

Generalized Wilson Loop Method for Nonlinear Light-Matter Interaction

Hua Wang,^{1,2,4} Xiuyu Tang,¹ Haowei Xu,² Ju Li,^{2,3*} and Xiaofeng Qian^{1,5*}

¹Department of Materials Science and Engineering, Texas A&M University, College Station, TX 77843, USA

²Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

³Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

⁴Future Science Research Institute, ZJU-Hangzhou Global Scientific and Technological Innovation Center, Zhejiang University, Hangzhou, Zhejiang 310058, China

⁵Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843, USA

*Correspondence to: liju@mit.edu, feng@tamu.edu

Abstract

Nonlinear light-matter interaction, as the core of ultrafast optics, bulk photovoltaics, nonlinear optical sensing and imaging, and efficient generation of entangled photons, has been traditionally studied by first-principles theoretical methods with the sum-over-states approach. However, this indirect method often suffers from the divergence at band degeneracy and optical zero points as well as convergence issue and high computation cost when summing over the states. Here, using shift vector and shift current conductivity tensor as an example, we present a gauge-invariant generalized approach for efficient and direct calculations of nonlinear optical responses by representing interband Berry curvature, quantum metric, and shift vector in a generalized Wilson loop. This generalized Wilson loop method avoids the above cumbersome challenges and allows for easy implementation and efficient calculations. More importantly, the Wilson loop representation provides a succinct geometric interpretation of nonlinear optical processes and responses based on quantum geometric tensors and quantum geometric potentials, and can be readily applied to studying other excited-state responses.

Introduction

Nonlinear light-matter interaction plays a pivotal role in ultrafast optics¹, bulk photovoltaics², nonlinear optical sensing and imaging³, optical transistor⁴, efficient generation of entangled photon pairs for quantum computing⁵, etc. In particular, noncentrosymmetric materials are known to hold even-order nonlinear photocurrent responses under external electromagnetic field. For example, the wave packet of charge carriers can be displaced in real space upon photon excitation via a 2nd order process, resulting in shift current^{2,6} that accounts for the shift mechanism for bulk photovoltaic effect.

Field-dependent nonlinear photocurrent can be obtained by solving the quantum kinetic equation of density matrix using perturbation theory. Subsequently, it can be calculated by first-principles methods such as density functional theory⁷⁻¹⁰ and Wannier interpolation^{11,12} with sum rules. However, the sum-over-states approach involves *ad hoc* cutoff that induces divergence at band degeneracy and optical zero points. Moreover, it suffers from the convergence issue with respect to the number of states. A direct approach is largely underexplored.

The Wilson loop method was originally proposed by Wilson¹³ in 1974 for computing gauge field on a closed path. It is ubiquitous to gauge theories and has been widely used to calculate Berry curvature, Chern number, and other topological invariants in condensed matter physics, which are the hallmarks of a rich set of low-energy transport phenomena governed by the linear response of intraband process, including quantum Hall effect¹⁴, quantum anomalous Hall effect¹⁵, spin Hall effect¹⁶, and quantum spin Hall effect^{17,18}. Unlike the above linear responses, shift current involves interband transitions and its conductivity tensor is proportional to the quadratic electric field E^2 . Young and Rappe¹⁹ reformulated the shift vector using a gauge-invariant discrete expression similar to the King-Smith and Vanderbilt formalism of electric polarization²⁰. Recently, Shi *et al.* represented the photon-drag shift vector with the Wilson loop formalism, important geometric quantity in shift current tensor and photon-drag shift current tensor²¹. These motivates us to develop a general approach for nonlinear optical (NLO) responses by representing interband Berry curvature, quantum metric, and shift vector in a generalized Wilson loop.

Here we present a physically intuitive gauge-invariant Wilson loop approach for direct and efficient calculations of NLO responses with Wilson loop representation, using the shift vector and shift current conductivity tensor as examples. In the Wilson loop picture, the geometrical nature of the shift current can be viewed as the difference of the spontaneous polarization determined by interband Berry connection between the valence and conduction bands upon direct optical transition. Unlike the standard sum-of-rule method, our Wilson loop approach is free of the convergence issue with respect to the number of states, and avoids the cumbersome divergence at band degeneracy and optical zero points. This new approach can be easily implemented and allow for efficient calculations.

