Manipulation of antichiral edge state based on modified Haldane model

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Abstract
Antichiral edge state (AES) was theoretically proposed by Colomés and Franz (2018 Phys. Rev. Lett. 120(8): 086603), which is recently realized in experiment. Under increasing the intensity of the off-resonant circularly polarized light, the AES can be induced as anisotropic, flat types and then anisotropic chiral edge state in zigzag honeycomb nanoribbon. More interestingly, the spin-polarized AESs can be further induced by the antiferromagnetic exchange field and electric field instead of the OPCP light. In particular, according to the propagating direction mismatch, we find the spin-degenerate (spin-polarized) dual propagating channel of the AES can be transformed into the spin-degenerate (spin-polarized) single propagating channel along the upper or lower boundary in topological heterojunction with different edge states. In the switch of the propagating channel, the local bond currents along the outer boundaries are reflected back in the lead and device with bulk states for spin-degenerate and spin polarized cases, respectively. In addition, these propagating channels are also robust against weak normal dephasing effect, which paves diverse platforms to design the topological devices in the future.

1. Introduction
In the two-dimensional materials, such as graphene, silicene, stanene and germanene [1–4], topological phases determinate the protected edge states in corresponding nanoribbons. And these topological phases are modulated by the exchange field, staggered electric field, off-resonant circularly polarized light, spin–orbit coupling and edge magnetism [5–9]. Due to the bulk-edge correspondence [10, 11], different topological phases correspond to different topological edge states in their quasi-one-dimensional systems. For instance, the quantum spin Hall effect, quantum anomalous Hall effect (QAH) and the spin-polarized QAH correspond to the helical, chiral and spin-polarized edge states, respectively. These topological edge states have some applications in the transport devices [12–15], which have many advantages such as efficient transport and low consumption.

The antichiral edge state (AES) is theoretically achieved based on the modified Haldane model [16], where the edges states propagate in the same direction at two parallel boundaries and the bulk states propagate in opposite directions. Based on the Haldane model realized by ultracold atoms in optical lattice [17], some possible schemes [18–20] have been proposed for realizing the AES, but these schemes are difficult to achieve in experiments. Lately, some experiments for achieving the AES are carried out in the classical circuit lattice [21] and the gyromagnetic photonic crystal system [22], which is realistic significance for theoretical applications.

Soon, some interesting phenomena based on the modified Haldane model have been theoretically investigated. For example, the topological phase transitions under uniaxial strain in graphene nanoribbon [23], unipolar-bipolar filters in P/N graphene junction [24] and circular dichroism and valley polarization...
in honeycomb lattice [25], etc [16, 26, 27]. In transport properties, the AES not only has extraordinary transport properties but also the robustness against disorder [16] in addition to the ordinary edge states discussed above. In topological properties, the AES can be transformed into the trivial one under uniaxial strain [23]. But the corresponding investigations on the transport and topological properties of the AES are still less considered.

Recently, the modified Haldane model are theoretically proposed and experimentally realized. In this work, we focus on these properties in zigzag graphene nanoribbons. First, based on initial AES, we investigate the topological properties of AES under off-resonant circularly polarized light and staggered electric field with fixed antiferromagnetic exchange field. We find that with increasing the intensity and changing the polarization direction of the light, the AES can be transformed into the anisotropic AES, flat AES and chiral edge state. Also, the spin polarized AES is found out with the staggered electric field and antiferromagnetic exchange field instead of the light. Then, these edge states can be used to construct edge-state heterojunction made of zigzag graphene nanoribbon to design the dual- and single-channel transistors and the switch between them. And the location of single-channel transistors can be transformed from the upper to lower boundaries of the system by the polarized direction of the light. In addition, these transistors can also be cut off via a staggered electric field. These findings could find some applications in designing topological devices.

