1. Introduction

During the past decade, resonant perfect absorbers (PAs) made of nanostructures have been attracting a great interest, because they have good properties such as ultrasmall thickness, wide-angle and polarization insensitive absorption, tunability and scalability from microwave to optical range [1–3]. These characteristics make them very promising in applications like thermal emitters [4], thermal photovoltaic (TPV) [5], bolometers [6], sensing [7], THz SLM [8] and so on. The most investigated resonant PAs are consisted of metal-dielectric-metal (MDM) layers: a top subwavelength periodic metal pattern, a middle ultrathin dielectric gap layer, and a bottom optical-thick continuous metal layer. Broadband perfect absorber (BPA) is a branch of them, which is necessary in cases such as TPV [5], bolometer [6] and photodetection [9]. However, due to the resonant nature of the PAs, they are usually narrow band. A straightforward method to broaden the absorption spectra is to integrate multiple resonances in one unit cell. Collected in [2, 10, 11], there are four mainstream tactics: planarly tiling multi-size resonators [12–14], vertically stacking multi-size resonators [15, 16], dispersing plasmonic nanocomposites [3, 17–22] and space-filling with nontrivial patterns [23, 24]. Some designs like using lumped elements [25], adopting high intrinsic loss material [26–28] and constructing non-resonant impedance match materials [11, 29] are also proposed to achieve broadband absorption.

As for the numerical optimization of these BPA designs, most studies use full-vector simulation algorithms such as Finite-Difference Time-Domain (FDTD) [16], Finite Element Method (FEM) [13,30,31], Finite Integration Time Domain (FITD) [7, 24], Finite Integration Frequency Domain (FIFD) [14, 23] and Rigorous Coupled Wave Analysis (RCWA) [12, 15] to obtain the spectra directly, which can be computationally expensive and time-consuming when searching a large parameter space with high spectra resolution. Meanwhile, the strong resonance nature of BPAs permits reduced order methods based on their eigenfrequencies to reconstruct the absorption spectra for a fast initial design. In [13], an elegant series combination model is applied to approximate the impedance of the BPA where the impedance of each subunit is derived from the temporal coupled mode theory (TCMT). As is proved by the authors, this method works well for BPAs where there is little spatial mutual coupling between subunits, but fails in cases where the spatial mutual coupling is strong. Another method regards the BPA as a whole and applies TCMT [32, 33] to retrieve the scattering matrix and absorption spectra, this method is suitable for cases where the multiple resonances separate properly in frequency and the mutual coupling is low, but fails when the resonances are too close with high mutual coupling because it is usually difficult to estimate the mutual coupling. Note that for BPAs made of only continuous coatings [34,35] or plasmonic nanocomposites layers [3, 17–21] described by effective media theory (EMT), the transfer matrix method (TMM) [18–20,29,35] can be used to find the ideal effective permittivity, $\varepsilon_{\text{null}}$, to achieve broadband perfect absorption. TMM provides an analytical yet simple way to guide the design of BPA and qualitatively explain the experimental results. However, the application of TMM in plasmonic nanocomposites layers depends on the availability of EMT, which often fails for real structures with specific microscopic features, where full wave simulations are required to retrieve effective media parameters for quantitative analysis [18], thus weakening its practicability. Nevertheless, we believe TMM can be also used to extract poles and zeros of the scattering matrix.

Here we present a new method to optimize the absorption spectra of BPA based on Weierstrass factorization theorem, by which the diagonal elements of the scattering matrix can be decomposed into continued product related with their poles and zeros [35, 37]. We compare the performance of this method with the series combination model and TCMT method, which proves the versatility of our method. By optimizing the geometric parameters, We then design a one-dimensional (1D) planarly tiling BPA from 1300nm to 1500nm and a 1D vertically stacking tapered BPA from 1000nm to 2000nm, both show high (almost...
over 90%) and wide-angle absorption in the concerned range. Because only the eigenfrequencies at poles and zeros are needed in the decomposition, this method proves an efficient alternative to the full vector methods for initial design.

