurfaces. The 10 nm thick Al₂O₃ thin film can be grown on both sides by atomic layer deposition [43], [58], as an encapsulating layer to protect the BP monolayer from degradation.

First, we consider the case of a single normal incident TM-polarized THz wave impinging on the device. The simulated spectra of transmission, reflection, and absorption coefficients, and the phase difference \( \Delta \theta \) between the transmission and reflection coefficients are shown in Fig. 3(a). In these results, the same parameters were chosen for the system with those used in the equivalent circuit model presented in Section II. We will keep using these parameters during this work unless otherwise specified. It can be clearly seen in Fig. 3(a) that the phase difference between the transmission and reflection coefficients is \( \Delta \theta = \pi \) and the transmission \( |t| \) and reflection \( |r| \) amplitudes are very close to each other at the peak absorption resonance frequency (8.4 THz). According to the theoretical analysis, the CPA condition \( r \approx -r \approx 0.5 \) is perfectly satisfied at this point. Note that the simulation results shown in Fig. 3(a) agree very well with the theoretical results presented in Fig. 2(b), despite that in the simulations the encapsulation of BP with a thin dielectric layer was also included. This dielectric layer is extremely thin compared to the wavelength of the operating THz frequency. The small frequency shift between the theoretical and simulation results can be attributed to both the finite mesh size used during the simulations and the thin dielectric layer. The broadband absorption response \( \theta = 0.5 \) under a single beam illumination shown in Fig. 3(a) implies the potential to attain broadband CPA performance, since the CPA condition is satisfied for a relative broad frequency range.

It is expected that the proposed device will function as a deep-subwavelength CPA ultrathin film. In order to further verify the CPA formation condition, we calculate the effective surface conductivity \( \sigma'_e \) by using a retrieval method adapted to thin films [59]. Fig. 3(b) presents the real, imaginary, and absolute values of the effective surface conductivity of the proposed structure normalized to the free space admittance \( Y_0 = 1/Z_0 \). It is verified that the CPA condition \( |\sigma'_e| Z_0 = 2 \) [55][60] is fulfilled around the resonant frequency, which coincides with the 50% absorption maximum [53].

Similar to the theoretical analysis in Section II, we launch a second incident wave to the device from the opposite side that has the same intensity and polarization with the first one. Then, the two counter-propagating waves destructively interfere at the nanoscale thickness of the proposed metasurface leading to CPA formation. To further investigate the CPA process and confirm its dependence on the phase difference between the incident waves \( \Delta \phi \), we create a contour plot of the computed output coefficient \( \Theta \) as a function of the incident frequency \( f \) and phase difference \( \Delta \phi \) that is shown in Fig. 4(a). Interestingly, the total absorption can reach to 100% (CPA, \( \Theta = 0 \)) with a proper phase difference of \( \Delta \phi \), while it is almost 0% (complete transparency, \( \Theta = 1 \)) with \( \Delta \phi = (2n + 1)\pi \).

The output coefficient \( \Theta \) as a function of the phase difference at four different frequencies is shown in Fig. 4(b). It is important to notice that the simulation results agree well with our
analytical calculations in Fig. 2(c). In order to quantitatively measure the tunable performance of the CPA response, we define the CPA modulation contrast as the ratio of the maximum to the minimum output coefficient $\Theta$ value. The CPA modulation contrast can reach very high values of approximately 54dB at 8.4 THz, outperforming the modulation contrast predicted in [61] for a graphene device. Furthermore, we calculate the CPA modulation contrast at 7.7 THz and 9.2 THz, which is 21.9dB and 20dB, respectively. For comparison, the pink dotted line in Fig. 4(b) is the output coefficient versus the phase difference at a non-resonant frequency (10 THz), where no CPA is achieved. Clearly, Figs. 4(a) and 4(b) demonstrate that almost perfect absorption can be obtained within a wide frequency range when the phase difference is fixed to $\Delta \phi = 2n\pi$. The broad bandwidth feature is a major advantage of the proposed CPA device. It can be attributed to its extremely thin planar geometry, since it is known that the CPA bandwidth is inversely proportional to the CPA film thickness [55]. However, extremely thin conventional materials will require enormous and non-practical loss coefficients in order to achieve CPA [10].

Next, we consider how the CPA response of the proposed BP-based device varies with its geometrical features. The dependence of the output coefficient on the thickness of the dielectric spacer layer under TM-polarized normal incident counter propagating waves is shown in Fig. 5(a). It is worth noting that broadband CPA can be achieved under a wide range of thickness values. This is really crucial to the practical implementation of the proposed device, since the thickness of the ultrathin dielectric spacer layer might be slightly changed during the fabrication process. Moreover, the resonant frequency demonstrates a minor redshift, as we gradually increase the thickness of the dielectric layer. This is due to the fact that the absorption resonance is mainly determined by the size of the BP patches [31][42] and not the dielectric layer thickness. In addition, the thickness of the dielectric layer between the two BP patch arrays is substantially smaller compared to the operation wavelength and, as a result, its influence in the optical response is minor [48].

