Graphene Electron Metasurfaces

Ruihuang Zhao,1,∗ Pengcheng Wan,1,∗ Ling Zhou,1 Di Huang,1 Haiqin Guo,1 Hao Xia,1 and Junjie Du1,†

1State Key Laboratory of Precision Spectroscopy, School of Physics and Electronic Science,
East China Normal University, Shanghai 200062, China
(Dated: January 10, 2022)

The propagation effect is so far the only available implementation mechanism when electronic components in graphene are developed based on Dirac fermion optics. The resulting optics-inspired components are large in size and operate normally only in the lowest possible temperature environment so that the ballistic limits are not violated. Here electron metasurfaces based on the generalized Snell’s law, a linear array of gate-bias-controlled circular quantum dots in form, are proposed to manipulate graphene electrons within the distance of the quantum-dot diameter, far less than the ballistic limits at room temperature. This provides opportunities to create untracompact optics-inspired components which are comparable in size to components arising from other principles and hence can operate at any temperature below room temperature. Moreover, unlike their optical counterparts, electron metasurfaces have near-perfect operation efficiencies and their high tunability allows for free and fast switching among functionalities. The conceptually new metasurfaces open up a promising avenue to pull optics-inspired components to a desired level of performance and flexibility.
Low energy graphene electrons behave like light because of the light-like dispersion and the ballistic transport [1]. Electron optics in semiconductor structures are naturally extended to graphene. Both naturally-occurring and non-naturally-occurring optical phenomena such as Goos-Hanchen shift [2], self collimation [3], whispering-gallery modes [4–8], negative-index [9–12] and zero-index [13] behaviors of electrons, can be reproduced by graphene electrons. Accordingly, various optics-inspired functional units, such as two-dimensional electron microscopies [14, 15], quantum switches [16–18], Fabry-Pérot cavities [19], electron waveguides [20–22], splitters [23, 24] and Vesolago lens [10–12], have been demonstrated. The remarkable achievements are made in the theoretical framework of bulk optical materials where the phase and amplitude changes are accumulated over a sufficiently long propagation distance. This is termed the propagation effect [25] which dictates that the electric units have a large size. However, electrons can exhibit the light-like behaviors only below the mean free path of \( l = \mu \sqrt{\rho / \pi h^2} e \). Thus the optics-inspired transistors have to work at the lowest possible temperature so that \( l \) is greater than their sizes because large carrier mobility \( \mu \) [26] and thus large \( l \) can be gained at low temperature.

The emergence of optical metasurfaces opens the door to flat optics technology, characterized by single-particle-layer materials [27, 28]. Light is steered over the scale of the free-space wavelength or the smaller scale by introducing abrupt changes in phase or amplitude. This is fundamentally different from conventional diffractive optics in which optical components based on the propagation effect is as thick as a few to dozens of wavelengths to achieve sufficient phase accumulation. Such single-layer designs not only tremendously simplify the fabrication process and lower the loss in contrast to bulk materials, but also can mould optical wavefronts into shapes that is designed at will [25]. Inspired by the compactness features and the drastic capabilities of wavefront engineering, we explore the possibility of realizing electron metasurfaces in graphene, aiming to develop ultrasmall optics-inspired transistors which can operate at any temperature below room temperature. In addition to the inherent advantages of metasurfaces such as low-loss and easy-fabrication, we will show that the electron metasurfaces also possess other remarkable properties such as near-perfect operation efficiency and high tunability which are difficult to achieve in their optical counterparts.

Here the electron metasurfaces are a linear array of gate-bias-controlled circular quantum dots (QDs) in form. The QDs are responsible for providing the required phase response in constructing a constant gradient of phase jump. The phase response capability of QDs is related to their “refractive index” which is defined as \( n_s = (E - V_s) / E \) with \( E \) the incident energy and \( V_s \) the bias applied on them [29]. Their electron scattering problem in the single valley case
(see SI Appendix) where the low-energy electron dynamics can be described by the Dirac-Hamiltonian
\[ H = -i\hbar v_F \nabla \sigma + V_s \Theta(R_s - r), \]  
(1)
is analogue to the light scattering problem of an infinite dielectric cylinder. The Mie scattering method used widely in optics is applicable and some of results predicted by the method have been experimentally verified. The QDs with the radius \( R_s \) have been denoted as a step potential in Eq. (1) with the Heaviside step function \( \Theta(R_s - r) \). The potential is smooth on the scale of the graphene’s intrinsic lattice constant but sharp on the scale of de Broglie wavelength so that the intervalley scattering is negligible. Meanwhile, theoretical studies have also shown that the QDs have nearly the same electron scattering behaviors for the gradual transition of potentials \( \Delta R_s \) smaller than 0.5\( R_s \).