2. Model and methods

The new types of AES and their transport phenomena are investigated in zigzag honeycomb nanoribbon with modified Haldane model. With the tight-binding model, the corresponding Hamiltonian is described as:

$$H = -t \sum_{\langle i,j \rangle} c_i^\dagger c_j + t_\Omega \sum_{\langle\langle i,j \rangle\rangle} e^{-i\eta \lambda c_i^\dagger c_j} + i \frac{\lambda}{3\sqrt{3}} \sum_{\langle\langle i,j \rangle \rangle} \gamma_{ij} c_i^\dagger c_j$$

$$+ \Delta \sum_i \mu_i c_i^\dagger c_i + \lambda_{AF} \sum_i \mu_i c_i^\dagger \sigma_z c_i,$$

where $c_i^\dagger (c_i)$ is the creation (annihilation) operator for an electron at site $i$, the summations with $\langle i,j \rangle$ and $\langle\langle i,j \rangle \rangle$ run over the nearest- and next-nearest neighbor sites, respectively. The first term denotes the nearest hopping with $t = 2.7$ eV. The second term denotes a modified Haldane model that leads to the AES, which has been experimentally demonstrated [21, 22]. This term is rewritten by the other form $-i \lambda M/3\sqrt{3} \sum_{\langle\langle i,j \rangle \rangle} \nu_{ij} c_i^\dagger c_j$ as the phase is set as $\phi = -\pi/2$ throughout the paper, where $\lambda M$ is defined as $\lambda M = 3\sqrt{3} t_\Omega$ with the next-nearest hopping $t_\Omega$. In the modified Haldane model, $\nu_{ij} = 1(-1)$ denotes the counterclockwise (clockwise) hopping between the sublattice A, while $\nu_{ij} = -1(1)$ for the sublattice B [16, 25] shown in figure 1(a). Besides, the crucial difference between the modified Haldane model and original Haldane model is reflected in the direction of the hopping. For instance, the third term denotes the Haldane interaction induced by the off-resonant circularly polarized light with the intensity $\lambda_{\Omega}$ [24, 28], where $\gamma_{ij} = 1(-1)$ presents the counterclockwise (clockwise) hopping for sublattices A and B, which is different from the second term shown in figure 1(b). In addition, the positive and opposite values of the intensity $\lambda_{\Omega}$ represent the right and left polarized light, respectively. The fourth term denotes the staggered electric field $\Delta$ with $\mu_1 = 1$ for the sublattice A and $\mu_1 = -1$ for the sublattice B shown in figure 1(c), and this term can be induced by an h-BN substrate in the honeycomb nanoribbon [29, 30]. The last term denotes the antiferromagnetic exchange field with the strength $\lambda_{AF}$ induced by ferromagnetic substrates [24, 31, 32], where $\sigma_z$ is the Pauli matrix of the $z$ component for the electron spin. In addition, the last two terms are only applied on the device in figure 1(d).

In the continuum theory with the phase $\phi = -\pi/2$, the low-energy Hamiltonian of equation (1) can be expressed as:

$$H_\eta^S = \hbar \nu \tau_z k_x + \eta \lambda M \tau_0 + \eta \lambda_{\Omega} \tau_z + \Delta \tau_z + S \lambda_{AF} \tau_z,$$

where the Pauli matrices $\tau_i$ denote the sublattice pseudospin, $\eta = 1(-1)$ for the Dirac point $K(K')$ and $S = 1(-1)$ for the spin-up (spin-down) mode. Then, the corresponding energy dispersion reads:

$$E_\eta^S = \eta \lambda M \pm \sqrt{(\hbar \nu k)^2 + (\Delta + S \lambda_{AF} + \eta \lambda_{\Omega})^2},$$

which can be used to approximately determine the edge states crossing between the Dirac points. The non-equilibrium Green’s function method is generally used to evaluate the transport properties [33, 34].
Figure 1. The visual models of the Hamiltonian and corresponding proposed system. (a) The Haldane model, (b) the modified Haldane model, (c) the staggered electric field model, (d) the blue regions denote the leads and the yellow region denotes the device, where $N_x$ is the number of the unit cell along the transport direction, $N_y$ is the number of the zigzag chains along the width of the system and the solid red circles denote the virtual leads at the upper and lower boundaries of the device.

Based on this method, the transmission coefficient can be expressed as:

$$T^s = \text{Tr}[\Gamma^s_L G^\sigma \Gamma^s_R G^\sigma]$$.