We demonstrate this powerful approach in two representative cases, including (1) a Rice-Mele model with an extra staggered onsite potential and (2) monolayer ferroelectric GeS with first-principles Wannier tight-binding Hamiltonian. The results calculated by the Wilson loop approach are in excellent agreement with the exact analytic solutions of the Rice-Mele model and the numerical results of monolayer GeS with the sum-over-states approach. Furthermore, we provide a Wilson representation of geometrical shift vector where the integral of the Wilson loop results in polarization difference between two bands upon optical transition, illustrating the geometrical nature of shift current. In general, gauge-invariant geometric quantities, e.g., quantum metric, Berry curvature, and shift vector, can be all represented by Wilson loop naturally. The generalized Wilson loop approach developed here can be readily applied to other nonlinear optical responses and allow for direct geometric interpretation of these quantities.

Results

Geometrical shift current response

Shift current originates from the difference of the real-space charge center of the valence and conduction bands upon optical transition. It is a bulk effect as the separation of photoexcited electrons and holes does not rely on p - n junction with built-in electric field. Unlike conventional photovoltaics, the generated open-circuit voltage can go beyond the bandgap, hence the power conversion efficiency is not limited by Shockley–Queisser limit for a single p - n junction. Under homogeneous linearly polarized light illumination, shift current can be written as^{2,6,7,19}

$$J^a(0) = \sum_b 2\sigma^{abb}(0; \omega, -\omega) E^b(\omega) E^b(-\omega), \quad (1)$$

$$\sigma^{abb}(0; \omega, -\omega) = -\frac{\pi e^3}{\hbar^2} \int \frac{d\mathbf{k}}{(2\pi)^d} \sum_{nm} f_{nm} R_{mn}^{a,b}(\mathbf{k}) r_{nm}^b r_{mn}^b \delta(\omega_{nm} - \omega), \quad (2)$$

$$R_{mn}^{a,b}(\mathbf{k}) = -\partial_{k_a} \Phi_{mn}^b(\mathbf{k}) + \mathcal{A}_m^a(\mathbf{k}) - \mathcal{A}_n^a(\mathbf{k}), \quad (3)$$

where $\mathbf{r}_{nm} = i\langle n | \partial_{\mathbf{k}} | m \rangle$ for $n \neq m$ and $\mathcal{A}_n = i\langle n | \partial_{\mathbf{k}} | n \rangle$ are interband and intraband Berry connection for states $|m\rangle$ and $|n\rangle$, respectively. f is the Fermi-Dirac distribution with $f_{nm} \equiv f_n - f_m$. $\Phi_{nm}^b(\mathbf{k})$ is the phase of Berry connection $r_{nm}^b(\mathbf{k})$ with $r_{nm}^b(\mathbf{k}) = |r_{nm}^b(\mathbf{k})| e^{i\Phi_{nm}^b(\mathbf{k})}$. $R_{mn}^{a,b}(\mathbf{k})$ is the well-known shift vector described by the derivative of the phase and the difference of intraband Berry connection, also known as the quantum geometric potential²². Although the difference of Berry connections is gauge dependent, the shift vector is gauge invariant. We will discuss the gauge transformation property later.

The geometric aspect of the shift current is related with quantum metric and Berry curvature through the Christoffel symbols of the second kind^{23,24}. The local quantum geometric tensor $Q_{mn}^{ab} = \langle \partial_a m | \tilde{Q} | \partial_b n \rangle$ was originally proposed by Provost and Vaille²⁵, where $\tilde{Q} = 1 - \tilde{P}$ and \tilde{P} is the ground-state projection operator²⁶. It indicates that the geodesic quantum distance between two quantum states in the Hilbert space can be viewed as absorption strength in the interband optical process, e.g., $Q_{mn}^{ab} = r_{mn}^a r_{nm}^b$. Q_{mn}^{ab} consists of a symmetric quantum metric g_{mn}^{ab} and an antisymmetric Berry curvature Ω_{mn}^{ab} , i.e. $Q_{mn}^{ab} = g_{mn}^{ab} - \frac{i}{2} \Omega_{mn}^{ab}$. Quantum metric g_{mn}^{ab} and Berry curvature Ω_{mn}^{ab} play quite different roles. For example, the off-diagonal g_{mn}^{ab} and diagonal Ω_{mn}^{ab} contribute to the linear response coefficients of interband and intraband processes, respectively. In contrast, both quantum metric g_{mn}^{ab} and Berry curvature Ω_{mn}^{ab} play a crucial role in second order responses. As we will show below, gauge-invariant geometric quantities such as quantum metric g_{mn}^{ab} , Berry curvature Ω_{mn}^{ab} , and shift vector $R_{mn}^{a,b}$ can be all represented by Wilson loop naturally.

Wilson loop approach of Berry curvature, shift vector, and shift current.