As known to us, the behaviors of waves follow the generalized Snells law of refraction in metasurfaces
\[ n_s \sin \theta_t - n_i \sin \theta_i = \frac{1}{k_0} \frac{d\Phi}{dx}, \]  
(2)
where \( k_0 \) is the magnitude of the free space wavevector, \( \theta_i \) and \( \theta_t \) are respectively the angle of incidence and refraction, and \( n_i \) and \( n_t \) are the “refractive indices” of media on the incident and transmission sides of the metasurface, respectively. The phase gradient \( \frac{d\Phi}{dx} \) implies an effective wavevector (alternatively, an effective momentum) along the interface is produced and is imparted to the transmitted and reflected electrons. Thus the transmitted and reflected electron beams can be bent into arbitrary directions, depending on the direction and magnitude of the phase gradient. The phase gradient is created within a unit cell consisting of several QDs to which the linearly increasing biases \( V_s \) are respectively applied. The variation of bias indicates the difference in “refractive index” between the QDs and thus the difference in phase response of electron waves. Figure 1 illustrates a linear phase distribution of the scattering fields in a unit cell composed of ten QDs. Throughout the paper, the energy of the incident electron beams is \( E = 65.82 \) meV and the radius of the QDs is 5 nm with the spacing between them is \( d = 14.6 \) nm. So the period of the metasurface is \( \Gamma = 9d = 131.4 \) nm in Fig. 1 and the biases are respectively given above each scattering field plot. Figure 1 shows a complete phase coverage from 0 to \( 2\pi \) is obtained with the constant phase difference \( \Delta \phi = \pi/5 \) between neighbors approximately. Thus the magnitude of the introduced wavevector in the x direction is \( k_x^{add} = \frac{d\Phi}{dx} = 2\pi/\Gamma = 0.048 \). When a normal-incidence electron beam impinges the metasurface, the transmitted beam will be bent at an angle of \( \theta_{calc} = \arctan(k_x^{add}/k_0) \) where \( k_0 \) is the magnitude of the free space wavevector with \( n_i = n_t = 1 \). This is simulated in Fig. 2(a) and the travel direction of the transmitted beam agrees well with
the calculated bending angle $\theta_{\text{calc}} = 25^\circ$. Note that the scattering field of each QD in Fig. 1 is calculated under the consideration of the inter-QD coupling interaction by employing the multiple scattering theory [38, 39] (also see SI Appendix). This ensures that the constant gradient of phase jump really exists in the metasurface since the scattering field of an isolated QD may be very different from that of the same QD residing in a linear array.

A unit cell which covers the entire $0-2\pi$ range can also be composed of different numbers of QDs by only adjusting bias while keeping the array invariant. We denote the number of the QDs in a unit cell with $m_{\text{unit}}$. The decrease of $m_{\text{unit}}$ implies a larger phase gradient and furthermore a larger introduced wavevector. Figs. 2(b) to (f) show the bending of the electron beams by the metasurfaces with $m_{\text{unit}} = 9, 8, 7, 6, 5$, respectively. The bending angle increases gradually from Fig. 2(b) to (f). Besides, the electron metasurfaces show a remarkable property in Fig. 2, that is, electron waves can be bent at nearly perfect efficiency. This is strikingly different from optical metasurfaces in which the efficiency of nearly 100% is difficult to achieve. It shows that electrons can more easily perceive the lateral momentum introduced by the phase gradient than photons. Moreover, the comparison between the panels in Fig. 2 demonstrates the efficiency is closer to 100% in the case of the longer unit cells because electrons have more opportunities to perceive the introduced lateral momentum. Finally, perfect efficiency can not be divorced from the successful suppression of reflection in the metasurfaces (see SI Appendix).