(4)

This formula describes the electronic transmission form the lead L to lead R, and the index $S = \uparrow$, $\downarrow$ denoted the spin-up and spin-down modes, respectively. $\Gamma^s_L$ ($\Gamma^s_R$) is the linewidth function of the left (right) lead, which is expressed as $\Gamma^s_{L/R} = i(\Sigma^s_{L/R} - \Sigma^s_{L/R})$. And the retarded and advanced self-energy functions of the left and right leads can be obtained by $\Sigma^s_{L/R} = H^s_{DL/R} g^s_{DL/R} H^s_{L/R}$, where the surface Green’s function $g^s_{DL/R}$ can be calculated by the Lopez–Sancho’s iterative method or transfer matrix [35, 36]. Based on these calculations above, the retarded and advanced Green’s function can be easily obtained by the formula [37]:

$$G^s_{L/R} = \left[(E \pm i\delta) - H^s_D - \Sigma^s_{L/R} - \Sigma^s_{L/R}\right]^{-1},$$

(5)

where $\delta$ is an infinitesimal real number. In addition, when the matrix Hamiltonian $H_D$ is larger, one can employ a simple technique presented in references [38, 39] to significantly reduce the amount of calculation of equation (4). In the following formula, we ignore the index $S$ for simplicity. In order to analyze the detailed transport properties of the zigzag honeycomb nanoribbon, with the help of the Heisenberg equation of motion and current conservation relation, we introduce the energy-resolved local bond current between sites $i$ and $j$ as [40, 41]:

$$J_{ij}(E) = H_{ij} G^\sigma_{ij}(E) - H_{ji} G^\sigma_{ji}(E),$$

(6)

where $G^\sigma = -iG^\Gamma G^\sigma$ is the lesser Green’s function of the left lead and $H_{ij}$ is the relevant matrix element of the Hamiltonian $H$ in equation (1), where the subscripts $i$ and $j$ denote the site. Accordingly, $J_{ij}$ denotes the current flowing from the site $i$ and the site $j$. This formula is based on the suppose that the local currents are from the left lead. The normal dephasing effect is taken into account to test the stability of the single-channel and dual-channel transistors, which is calculated by the useful tool of the Büttiker’s virtual probes method [13, 42–44]. This method describes that the virtual probes are attached to the active region,
Figure 2. The band structures (a) and the corresponding transmissions with the ribbon width $N_y$, (b) and the fixed parameters of the zGNR are set as $t = 2.7\, eV, \lambda_M = 0.04\, eV, \lambda_{AF} = \Delta = \lambda_{AF} = 0$.

where no net charge flows ($I_q = 0$). With this effect, the current of the virtual lead is expressed as:

$$I_q = \frac{e^2}{h} \sum_{m \neq q} T_{q,m} (V_m - V_q),$$

(7)

where $T_{q,m} = \text{Tr}[\Gamma_q G_T \Gamma_m G_a]$ is the transmission coefficient from the leads $m$ to $q$, $V_q$ is the voltage of the lead $q$ and $\Gamma_q (\Gamma_m)$ is the linewidth function, where the value of the linewidth function between the sites of the device and virtual leads are set as $\Gamma_q$ denoting the normal dephasing strength. Finally, the effective transmission coefficient from the leads L to R is expressed as:

$$T_{\text{eff}} = \sum_{q \neq L} T_{q,L} (V_L - V_m) / V.$$

(8)

$V = V_L - V_R$ is the very small voltage between leads L and R, where the voltage of the lead R is set as zero. Besides, this work aims at investigating the propagating channels only located at one and two boundaries of the device, we assume that the normal dephasing has an influence on the boundaries in the device denoted by the solid red circles in figure 1(d).