Moreover, it is interesting to investigate the effect of the electron doping level on the CPA performance, since it can alter the surface conductivity of the BP monolayer. This interesting tunable characteristic has been employed in optical modulator [62] and photodetector [63] applications. The change in the CPA performance by tuning the electron doping level of the BP monolayer between moderate practical values from $2 \times 10^{13}$ cm$^{-2}$ to $1 \times 10^{14}$ cm$^{-2}$ [64] is shown in Fig. 5(b). The coherent absorption is kept nearly perfect, as long as the electron doping level $n_i$ is higher than $2.5 \times 10^{13}$ cm$^{-2}$. In addition, the CPA resonance frequency blue shifts as the electron doping level of the BP monolayers increases. This is because the electron doping values can significantly alter the BP properties. An approximate relationship between the resonance frequency and the electron doping level is $f \propto \sqrt{n/L}$ [34], [42], where $n$ is the electron doping level and $L$ is the length of the BP patch. Clearly, this relationship is consistent with the simulation results shown in Fig. 5(b). The electron doping level also has a substantial influence on the bandwidth of the CPA effect, as shown in Fig. 5(b), which is attributed to the slower variation of the BP patches’ surface impedances at higher frequencies. Thus, the CPA effect can be flexibly tuned by dynamically changing the electron doping level values of each BP patch.

Up to now we have considered only the CPA performance with TM-polarized wave, similar to several previous works relevant to plasmonic CPA devices [60], [65], [66]. However, BP has uniquely strong in-plane anisotropic optical properties, which result from the arrangement of its atoms. Hence, it will be interesting to investigate the CPA performance of the proposed device under TE-polarized incident beams. In this case, the electric field of the incident plane waves will be polarized along the zigzag (y) direction of the BP patches. First, a single incident wave is launched. The computed reflection and transmission coefficients are not equal but very close to each other at the resonance frequency of 8 THz, as it is shown in Fig. 6(a). However,
the computed absorption can reach to 50% in this case, which is the most vital and prevalent point to achieve CPA. In addition, the phase difference between reflection and transmission coefficients is exactly 180° at this resonant frequency, indicating that the CPA effect can also be achieved for TE-polarized incident waves.

Next, we launch a second beam with the same TE polarization but from the opposite side. In order to achieve CPA, the electron doping level in this case is chosen to have a slightly larger value: \( n_e = 9 \times 10^{13} \text{ cm}^{-2} \), because BP has increased losses along its zigzag direction [31]. The tenability of the proposed CPA device under TE-polarized excitation is investigated in Fig. 6(b). CPA (\( \Theta = 0 \)) can be achieved when the electron doping level is larger than \( 7 \times 10^{13} \text{ cm}^{-2} \).

Note that the increase of the electron doping level in the zigzag direction due to the TE-polarized excitation has the same effect with the TM-polarized case, leading to blue shift in resonance frequency and broader CPA bandwidth. The polarization-insensitive property of the proposed planar device can be of great significance to different CPA applications. Polarization-insensitive CPA devices have been reported before based on dipolar meta-atoms [9] and single-layer fishnet metasurfaces [13] due to the exotic material properties and the structural features, respectively. These devices were bulkier compared to the currently proposed ultrathin structure. In our case, the polarization independence feature is due to both material (BP) and structural (metasurface) effects. BP shows strong anisotropic characteristics in armchair (x) and zigzag (y) directions and its electron doping level can be tuned, making it possible to attain CPA for both polarizations and different doping levels.

We further study the CPA performance of the proposed device, now under oblique TM-polarized incident waves. The simulated spectra of the transmission, reflection, and absorption coefficients, and the phase difference between the transmission and reflection coefficients, under a single incident wave with an angle of 60° are shown in Fig. 7(a). The reflection and transmission coefficients are equal to each other at the resonance frequency of 9.4 THz, which is slightly shifted due to the oblique incident illumination. Meanwhile, their phase difference is exactly 180° at this point. Clearly, Fig. 7(a) demonstrates that the requirement to achieve CPA can be fulfilled with the proposed device even under 60° oblique incidence. In order to fully investigate the range of incident angles over which CPA can be attained, we compute the output coefficient as a function of the incident angle ranging from 0° to 89° and the frequency varying from 2 to 14 THz. The computed contour plot is presented in Fig. 7(b), where the omnidirectional CPA response of the proposed device is demonstrated. CPA can be achieved under incident angles as high as 70°. Omnidirectional CPA operation is another unique and very important feature of the proposed planar CPA device.