**TABLE I. The comparison between the calculated and actual bending angles for various $m_{\text{unit}}$.**

| $m_{\text{unit}}$ | 10  | 9  | 8  | 7  | 6  | 5  |
|-------------------|-----|----|----|----|----|----|
| $\tan \theta_{\text{calc}}$ | 0.480 | 0.535 | 0.600 | 0.715 | 0.861 | 1.074 |
| $\tan \theta_{\text{actu}}$ | 0.468 | 0.526 | 0.620 | 0.760 | 1.000 | 1.700 |

To verify that the beam bending at various $\theta_{\text{actu}}$ in Fig. 2 can be well explained by the introduced wavevectors due to phase gradient, we make a comparison between the two for all the cases in Table I where $\tan \theta_{\text{calc}} = k_x^{\text{add}}/k_0$ and $\tan \theta_{\text{actu}}$ are given, respectively. Here $k_x^{\text{add}} = 2\pi/\Gamma = 2\pi/m_{\text{unit}}d$ and $\theta_{\text{actu}}$ is directly read off from Fig. 2. It is shown that the calculated bending angles agree well with the actual those for $m_{\text{unit}}$ between 7 and 10. But there is distinct deviations for $m_{\text{unit}} = 6$ and 5. To make matters worse, a weak beam is transmitted to the left of the normal in the later two cases. In an effort to find the causes of these deviations, we examine the phase response of each quantum dot for the case of $m_{\text{unit}} = 6$ in Fig. 3(a). One can see that only the former five QDs contribute to the formation of the linear phase gradient, whereas the QD with $V_s = 750$ meV has the phase which goes against the linear gradient change. Moreover, the QD and the adjacent two QDs of $V_s = 680$ meV and $V_s = 400$ meV (in the next unit cell) together form
a phase gradient increasing in the opposite direction and hence a left-oriented wavevector is produced, as shown in Fig. 3(a). Thus a small portion of electrons will propagate on the left side of the normal in Fig. 2(e). Accordingly, the magnitude of the introduced right-oriented wavenumber should be calculated in terms of the period $\Gamma' = 4d = 58.4\text{nm}$.

The new $\tan \theta_{\text{calc}}$ calculated by $k_{x\text{add}} = 2\pi/\Gamma'$ is equal to 1.075 and has a good agreement with $\tan \theta_{\text{actu}}$ in Table I. Similarly, the deviation in the case of $m_{\text{unit}}=5$ in Table I are also caused for the same reason (see SI Appendix).

Exploring the causes of deviations can help us to improve the efficiency of metasurfaces. We note that the electron scattering of the QD of $V_s=750$ meV is weak in contrast to the other QDs in the unit cell. So the scattering of the other QDs will hardly be impacted if the QD is removed from the unit cell. Such a unit cell is schematically shown in the lower panel in Fig. 3(b) and the phase distribution is given in Fig. 3(c). We see that the opposite phase gradient is eliminated and thus only a right-oriented wavevector is introduced. The electron density distribution displayed in Fig. 3(d) demonstrates the electron beam bends to the right side of the normal with near-unity efficiency when removing the QD of $V_s=750$ meV.

Since two equal and oppositely directed phase gradients represent left- and right-oriented equal-magnitude wavevectors, respectively, we can simultaneously introduce them in a metasurface to design an untrathin electron splitter. One simple route for splitters is to achieve a right-oriented wavevector by the unit cells in the right half of the array and a left-oriented wavevector by the unit cells in the left half. This can be implemented by applying the biases enhancing from left to right to the QDs in the unit cells in the right half, as done in Fig. 2, and the same biases but enhancing in opposite directions in the left half. The impinging beam is split into two sub-beams which make various angles between each other, as demonstrated by Figs. 4(a)-(f). We see the beams are split at nearly perfect efficiency again and the splitting ratio is half to half in all cases.

Three points are worth emphasizing in the model. First, all the results in this paper are obtained in the same linear array of QDs. Namely, the radius of the QDs and the spacing between them remain invariant in all simulations and we only modulate the biases on the QDs to realize both beam bending and beam splitting at various angle. The fast switching time of bias systems allows for high modulation efficiency. Second, nearly perfect efficiency is obtainable, different fundamentally from its optical counterparts. The performance of optical metasurfaces is subject to the intrinsic nature of light. The introduced momentum through the phase gradient can not be perceived by all the photons due to the absence of interaction between photons. Electrons are distinct from photons in nature and the electron metasurfaces have the near-perfect operation efficiency. Third, the 5nm-radius QDs used in our simulations
fall within the current experimental manufacturing accuracy [40–42]. Very recently, even smaller circular QDs with atomically sharp boundaries have been obtainable in experiment [40–42]. The fabrication techniques of high-precision QDs makes experimental realization of the metasurfaces feasible.