3. Results and discussions

3.1. Antichiral and chiral edge states

Before introducing the following results, we discuss the effect of the width of the zigzag honeycomb system on the AES (shown in thick red lines in figures 3(a)–(d)) without external fields. In figure 2(a), we find that with the increasing width $N_y$, the gap between different valleys increases, where the AES exists. But the group velocities keep unchanged independent on the width. Beyond the width $N_y = 18$, the gap between different valleys slowly increases until the steady value. And the corresponding transmissions in figure 2(b) clearly indicate this tendency, which can be qualitatively explained by the energy dispersion. According to equation (3), this gap in this case between different Dirac points is $2\lambda_M = 0.216\, eV$. Therefore, we expect the maximum of the gap crossing the edge state is $2\lambda_M$ with long enough width $N_y$. Actually, these phenomena under the width effect are also consistent with other topological edge states [5, 6], not shown here.

The width effect just changes the gaps of the edge states, but not essential properties. So, in the following calculations, we set the width as $N_y = 5$ for simply consideration. When the off-resonant light is applied on the zGNR with a modified Haldane model, the initial AES will undergo a series of changes. In figures 3(a)–(d), the slope of the edge state, crossing the lowest conduction band in the valley $K'$ and highest valence in the valley $K$, gradually decreases to zero and then the opposite value with increasing the intensity of off-resonant light. In this process, the slope of the other edge state gradually increases. In addition, the slope of the band is equivalent to the group velocity. The corresponding edge states denoted by the thick red lines are shown in figures 3(e)–(h), with increasing the light intensity, it can be seen that the AES is transformed into the anisotropic AES and then the flat AES according to their group velocity. For instance, in figure 3(f), the anisotropic AES is that the group velocity of upper and lower edge state is...
Figure 3. The band structures and corresponding edge states with different off-resonant circularly polarized light of (a) and (e) \( \lambda_\Omega = 0 \); (b) and (f) \( \lambda_\Omega = 0.02t \); (c) and (g) \( \lambda_\Omega = 0.04t \); and (h) \( \lambda_\Omega = 0.06t \). (i)–(l) share the same band structures with (e)–(h), respectively, under opposite off-resonant light parameters of (i) \( \lambda_\Omega = 0 \); (j) \( \lambda_\Omega = -0.02t \); (k) \( \lambda_\Omega = -0.04t \); (l) \( \lambda_\Omega = -0.06t \). The width of the zGNR is set as \( N_y = 5 \), \( \Delta = 0 \), the length of black arrow represents the size of the group velocity and the thick red lines denote the edge states, and the ancient Roman numbers distinguish the differences of the types of the edge states.

3.2. Single- and dual-channel transistors

Here, we construct different types of the edge-state heterojunction with different edge states discussed above to design the switch between (spin-polarized) single-channel and dual-channel transistors. In figure 4(a)(1), each region shares same AESs including the group velocity and propagating direction, causing that the electrons in both upper and lower boundaries of the zigzag honeycomb nanoribbon freely pass through the device with double transmissions, shown in case (1) in figure 4(e). And the local bond current in figure 4(c)(1) clearly indicates the dual-channel transport, called as the dual-channel transistor. And this transistor depending on the AES is robust against disorder \[16\], also discussed in appendix A. As we apply the right polarized light on the device, the AES of the device in figure 4(a)(1) is transformed into the anisotropic chiral edge state of the device in figure 4(a)(2), and the corresponding band structure is shown in figure 3(c). Compared with the case (1) (in figure 4(b)) where the transmission is 2 in the region of \(-0.062 \text{ eV} \leq E \leq 0.062 \text{ eV}\), in the case (2) (in figure 4(b)), the transmission is suppressed from 2 to 1 in the same region with slight oscillation due to mismatched group velocity in upper edge, and the width of the system on slight oscillation is also presented in appendix A. In figure 4(c)(2), the corresponding local bond current shows that the electron almost passes through the upper boundary with same direction of the edge state and is completely reflected into the bulk state of the lead with opposite direction in lower boundary. The anisotropic chiral edge in figure 4(a)(2) is transformed into the reverse one in figure 4(a)(3) as we modulate the polarized direction from the right to the left. And the initial propagating channel of upper boundary is converted into lower boundary channel in figure 4(c)(3), while the electron of upper boundary is completely reflected into the bulk state in the lead. In addition, the transmission of the case (3) in figure 4(b) is the same with the case (2) when the staggered electric field \( \Delta = 0.06t \) is applied on the device instead of the light, one can obtain the band insulator in figure 4(a)(4), sharing the same band structure with spin-up mode in figure 5(c). The corresponding transmission and local bond current are shown in case (4) in figures 4(b) and (c)(4), respectively. We find that the dual and single propagating channels can be mutually switched by the light, in which the location of single propagating channel is converted from the upper to the lower boundary by the direction of the light. Moreover, the staggered
Figure 4. (a) Different edge-state heterojunctions with different types of the edge states taken from figure 3, (b) the transmissions $T$ correspond to the cases in (a), the device in case (a)/(4) is obtained by $\Delta = 0.06t$ instead of off-resonant light, sharing the same band structure with spin-up mode in figure 5(c). The local bond currents at $E = -0.0065\, eV$ in (c) correspond to the cases (a), respectively. The length of the device is set as $N_x = 50$, the blue regions denote the leads and the yellow region denotes the device.