2. Representation of absorption by poles and zeros

The schematic of a 1D narrowband MDM PA is shown in Fig. 1, which is the element to construct BPA in this paper. To reduce the ports where power travels, the PA is restricted to be subwavelength, i.e., period \( P < \lambda \). The p polarized incident light can excite SPP mode- or magnetic resonance in the MDM resonator, and significant magnetic enhancement can be observed in the localized area in the dielectric layer beneath the metal grid [12, 14, 15, 30, 31]. The resonant wavelength can be estimated by combining the standing wave resonant condition and the SPP dispersion relation of multiple layer structure [14, 38] as (a custom of \( \exp(-i\omega t) \) is used in this study).

\[
\begin{align*}
\text{Re}(\kappa)W_{\text{eff}} &= m\pi (m = 1, 2, 3, \cdots) \\
\left( \frac{k_{z,d}}{\epsilon_d} + \frac{k_{z,m}}{\epsilon_m} \right)^2 &+ \left( \frac{k_{z,inc}}{\epsilon_{inc}} \right)^2 \left( \frac{k_{z,d}}{\epsilon_d} - \frac{k_{z,m}}{\epsilon_m} \right)^2 e^{-2\pi j \alpha G} \\
&- \left( \frac{k_{z,d}}{\epsilon_d} - \frac{k_{z,m}}{\epsilon_m} \right) \left( \frac{k_{z,inc}}{\epsilon_{inc}} \right)^2 e^{-2\pi j \alpha D} (1 - e^{-2\pi j \alpha G}) = 0
\end{align*}
\]

Where \( k_x \) is the x component of the wave vector, while \( i k_{z,d}, i k_{z,m}, i k_{z,inc} \) are the \( z \) component of wave vector in the dielectric gap layer, metal layers and incident space, respectively, and they are related by

\[
k_{x,j}^2 = k_x^2 - \epsilon_j^j k_0^2 (j = d, m, inc)
\]

where \( \epsilon_d, \epsilon_m, \epsilon_{inc} \) are the permittivity of the dielectric, metal and incident media, respectively. \( W_{\text{eff}} \) in Eq. (1a) is the effective width of the resonator accounting for the additional edge reflection phase shift [14, 38, 39], which can be represented as \( W_{\text{eff}} = W + 2\Delta W \), where \( \Delta W \) is mainly determined by the dielectric layer thickness \( G \), and when \( W/G \gg 1 \), there is \( \Delta W = \alpha G \) and \( \alpha \approx 1 \), here \( \alpha \) is the extension factor. Eqs. (1) and (2) can be used to design the initial geometric parameters according to the expected resonant wavelength, and also to estimate the resonant wavelength for a specific structure, which can be used as initial values to search the eigenfrequencies.

As a subwavelength structure, the PA has only 0\(^{\text{th}}\) diffraction orders. Meantime, because the transmission is blocked by the bottom optical thick continuous layer, the scattering matrix of the PAs is a 1\times1 matrix. Assuming the scattering matrix is an analytic meromorphic function, which is usually true for physical problems, the Weierstrass factorization of the PA’s scattering matrix is [36, 37]

\[
S(\omega) = A \exp(iB\omega) \prod_m \frac{\omega - \tilde{\omega}_m}{\omega - \tilde{\omega}_m} \\
= A \exp(iB\omega) \left[ 1 + \sum_m \frac{\sigma_m}{\omega - \tilde{\omega}_m} \right]
\]

where \( \tilde{\omega}_m^- \) and \( \tilde{\omega}_m^+ \) are its poles and zeros, which correspond to perfectly emitting modes satisfying outgoing wave condition and perfect absorbing modes satisfying incoming wave condition, respectively. \( A \) and \( B \) are constants defined as

\[
A = S(0) \prod_m \tilde{\omega}_m^-
\]
\[ IB = \frac{S'(0)}{S(0)} + \sum_{m} \left( \frac{1}{\tilde{\omega}_m^+} - \frac{1}{\tilde{\omega}_m^-} \right) \]  

(4b)

where \( S(0) \) and \( S'(0) \) represent the asymptotic characteristics of scattering matrix in the low frequency (long wavelength) limit. For the PAs concerned in this study, it works as a perfect electric conductor at low frequency thus \( S(0) = -1 \), also the scattering parameter approaches a flat spectrum towards low wavelength [40] thus \( S'(0) = 0 \). Meanwhile, the continued product form of Weierstrass factorization can be also transformed into a summation of the partial fraction form in Eq. (3), where \( \sigma_m \) is the strength of each Lorentzian and is defined as

\[ \sigma_m = (\tilde{\omega}_m^- - \tilde{\omega}_m^+) \prod_{n \neq m} \frac{\tilde{\omega}_m^- - \tilde{\omega}_n^+}{\tilde{\omega}_m^- - \tilde{\omega}_n^-} \]  