In summary, we have theoretically demonstrated the feasibility of realizing metasurfaces for graphene ballistic electron. A simple metasurface is a linear array of QDs with the shared radius. Phase discontinuities, the essential ingredient of gradient metasurfaces, are acquired by applying difference biases to the QDs. Following the generalized Snell’s law, the metasurface imposes a control over electrons in a rather compact way with wavefront shaping accomplished below the ballistic transport limit at room temperature. Such metasurfaces can dramatically reduce the size of optics-inspired components and hence make them operate in any temperature below room temperature without violating the ballistic transport limit. Here two kind of transistors, beam benders and beam splitters, are achieved in the same linear array of QDs and can be conveniently switched between each other by tuning the biases applied to the QDs. Electrons metasurfaces might represent a promising way to develop more practical and accessible electron optics technologies. The theory applies equally to ballistic electrons in semiconductor structures and other two-dimensional materials.
These authors contributed equally to this work.

† phyjunjie@gmail.com

[1] A. K. Geim, K. S. Novoselov, The rise of graphene, Nat. Mater. 6, 183 (2007).

[2] C. W. J. Beenakker, R. A. Sepkhanov, A. R. Akhmerov, J. Tworzydło, Quantum Goos-Hänchen Effect in Graphene, Phys. Rev. Lett. 102, 146804 (2009).

[3] C.-H. Park, Y.-W. Son, L. Yang, M. L. Cohen, S. G. Louie, Electron beam supercollimation in graphene superlattices, Nano Lett. 8, 2920-2924 (2008).

[4] Y. Zhao, J. Wyrick, F. D. Natterer, J. F. Rodriguez-Nieva, C. Lewandowski, K. Watanabe, T. Taniguchi, L. S. Levitov, N. B. Zhitenev, J. A. Stroscio, Creating and probing electron whispering-gallery modes in graphene, Science 348, 672-675 (2015).

[5] Y. Jiang, J. Mao, D. Moldovan, M. R. Masir, G. Li, K. Watanade, T. Taniguchi, F. M. Peeters, E. Y. Andrei, Tuning a circular p-n junction in graphene from quantum confinement to optical guiding, Nat. Nanotech. 12, 1045-1049 (2017).

[6] F. Ghahari, D. Walkup, C. Gutiérrez, J. F. Rodriguez-Nieva, Y. Zhao, J. Wyrick, F. D. Natterer, W. G. Cullen, K. Watanabe, T. Taniguchi, L. S. Levitov, N. B. Zhitenev, J. A. Stroscio, An on/off Berry phase switch in circular graphene resonators, Science 356, 845-849 (2017).

[7] P. Hewageegana, V. Apalkov, Electron localization in graphene quantum dots, Phys. Rev. B 77, 245426 (2008).

[8] J. H. Bardarson, M. Titov, P. W. Brouwer, Electrostatic confinement of electrons in an integrable graphene quantum dot, Phys. Rev. Lett. 102, 226803 (2009).

[9] V. V. Cheianov, V. Fal’ko, B. L. Altshuler, The focusing of electron flow and a Veselago lens in graphene pn junctions, Science 315, 1252-1255 (2007).

[10] S. Chen, Z. Han, M. M. Elahi, K. M. M. Habib, L. Wang, B. Wen, Y. Gao, T. Taniguchi, K. Watanabe, J. Hone, A. W. Ghosh, C. R. Dean, Electron optics with p-n junctions in ballistic graphene, Science 353, 1522-1525 (2016).

[11] G.-H. Lee, G.-H. Park, H.-J. Lee, Observation of negative refraction of Dirac fermions in graphene, Nat. Phys. 11, 925-929. (2015).

[12] B. Brun, N. Moreau, S. Somanchi, V.-H. Nguyen, K. Watanabe, T. Taniguchi, J.-C. Charlier, C. Stampfer, B. Hackens, Imaging Dirac fermions flow through a circular Veselago lens, Phys. Rev. B 100, 041401(R) (2019).

[13] Y. Ren, P. Wan, L. Zhou, R. Zhao, Q. Wang, D. Huang, H. Guo, J. Du, Zero-index metamaterials for Dirac fermion in graphene, Phys. Rev. B 103, 085431 (2021).