Figure 5. The spin-dependent band structures and corresponding edge states with different staggered electric field and antiferromagnetic exchange field of (a) and (d) $\Delta = 0.04t, \lambda_M = 0.04t$; (b) and (e) $\Delta = -0.04t, \lambda_M = 0.04t$; (c) and (f) $\Delta = -0.1t, \lambda_M = 0.04t$. The red and blue represent the spin-up and spin-down modes, respectively, and the fixed parameters are set as $\lambda_M = -0.04t, \lambda_M = 0$. 
Figure 6. (a) The edge-state heterojunctions with different edge states taken from figures 3 and 5, and (b) denotes the corresponding spin-up transmissions $T^\uparrow$. (c) The spin-up local bond currents at $E = -0.0063 \text{ eV}$ correspond to the cases (a), respectively. The blue regions denote the leads and the yellow region denotes the device with the length $N_x = 50$.

electric field is used to cut off the working state. Actually, the anisotropic chiral edges in the devices in figure 4(a)(2) and (3) can be respectively replaced by the flat AESs in figures 3(f) and (j) for the same results, the only difference is that the electron is completely reflected by the opposite direction between the edge and the bulk states, not the edge states. In addition, the conductance at zero temperature can be written as $G(E) = \frac{4e^2}{h} T(E)$, where the factor 2 incorporates the spin degeneracy and $e^2/h$ is the conductance quantum. Therefore, the values of the conductance in unit of $e^2/h$ in figure 4(b) are twice the values of their own transmissions.

Here, we give a discussion on another type of the AES. With the staggered electric field and antiferromagnetic exchange field $\Delta = \lambda_{AF} = 0.04t$, the AES is transformed into the spin-polarized AES with spin-down mode in figure 5(d) and the band structure is shown figure 5(a), which can be used to design a spin filter. When the staggered electric field is reversed, one can obtain the spin-polarized AES with spin-up mode in figure 5(e) and the band structure is shown in figure 5(b). The band insulator in figure 5(f) can be obtained by the staggered electric field $\Delta = -0.01t$ with fixed $\lambda_{AF} = 0.04t$, and the band structure is shown in figure 5(c) with spin-up gap $2|\Delta + \lambda_M + \lambda_{AF}|$. It should be noted that the antiferromagnetic exchange field is very difficult to implement. But this work [45] reported that the antiparallel ferromagnetic exchange field applied on the boundaries could obtain the same effect induced by the antiferromagnetic exchange field.