(5)

Equation (5) clearly predicts the mutual coupling and Fano resonance [37] between neighboring modes, which is usually difficult to estimate in the TCMT methods. With the scattering matrix, we finally get the representation of absorption \( \text{Abs} \) as

\[ \text{Abs} = 1 - |S(\omega)|^2 \]  

(6)

Fig. 2. (a) Schematic of a unit cell of a 1D MDM BPA composed of two subunits. Comparison of frequency domain FEM method (black solid line), Weierstrass factorization method (red dash line), series combination model method (blue dash dot line) and TCMT method (cyan short dash line) for subunit parameters (b) \([P_1, P_2, W_1, W_2]=[383\text{nm}, 407\text{nm}, 227\text{nm}, 268\text{nm}]\) and \([D, G]=[17\text{nm}, 28\text{nm}]\), and (c) \([P_1, P_2, W_1, W_2]=[371\text{nm}, 432\text{nm}, 356\text{nm}, 409\text{nm}]\) and \([D, G]=[13\text{nm}, 15\text{nm}]\). For both cases, the grids are seated at the middle of corresponding subunits.

To verify the versatility of our approach, we first compare it with the series combination model [13] and TCMT [32, 33]. We use the structure parameters depicted on Fig. 2 of [13], where two subunits of MDM PAs are planarly integrated, as is shown in Fig. 2(a). The metal material is gold with a Drude permittivity [13, 31, 41] \( \varepsilon_m = 1 - \omega_p^2 / \left( \omega (\omega + i \gamma_c) \right) \), where \( \omega_p = 1.32 \times 10^{16} \text{rad/s} \) and \( \gamma_c = 1.2 \times 10^{14} \text{rad/s} \), note that for Fig. 2(c), \( \gamma_c \) is artificially reduced by 4 times. The dielectric material is silica with \( \varepsilon_d = 2.25 \), and the incident media is assumed to be air with \( \varepsilon_{inc} = 1 \). To obtain \( \tilde{\omega}_m^- \) and \( \tilde{\omega}_m^+ \), we adopt the freeware QNMeig [42] which is developed on the COMSOL environment and uses the auxiliary fields method to linearize the original nonlinear eigen-problem caused by material dispersion, and the estimated resonant wavelengths are used as initial points around which the eigenvalue solver searches. Meanwhile, we mimic the outgoing wave condition and incoming wave condition by editing the argument of the PML's constant complex coordinate stretching parameter \( \zeta \) to be \( \arg(\zeta) > 0 \) and \( \arg(\zeta) < 0 \), respectively [43]. Note that \( \tilde{\omega}_m^- \) and \( \tilde{\omega}_m^+ \) are not independent, for lossless materials there is \( \tilde{\omega}_m^- = (\tilde{\omega}_m^+)^* \) due to the energy conservation [37], while for low material loss cases [44], there is still \( \tilde{\omega}_m^- = \omega_{0m}^{-1} (\gamma_m + \delta_m) \) and \( \tilde{\omega}_m^+ = \omega_{0m}^{-1} (-\gamma_m + \delta_m) \), where \( \omega_{0m} \) is the central frequency of that resonance, and \( \gamma_m \) and \( \delta_m \) are the radiation and absorption decay rate, respectively, these byproducts are necessary for the series combination model and TCMT method. Interestingly, when \( \gamma_m = \delta_m \), \( \tilde{\omega}_m^- \) is real, and the structure reaches perfect absorption at this real frequency, which is just the critical coupling state [13, 31]. For structure parameters for Fig. 2(b), the
estimate resonant wavelengths are 1520nm and 1735nm, while the exact eigenfrequency calculations output 1472.87nm and 1701.28nm, which indicate the accurate extension factors $\alpha$ are 0.87 and 0.9, respectively. Meanwhile, for structure parameters for Fig. 2(c), estimate resonant wavelengths are 952nm and 1072nm, while accurate resonant wavelengths are 997.39nm and 1100.30nm, and accurate extension factors $\alpha$ are 1.67 and 1.42.