[14] P. BoGgild, J. M. Caridad, C. Stampfer, G. Calogero, N. R. Papior, M. Brandbyge, A two-dimensional Dirac fermion microscope, Nat. Commun. 8, 15789 (2017).
[15] A. W. Barnard, A. Hughes, A. L. Sharpe, K. Watanabe, T. Taniguchi, D. Goldhaber-Gordon, Absorptive pinhole collimators for ballistic Dirac fermions in graphene, *Nat. Commun.* **8**, 15418 (2017).

[16] K. Wang, M. M. Elahi, L. Wang, K. M. M. Habib, T. Taniguchi, K. Watanabe, J. Hone, A. W. Ghosh, G.-H. Lee, P. Kim, Graphene Transistor Based on Tunable Dirac Fermion Optics, *Proc. Nat. Acad. Sci.* **116**, 6575-6579 (2019).

[17] R. N. Sajjad, A. W. Ghosh, High efficiency switching using graphene based electron optics, *Appl. Phys. Lett.* **99**, 123101 (2011).

[18] Q. Wilmart, S. Berrada, D. Torrin, V. H. Nguyen, G. Fève, J.-M. Berroir, P. Dollfus, B. Plaçais, A Klein-tunneling transistor with ballistic graphene, *2D Mater.* **1**, 011006 2014

[19] A. V. Shytov, M. S. Rudner, L. S. Levitov, Klein backscattering and Fabry-Prot interference in graphene heterojunctions, *Phys. Rev. Lett.* **101**, 156804 (2008).

[20] J. R. Williams, T. Low, M. S. Lundstrom, C. M. Marcus, Gate-controlled guiding of electrons in graphene, *Nat. Nanotechnol.* **6**, 222-225 (2011).

[21] M. Kim, J.-H. Choi, S.-H. Lee, K. Watanabe, T. Taniguchi, S.-H. Jhi, H.-J. Lee, Valley-symmetry-preserved transport in ballistic graphene with gate-defined carrier guiding, *Nat. Phys.* **12**, 1022-1026 (2016).

[22] M.-H. Liu, C. Gorini, K. Richter, Creating and Steering Highly Directional Electron Beams in Graphene, *Phys. Rev. Lett.* **118**, 066801 (2017).

[23] P. Brandimarte, A tunable electronic beam splitter realized with crossed graphene nanoribbons, *J. Chem. Phys.* **146**, 199902 (2017).

[24] J. Li, R. Zhang, Z. Yin, J. Zhang, K. Watanabe, T. Taniguchi, C. Liu, J. Zhu, A valley valve and electron beam splitter, *Science* **362**, 1149 (2018).

[25] N. Yu, F. Capasso, Flat optics with designer metasurfaces, *Nat. Mater.* **13**, 139-150 (2014).

[26] A. S. Mayorov, R. V. Gorbachev, S. V. Morozov, L. Britnell, R. Jalil, L. A. Ponomarenko, P. Blake, K. S. Novoselov, K. Watanabe, T. Taniguchi, A. K. Geim, Micrometer-Scale Ballistic Transport in Encapsulated Graphene at Room Temperature, *Nano Lett.* **11**, 2396 (2011).

[27] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, Z. Gaburro, Light propagation with phase discontinuities: Generalized laws of reflection and refraction, *Science* **334**, 333-337 (2011).

[28] X. Ni, N. K. Emani, A. V. Kildishev, A. Boltasseva, V. M. Shalaev, Broadband light bending with plasmonic nanoantennas, *Science* **335**, 427 (2012).

[29] R. L. Heinisch, F. X. Bronold, H. Fehske, Mie scattering analog in graphene: lensing, particle confinement, and depletion of Klein tunneling, *Phys. Rev. B* **87**, 155409 (2013).

[30] M. I. Katsnelson, F. Guinea, A. K. Geim, Scattering of electrons in graphene by clusters of imputies, *Phys. Rev. B* **79**, 195426 (2009).
[31] P. M. Ostrovsky, I. V. Gornyi, A. D. Mirlin, Electron transport in disordered graphene, *Phys. Rev. B* **74**, 235443 (2006).

[32] M. Hentschel, F. Guinea, Orthogonality catastrophe and kondo effect in graphene, *Phys. Rev. B* **76**, 115407 (2007).

[33] D. S. Novikov, Elastic scattering theory and transport in graphene, *Phys. Rev. B* **76**, 245435 (2007).

[34] A. Pieper, R. L. Heinisch, H. Fehske, Scattering of two-dimensional Dirac fermions on gate-defined oscillating quantum dots, *Phys. Rev. B* **91**, 045130 (2015).