A similar bifacial metasurface design made of graphene is also expected to exhibit CPA performance. Graphene is the most widely-used 2D plasmonic material and has been studied in a variety of applications [67][68]. The envisioned graphene-based device is designed to resonate around 8 THz under TM-polarized incident waves just by slightly changing the dimensions of the presented structure. The lengths of each graphene patch and the period of the nanopatch array are changed to be \( L_x=L_y=360\text{nm} \), and \( P=400\text{nm} \), respectively. In addition, the conductivity of graphene is described by the Drude model [69] and its Fermi energy is set to be equal to 0.2 eV. We compute the output coefficient of the graphene metasurface and compare its CPA performance with the BP-based CPA device in Fig. 8. More than 90% coherent absorption can be obtained over a broad bandwidth (1.5 THz) only in the case of the BP-based CPA device, while a narrower bandwidth (0.5 THz) is achieved with the graphene-based CPA device. The bandwidth of the proposed BP-based device is three times larger compared to the graphene-based structure. Note that we have also investigated the CPA response of the graphene-based device under different Fermi levels (not shown here) and found that the Fermi level does not alter its CPA bandwidth, as it was also derived in [31]. The broad bandwidth CPA response of the BP-based device results from the unique anisotropic plasmonic properties
of BP.

4. Conclusions

To conclude, we designed a new broadband and polarization-independent THz CPA bifacial metasurface based on two metasurfaces of periodically arranged identical BP patches separated by a thin dielectric layer. We theoretically analyzed the proposed ultrathin CPA device based on an equivalent circuit model and then verified its performance by full-wave simulations. By calculating the output coefficient of the structure under two counter-propagating waves, we proved that broadband CPA can be achieved with this configuration. The CPA condition can be controlled by varying the phase difference between the two incident waves. In addition, the CPA frequency point can be tuned by dynamically changing the doping level of BP. Interestingly, the CPA effect can be realized for both TE- and TM-polarized illumination and achieved over a wide range of incident angles, leading to a unique omnidirectional CPA performance. The CPA bandwidth of the proposed device is much broader compared to a similar graphene-based structure. Thanks to its ultrathin, broadband, and polarization-insensitive features, the proposed CPA device is envisioned to be used in the design of planar THz modulators, switches, detectors, and signal processors.

5. References

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Fig. 1. (a) Schematic of the BP-based CPA device consisting of two metasurfaces made of BP patches separated by a thin dielectric spacer layer. $I_+$ and $O_+$ denote the input and output waves, respectively, from each side. $\theta_+$ and $\theta_-$ are the incident angles of the forward and backward incident waves. (b) Unit cell of the proposed device. $L_x$ and $L_y$ are the lengths of each BP patch in the x- and y-direction, respectively. $P$ and $d$ are the period of the BP patch array and the thickness of the dielectric layer.

Fig. 2. (a) Equivalent circuit model of the proposed BP-based CPA device under a TM-polarized incident excitation. (b) The reflection, transmission, and absorption coefficients spectra under a single TM-polarized wave illumination. (c) Output coefficient $\Theta$ as a function of the phase difference between the two incident counter-propagating beams at four different frequencies.

Fig. 3. (a) Transmission, reflection, and absorption coefficients, and the phase difference between the transmission and reflection coefficients, as a function of frequency for a single TM-polarized wave normally incident upon the CPA device. (b) Real, imaginary, and absolute values of effective surface conductivity $\sigma^e$ of the proposed BP-based CPA device normalized to the free space admittance.
Fig. 4. (a) Contour plot of the output coefficient $\Theta$ as a function of frequency $f$ and phase difference $\Delta\varphi$ between the two counter-propagating incident waves. (b) Output coefficient $\Theta$ as a function of the phase difference at four different frequencies. Perfect CPA is obtained at 8.4 THz for $\Delta\varphi = 2n\pi$.

Fig. 5. Contour plot of the computed output coefficient $\Theta$ as a function of the frequency $f$ of the TM-polarized incident waves and (a) the thickness of the dielectric spacer layer or (b) the BP electron doping level $n_e$. The two counter-propagating incident beams have a fixed phase difference equal to $\Delta\varphi = 2n\pi$.

Fig. 6. (a) Transmission, reflection, and absorption coefficients, and the phase difference between the transmission and reflection coefficients, as a function of frequency for a single TE-polarized wave normally incident upon the CPA device. (b) Contour plot of the computed output coefficient $\Theta$ as a function of the frequency $f$ and the electron doping level $n_e$. The two counter-propagating TE-polarized incident waves have a fixed phase difference equal to $\Delta\varphi = 2n\pi$. 

□
Fig. 7. (a) Transmission, reflection, and absorption coefficients, and the phase difference between the transmission and reflection coefficients, as a function of frequency $f$ for a single TM-polarized wave incident upon the CPA device with an angle of $60^\circ$. (b) Contour plot of the computed output coefficient $\Theta$ as a function of frequency $f$ and incident angle in the case of two counter propagating incident waves with a fixed phase difference $\Delta \phi = 2\pi$.

Fig. 8. Output coefficient $\Theta$ as a function of the frequency $f$ under two incident counter-propagating TM-polarized waves with the same intensity and phase for the BP- (red line) and graphene- (black line) based CPA devices.