Based on the spin-polarized AES, spin-degenerate AES and anisotropic chiral edge states, we construct edge-state heterojunctions to design spin-polarized single and dual-channel transistors and its off-state switch. We just discuss the device with spin-polarized AES with spin-up mode, and the one with spin-down mode in the device shares the same results. In figure 5(a)(1), the directions of the edge states with spin-up mode between the leads and device are the same, so the spin-up electron in both upper and lower boundaries can freely pass through the device with double transmissions with spin-up mode in case (1) in figure 6(b), and the spin-up local bond current in figure 6(c)(1) vividly displays these phenomena. In addition, the spin-down electron is reflected by the gap effect not shown here. When the right polarised
light is applied on the lead R in figure 6(a)(1), the AES is transformed into the anisotropic chiral edge state in figure 6(a)(2). It is shown that the propagating directions in the lower boundary between the device and lead R are opposite, the electron will be reflected into the bulk states due to the bulk states in the device and lead L shown in figure 6(c)(2). And the electron in upper boundary freely pass through the device with unit transmission with spin-up mode (figure 6(e)) due to the same propagating directions. Modulating the polarized direction from the right to the left in the lead R in figure 6(a)(2), one can get this heterojunction in figure 6(a)(3). Accoding to the same analysis, the electron in upper boundary is reflected into the bulk states, while the electron in lower boundary freely pass through the device. And the spin-up transmission and local bond current are shown in figures 6(b) and (c)(3), respectively. Finally, the larger staggered electric field is applied on the device in figure 6(a)(3), we get the band insulator in the device in figure 6(a)(4), and the electron in two boundaries are reflected into the bulk states in the lead L shown in figure 6(c)(4), the corresponding transmission is zero in case (4) in figure 6(e). Besides, the conductance with the spin mode reads G_s(E) = e^2/h T_s, which indicates that the values of the spin-up conductance in unit of e^2/h in figure 6(b) are equal to the values of their own transmissions.

3.3. Normal dephasing effect
The AES has been proved to be robust against the disorder, and the wider device is more robust against the disorder (presented in appendix A). Here, I take realistic effect, such as the normal dephasing effect, into account to test the stability of the dual-channel and single-channel transistors. The carries lose only the phase memory with preserving the spin memory, this dephasing process is called as the normal dephasing. The effective transmission with same propagating channel is not less than 70% of initial one without normal dephasing effect, which is defined as the stability of the transistor. There are the AES and anisotropic edge state in the device discussed above, we just discuss the typical cases in figures 4(a) and (b) to test the stability. In figure 7(a), the effective transmission of the dual-channel transistor decreases with increasing the strength of the normal dephasing effect \( \Gamma_d \) on two boundaries of the device [43], and the effective transmission still is not less than 1.4 until the strength exceeds the value \( \Gamma_d = 1 \) meV. We also find the dual propagating channels are steady under these strength of normal dephasing effect, but the local bond current gradually decreases during the spread shown in figure 7(c), corresponding to small effective transmission. Therefore, the dual-channel transistor has the stability in the range of \( \Gamma_d \leq 1 \) meV. In addition, the upper and lower propagating channels are blocked to the same degree, not shown here. In figure 7(b), the spin-up effective transmission of the single-channel transistor is also decreases with increasing the strength \( \Gamma_d \), while the propagating channel keeps steady with gradually decreasing the spin-up local bond current during the spread in figure 7(d). Therefore, this transistor is still valid in the
range of $\Gamma_d \leq 2.2$ meV. In addition, the size effect of the device on the robustness against normal dephasing effect is also discussed (in appendix A). The result shows that the longer the length of the device, the lower the effective transmission, which indicates that the device should be designed to be shorter for the robustness.

4. Conclusions

In summary, we find some new types of the AES in zigzag honeycomb nanoribbon based on modified Haldane model, and further investigate their transport properties in topological heterojunctions with different edge states under the NEGF and local bond current methods. With increasing the intensity of the off-resonant light, the initial AES is transformed into the anisotropic AES and then flat AES in the range of $\lambda_{\Omega} \leq \lambda_M$. When the light intensity satisfies the condition $\lambda_{\Omega} > \lambda_M$, the AES is finally transformed into the anisotropic chiral edge state in addition, with the fixed antiferromagnetic exchange field, the AES can be changed into the spin-polarized AES with spin-down and spin-up modes and then the band insulator under the control of staggered electric field. With these edge states, we construct different topological heterojunctions to investigate spin-degenerate (spin-polarized) dual and single propagating channels and their switch, which are completely controlled by the light and staggered electric field with fixed antiferromagnetic exchange field. In addition, for the purpose of cutting off the on state, we use the staggered electric field instead of the light. In particular, when the propagating directions between the edge states in the leads and the bulk or edge state in the device are same (opposite), the electron has almost 100% (0) transmission through the device, which is basis for designing these transistors under the normal dephasing effect, we also find these propagating channels are robust with the decreasing effective transmission.