[35] J. Cserti, A. Pályi, and C. Péterfalvi, Caustics due to a negative refractive index in circular graphene P-N junction, *Phys. Rev. Lett.* **99**, 246801 (2007).

[36] J. M. Caridad, S. Connaughton, C. Ott, H. B. Weber, V. Krsitić, An electrical analogy to Mie scattering, *Nat. Commun.* **7**, 12894 (2016).

[37] A. Pieper, R. L. Heinisch, H. Fehske, Electron dynamics in graphene with gate-defined quantum dots, *Europhys. Lett.* **104**, 47010 (2013).

[38] Y. Ren, Y. Gao, P. Wan, Q. Wang, D. Huang, J. Du, Effective medium theory for electron waves in a gate-defined quantum dot array in graphene, *Phys. Rev. B* **100**, 045422 (2019).

[39] P. Wan, Y. Ren, Q. Wang, D. Huang, L. Zhou, H. Guo, J. Du, Dirac fermion metagratings in graphene, *npj 2D Materials and Applications* **5**, 42 (2021).

[40] K. Bai, J. Zhou, Y. Wei, J. Qiao, Y. Liu, H. Liu, H. Jiang, L. He, Generating atomically sharp p-n junctions in graphene and testing quantum electron optics on the nanoscale, *Phys. Rev. B* **97**, 045413 (2018).

[41] C. Gutiérrez, L. Brown, C.-J. Kim, J. Park, A. N. Pasupathy, Klein tunnelling and electron trapping in nanometre-scale graphene quantum dots, *Nat. Phys.* **12**, 1069-1075 (2016).

[42] K. Bai, J. Qiao, H. Jiang, H. Liu, L. He, Massless Dirac fermions trapping in a quasi-one-dimensional npn junction of a continuous graphene monolayer, *Phys. Rev. B* **95**, 201406(R) (2017).
FIG. 1. **Formation of linear phase gradient.** The scattering filed of the individual QDs composing the unit cell of a metasurface. The tilted black straight line is the envelope of the projections of the cylindrical waves scattered by the QDs. A complete phase coverage from 0 to $2\pi$ is shown with the constant phase difference $\Delta \phi = \pi/5$ between neighbors approximately. The number of QDs in the unit cell is $m_{\text{unit}}=10$ and the biases applied on each QD $V_s$ are given above each plot, respectively. The inter-QD coupling interaction has been considered in this calculation.
FIG. 2. **Simulation of beam bending.** The bending of electron beams after passing through the metasurfaces composed of the unit cells with the number of QDs $m_{\text{unit}}=10$ (a), 9 (b), 8 (c), 7 (d), 6 (e) and 5 (f). The linearly increasing biases with constant gradient are applied on the QDs in the unit cells. They are $V_s=375, 420, 465, 510, 555, 600, 645, 690, 735$ meV for $m_{\text{unit}}=9$; $V_s=385, 440, 495, 550, 605, 660, 715, 770$ meV for $m_{\text{unit}}=8$; $V_s=385, 440, 495, 550, 605, 660, 715$ meV for $m_{\text{unit}}=7$; $V_s=400, 470, 540, 610, 680, 750$ meV for $m_{\text{unit}}=6$; $V_s=390, 450, 510, 570, 630$ meV for $m_{\text{unit}}=5$, respectively.
FIG. 3. The analysis on the deviation at $m_{\text{unit}} = 6$ in Table I. (a) The scattered filed of the individual QDs in the presence of all the six QDs. The tilted black and blue solid lines indicate the desired and undesired phase gradients formed in the unit cell, respectively. (b) Schematics of the unit cells in the presence of all the QDs in the upper panel and in the absence of the QD of $V_s = 750$ meV in the lower panel. (c) The scattered filed of the individual QDs when removing the QD of $V_s = 750$ meV. Compared to (a), the phase gradient increasing in the opposite direction is eliminated. (d) The beam bending with near-unity efficiency when removing the QD of $V_s = 750$ meV, which is in sharp contrast to Fig. 2(e).
FIG. 4. Simulation of beam splitting. The splitting of electron beams after passing through the metasurfaces composed of the unit cells with the number of QDs $m_{\text{unit}} = 10$ (a), 9 (b), 8 (c), 7 (d), 6 (e) and 5 (f). The unit cells in the right half of the metasurfaces in (a)-(f) is the same as those in Fig. 2(a)-(f), respectively, whereas the unit cells in the left half have the biases increasing in the opposite direction.