To evaluate the deviation between different approximation methods and the full vector method (here the frequency domain FEM is used), an average error is defined as

$$
error_{av} = \frac{1}{N} \sum_{n=1}^{N} \left| A'(\lambda) - A^{PV}(\lambda) \right| d\lambda
$$

where $j$ represents the Weierstrass factorization method, the series combination model or TCMT. In Fig. 2(b), the average errors for the three methods are 0.0115, 0.0380 and 0.1987, respectively, and in Fig. 2(c), the average errors are 0.0054, 0.1801, and 0.0097, respectively. Figures 2(b) and 2(c) indicate that the series combination model is suitable for cases where subunits have little coupling in space but fails when spatial coupling is strong, while the TCMT method is suitable for cases where the modes are well separate in spectrum but fails when the modes are too close to each other. On the contrary, our method based on Weierstrass factorization works well for both cases with higher accuracy, because this method treats the structure as a whole to find its singularities, and the interference between different modes are inherently included in the $\sigma_m$ term according to Eq. (3). Therefore, the Weierstrass factorization method can be a more general approach to approximate the absorption efficiently. Besides, as the poles are related with the resonance modes of the BPAs, the Weierstrass factorization method also reveals the physics of the BPAs.

3. Design of the planar BPA

By planarly tiling the MDM subunits, a BPA can be achieved, which has already shown in Fig. 2, and with more subunits, the full width of half maximum (FWHM) can be larger. For design purpose, we need to figure out the parameter dependence of the subunits to get a prior knowledge for parameter selection strategy, here we are only concerned on the geometric parameters which are more convenient to adjust in design.

![Fig. 3. Dependence of imaginary part of $\varphi_m^-$ and $\varphi_m^+$ on (a) thickness of dielectric layer $G$, (b) thickness of metal grid $D$, (c) metal grid width $W$ and (d) the period $P$. The geometric dimensions are varied around $[G, D, W, P] = [15nm, 20nm, 250nm, 350nm]$. The black dash line indicates real $\varphi_m^+$ and perfect absorption. Insets: dependence of the resonant wavelength on geometric parameters.](image)

According to Fig. 3, the effect of dielectric layer $G$ and metal grid thickness $D$ are similar, both $\text{Im}(\varphi_m^-)$ and $\text{Im}(\varphi_m^+)$ change dramatically with $D$ and $G$, and resonant wavelength $\lambda_0$ decreases significantly with the increase of $D$ and $G$ when they are small, while $\lambda_0$ changes little when $D$ and $G$ become large. Meantime, the effect of grid width $W$ and period $P$ on $\text{Im}(\varphi_m^+)$ and
Im(\(\tilde{\alpha}_m^+\)) are mild, and Im(\(\tilde{\alpha}_m^-\)) are around 0 for a large range of \(W\) and \(P\), indicating a high absorption. Besides, \(\lambda_0\) increases almost linearly with the increase of \(W\) but changes little with \(P\).

With these \textit{a priori} knowledge in hand, we propose the procedure to design a planar BPA: a range of \([G, D]\) is first set; then several anchor points are selected in the concerned spectra range, the corresponding grid width \(W\) is thus estimated by Eq. (1a) and (1b); After that a sweep of the period is carried out to minimize a cost function, the extension factors are updated during the sweep; and a final minor revision of \(W\) and \(P\) is undertaken to polish the obtained spectra. Here the cost function is defined as

\[
Cost = \frac{1}{\lambda_{max} - \lambda_{min}} \int_{\lambda_{min}}^{\lambda_{max}} f(\lambda) d\lambda
\]

where \(f(\lambda) = 0\) for \(A(\lambda) \geq 0.9\) and \(f(\lambda) = |A(\lambda) - 0.9|^2\) for \(A(\lambda) < 0.9\), and \(A(\lambda)\) are obtained with the Weierstrass factorization method. As an example, we design a BPA with three subunits in the range of \([1100\text{nm}, 1700\text{nm}]\) with the same material in Fig. 2; \(G\) is in the range of \([20\text{nm}, 35\text{nm}]\); \(D\) is in \([10\text{nm}, 25\text{nm}]\); three anchor points are set at 1300nm, 1400nm and 1500nm; \(P = \sum_j P_j\) is in \([\sum_j (W_j + 2D_j), 1100\text{nm}]\). The final optimized structure parameters are \([G, D] = [34\text{nm}, 12\text{nm}], [W_1, W_2, W_3] = [184\text{nm}, 205\text{nm}, 226\text{nm}],\) and \([P_1, P_2, P_3] = [300\text{nm}, 296\text{nm}, 330\text{nm}]\). Its absorption under normal incident p polarized light is shown in Fig. 4(a), the result by Weierstrass factorization method matches well with the full wave frequency domain FEM method, while the minor deviation in the short wave side resonance is due to higher order resonance beyond the concerned range. The BPA shows absorption over 90% in the range of \([1284\text{nm}, 1550\text{nm}]\) except for a dip in \([1324\text{nm}, 1370\text{nm}]\), and it has a FWHM of 344nm. Further study shows that this BPA has a wide-angle absorption over 70% up to 60° in the range of \([1270\text{nm}, 1450\text{nm}]\), as is depicted in Fig. 4(b).