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Appendix A

A.1. The width effect on slight oscillation

In our previous work [9, 13], we discussed the large oscillations as a function of the mismatched group velocity and the length of the scattering region. Our works shown that the separation period $T$ increases (decreases) as the degree of mismatched group velocity (the length of the scattering region) gets large. But the slight oscillation affected by the width is not discussed, which is new and interesting. Here, we only discuss roughly this relation between the slight oscillation and the width for the degree of simplicity.

In figure 8, it shows that with mismatched group velocity the separation period $T$ almost keeps steady with different width. One can also see that the amplitude of slight oscillation gets smaller near the transmission 1 as the width gets larger. But with respect to the transmission 1, the values of all slight oscillations are roughly close to 1, which can be ignored for our discussed results.

A.2. The disorder effect on antichiral and chiral edge states

We consider Anderson on-site disorder energy to investigate the robustness against disorder, assumed to be randomly distributed in the region $[-W/2, W/2]$ with the disorder strength $W$. And the transmission is calculated by taking the average over 200 times for random disorder configurations. In figure 9(a), it shows that the transmission of AES can be affected by the disorder strength and the width of the system. With fixed width $N_y$, one can find that the transmission will decreases under stronger disorder strength, showing the disorder can inhibit the transport channel. But in figure 9(a), it should be noted that with fixed disorder strength the transmission will increase under larger value of the width $N_y$, which indicates the wider system is more robust against disorder. In figure 9(b), it can be seen that with different widths $N_y$ the tendency of the transmission under different disorder strengths is the same with the case in figure 9(a), but one can see that the chiral edge state is more robust. These results reflect that the device should be designed with larger width for robustness against disorder.
Figure 8. Slight oscillation of transmission under different widths $N_y$ of the system from the case in figure 4(e).

Figure 9. The transmission under different disorder strengths $W$ for (a) the case taken from figure 4(a); (b) the case taken from figure 4(b). The lengths of the systems are set as $N_x = 50$ and the energy for the transmission is set as $E = -0.01$ eV.

A.3. The size effect on antichiral and chiral edge states with normal dephasing effect

In figures 7(a) and (b), we present the results of the robustness of antichiral and chiral edge states against normal dephasing effects, and the chiral edge state is more robust than the AES. Besides, we also choose two types of antichiral and chiral edge states in figures 7(a) and (b) as an example to further discuss the size effect of the scattering region on the robustness with fixed dephasing strength. In addition, this work aims at the edge states and their corresponding transport properties, so we can carefully ignore the discussion of normal bulk states.

In figures 10(a) and (a1), they represent the robustness of AES dependent on the length and the width of the scattering region with fixed dephasing strength. From figure 10(a), we can see that with fixed width and dephasing strength the effective transmission linearly decreases with the increasing length $N_x$. Because the length of dephasing process gets large, leading to the loss of the momentum memory. In figure 10(a1), it shows that the tendency of effective transmission slightly decreases for narrow width, and then hold steady for wider width, which means the width has small influence on the effective transmission with fixed length and dephasing strength. In order to investigate the transport properties of chiral edge state, we also follow the same manner as the cases in figures 10(a) and (a1). From figure 10(b), we can find that the effective transmission is also inhibited by the length $N_x$, but the tendency is not linear due to the oscillation dependent on the length of the scattering region [9, 13]. In figure 10(b1), the effective transmission slightly increases and then also hold steady with the increasing width $N_y$. Actually, the slight upward tendency of effective transmission with the increasing width $N_y$ originates from the oscillation shown in figure 8.
Figure 10. (a) and (a1) The effective transmissions taken from the case in figure 4(a) are under different lengths and widths of the scattering region with fixing dephasing strength $\Gamma_d = 1 \text{ meV}$, (b) and (b1) the effective transmissions taken from the case in figure 4(b). The energy for effective transmissions is set as $E = -0.01 \text{ eV}$.

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