![Fig. 4. (a) Absorption spectra of the optimized BPA. The black dash line indicates the absorption level of 90%. Inset: the schematic of the BPA with 3 subunits. (b) The dependence of absorption on the incident angle.](image)

### 4. Design of tapered BPA

![Fig. 5. (a) Schematic of a unit cell of the tapered multi-layer MDM BPA. \(D\) and \(G\) are the thickness of metal layer and dielectric layer, respectively; the total thickness of the layer stack is \(h = N(D + G)\), where \(N\) is number of pairs; \(P\) is the period, and \(W_1\) and \(W_2\) are the widths of the bottom layer and top layer, respectively. The incident light is p polarized. (b) Comparison of the absorption spectra in normal incidence calculated by the frequency domain FEM and Weierstrass factorization. The black dash line shows the absorption level of 90%, and the bottom blue line represents the absolute error between these two methods. Insets: left and right insets show the magnetic field of the eigenmodes around two resonances (Re(\(\tilde{\alpha}_m^-\))) and the middle inset compares the resonant wavelength extracted from poles (black line, here \(W\) is the width of the tapered BPA at the peak magnetic field of eigenmodes) and estimated by Eq. (8) and (1a) (red dash line, here \(W\) is the average width of metal strip in each MDM pair).](image)
Due to the subwavelength requirement of the BPA, the numbers of subunits tiled in one unit cell is limited, which fundamentally restrict the bandwidth of the planar BPA. To bypass this restriction, one of the solutions is to integrate multiple metal-dielectric layers vertically in a tapered shape, as is shown in Fig. 5(a). Each macroscopic stacking MDM assemble can be regarded as an effective media with anisotropic permittivity, or the hyperbolic metamaterial (HMM) PA [15, 16], which can support slow light waveguide mode and absorb light efficiently. However, the HMM assumption is only valid asymptotically for large number of MDM pairs (N>5), while for small N, the rigorous spectra deviates HMM predictions significantly; the Weierstrass factorization method, on the contrary, does not have this restriction. The slow light waveguide mode for the HMM PA views the stacking MDM assemble as macroscopic tapered “bulky” structure, while we recognize that the resonance modes supported by this tapered PA are essentially complicated hybridized modes of adjacent MDM pairs [16, 45], giving it a microscopic explanation. Meantime, the estimated resonant wavelengths by slow light waveguide modes deviate the accurate ones a little, and it still needs to resort to laboursome full wave simulations though with HMM approximation, thus this method is not very convenient for design purpose. Below we will see decoupling the hybridized modes can still give decent estimate of the resonant wavelength, which can accelerate the optimization when cooperated with the Weierstrass factorization method with less computation.

For each MDM pair, we can still ignore the other pairs and regard the metal layer to be infinitely thick to estimate the fundamental mode whose magnetic field are mainly enhanced in the corresponding dielectric layer, and thus Eq. (1b) degenerates to the dispersion relation of odd mode [46]:

$$\tanh\left(\frac{k_{c,d} G}{2}\right) = \frac{k_{c,m} \epsilon_{d}}{k_{c,d} \epsilon_{m}}$$

(9)

To verify the availability of the Weierstrass factorization method, we compare an example tapered BPA made of gold and silica, the geometric parameters are \(G, D, N, P, W_1, W_2=\) [20nm, 20nm, 20, 600nm, 450nm, 100nm], the obtained absorption spectra are shown in Fig. 5(b), which are over 90% in the range of [1050nm, 2190nm]. The two spectra match each other very well, as the absolute error line shows, while the minor deviation at two sides is owing to modes beyond the concerned range. The magnetic fields of the eigenmodes around the spectra peaks clearly show the maximum localized enhancement of field in specific dielectric layer, which provides a basis for the assumption to estimate the resonant wavelength. Meanwhile, the magnetic fields also diffuse into adjacent layers around center layer, proving the hybridization of the resonant modes. In fact, the estimated resonant wavelengths are quite close to those extracted from poles as shown in the middle inset in Fig. 5(b). Besides, we find that the resonant wavelength changes linearly with width \(W\) (the estimated resonant wavelength can be fitted with \(\lambda=5.35W+258.72nm\), and the extracted resonant wavelength can be fitted with \(\lambda=5.11W+235.66nm\)), which can also be observed in Fig. 3(c). This linearity is essentially related to the dispersion relation of the odd mode in deep subwavelength limit [46]. Assume \(G/\lambda <<1\) and consider perfect metal (\(\text{Im}(\epsilon_m)=0\)), the effective index \((n_{\text{eff}}=k_d/k_0)\) approaches infinity and becomes insensitive to frequency and can be regarded as a constant. And if we set the extension factor \(a=0\), we can simply derive from Eq. (1a) that for fundamental mode \(\lambda=2n_{\text{eff}}W\). Still the extracted resonant wavelengths (black line) shows some fluctuation, this is reasonable because the resonant modes are actually quite complicated hybridized modes which show complex field patterns and interaction, thus it can deviate the predicted linearity of estimated resonant wavelength (red dash line) of decoupled single MDM a little.

Although the resonant modes are much more complicated than those in the structure shown in Fig. 4, the dependence of fundamental modes on geometric parameters should similar to that discussed for Fig. 3. The structure shown in Fig. 4 already shows a very high absorption in [1050nm, 2190nm], so to design a BPA in the range of [1000nm, 2000nm], we can estimate \(W_1\) and \(W_2\) by Eq. (8) and (1a) while keeping \(G\) and \(D\) the same with those in Fig. 5. Meantime, considering the systematically deviations between the estimate and accurate resonant wavelength, and also the quick drop of absorption spectra at the two sides, we then set \([W_1, W_2]=[130nm, 400nm]\). With the increase of numbers of the metal-dielectric layers [15], the absorption spectra become smoother and gradually approach the performance of an ideal HMM absorber, but this brings new challenge for fabrication, so we just set \(N=20\). And just like what we do in Sec. 3, we sweep the period to minimize the cost function defined by Eq. (7), and the ultimate optimized period is \(P=550nm\). The optimized absorption spectrum is shown in Fig. 6(a), the absorption spectra by the two methods match quite well, and the BPA shows over 90% absorption in the range of [1035nm, 2020nm] except for a dip between 1060nm and 1120nm. In the meantime, the tapered BPA also has wide angle absorption. Figure 6(b) shows that it has an absorption over 80% in the range of [1150nm, 2070nm] up to 50° incident angle.
Fig. 6. (a) Absorption spectra of the optimized structure calculated by frequency domain FEM and Weierstrass factorization method. The black dash line shows the absorption level of 90%, while the blue line indicates the absolute error of the two methods. (b) The dependence of absorption on the incident angle.

5. Discussion and conclusion

Although we only design 1D BPA in this paper, the Weierstrass factorization method can be straightforwardly used to optimize 2D subwavelength BPA. Besides, for BPA with no simple semi-analytical equations to estimate its resonant wavelengths, we can still search the eigenfrequencies in the concerned wavelength range directly. For BPAs not made of the MDM structure, the Weierstrass factorization method is also applicable. As an efficient and general method, we can use the Weierstrass factorization method as an alternative to the full vector solver to find an initial design.

In conclusion, we have proposed a new method based on Weierstrass factorization to optimize the absorption of BPA, and prove it to be an efficient and good approximation method. Together with semi-analytical equations to estimate the resonant wavelengths, We use this method to design two different kinds of BPA constructed by simple MDM subunits: the first one is a planarly BPA with three MDM subunits tiling in the unit cell, and it has almost over 90% in the range of [1284nm, 1550nm], and higher than 70% in [1270nm, 1450nm] up to 60° incident angle; The second BPA is a structure with 20 pairs of metal-dielectric layers stacked vertically in a tapered shape, and it has almost higher than 90% absorption in [1035nm, 2020nm], and higher than 80% in [1150nm, 2070nm] up to 60° incident angle. Besides these two kinds of BAP, we will explore the integration of this method with heuristic methods like genetic algorithm (GA) to design the space-filling type BPA.

Acknowledgement

This work is funded by National key research and development plan (development of major scientific instruments and equipment, 2018YFF0109600). We acknowledge Prof. Benfeng Bai’s support in numerical simulation, and we appreciate Dr Wei Yan’s and Prof. Min Qiu’s fruitful discussion on the QNMEig solver.

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