Gauge-invariant single band Berry curvature in a discretized Brillouin zone can be calculated by Fukui-Hatsugai-Suzuki method²⁷, $\Omega_n^c(\mathbf{k}) = \text{Im} \ln W_n(\mathbf{k})$, with

$$W_n(\mathbf{k}) = \epsilon_{abc} \langle n, \mathbf{k} | n, \mathbf{k} + \mathbf{q}_a \rangle \langle n, \mathbf{k} + \mathbf{q}_a | n, \mathbf{k} + \mathbf{q}_a + \mathbf{q}_b \rangle \langle n, \mathbf{k} + \mathbf{q}_a + \mathbf{q}_b | n, \mathbf{k} + \mathbf{q}_b \rangle \langle n, \mathbf{k} + \mathbf{q}_b | n, \mathbf{k} \rangle, \quad (4)$$

where \mathbf{q}_a is an infinitesimal displacement vector along the corresponding a direction near \mathbf{k} point and ϵ_{abc} is the Levi-Civita symbol. Now we derive a Wilson loop formula for the shift current response by

reformulating shift vector with a similar strategy of King-Smith and Vanderbilt²⁰. The intraband Berry connection reads $\mathcal{A}_m(\mathbf{k}) = i\langle m, \mathbf{k} | \partial_{\mathbf{k}} | m, \mathbf{k} \rangle = \lim_{q \rightarrow 0} \partial_q \text{Im} \ln \langle m, \mathbf{k} + \mathbf{q} | m, \mathbf{k} \rangle$. In contrast, the interband Berry connection between states $|m\rangle$ and $|n\rangle$ is given by $\mathbf{r}_{mn}(\mathbf{k}) = i\langle n | \partial_{\mathbf{k}} | m \rangle = |\mathbf{r}_{mn}(\mathbf{k})| e^{i\phi_{mn}}$, where ϕ_{mn} is the phase of interband Berry connection: $\phi_{mn}^b(\mathbf{k}) = \text{Im} \ln(r_{mn}^b(\mathbf{k}))$. For small \mathbf{q} , $\langle m, \mathbf{k} | m, \mathbf{k} + \mathbf{q} \rangle = e^{-i\mathbf{q} \cdot \mathcal{A}_m(\mathbf{k}) + O(q^2)}$, and $\langle m, \mathbf{k} + \mathbf{q} | m, \mathbf{k} \rangle = e^{i\mathbf{q} \cdot \mathcal{A}_m(\mathbf{k}) + O(q^2)}$. Thus, shift vector can be reformulated as

$$\begin{aligned} R_{mn}^{a,b}(\mathbf{k}) &= -\partial_{k_a} \phi_{mn}^b(\mathbf{k}) + \mathcal{A}_m^a(\mathbf{k}) - \mathcal{A}_n^a(\mathbf{k}) = -\partial_{k_a} \text{Im} \ln(r_{mn}^b(\mathbf{k})) + \mathcal{A}_m^a(\mathbf{k}) - \mathcal{A}_n^a(\mathbf{k}) \\ &= -\partial_{k_a} \text{Im} \ln(r_{mn}^b(\mathbf{k})) - \lim_{q_a \rightarrow 0} \partial_{q_a} \text{Im} \ln \langle m, \mathbf{k} | m, \mathbf{k} + \mathbf{q}_a \rangle \langle n, \mathbf{k} + \mathbf{q}_a | n, \mathbf{k} \rangle. \end{aligned} \quad (5)$$

The first term on the right-hand side can be evaluated using finite difference around \mathbf{k} along direction a ,

$$\partial_{k_a} \text{Im} \ln(r_{mn}^b(\mathbf{k})) = \lim_{q_a \rightarrow 0} \partial_{q_a} \text{Im} \ln \langle m, \mathbf{k} + \mathbf{q}_a | r^b | n, \mathbf{k} + \mathbf{q}_a \rangle. \quad (6)$$

Thus,

$$R_{mn}^{a,b}(\mathbf{k}) = - \lim_{q_a \rightarrow 0} \partial_{q_a} \text{Im} \ln \langle m, \mathbf{k} | m, \mathbf{k} + \mathbf{q}_a \rangle \langle m, \mathbf{k} + \mathbf{q}_a | r^b | n, \mathbf{k} + \mathbf{q}_a \rangle \langle n, \mathbf{k} + \mathbf{q}_a | n, \mathbf{k} \rangle. \quad (7)$$

Since $\langle n, \mathbf{k} | r^b | m, \mathbf{k} \rangle$ does not depend on \mathbf{q} , we can rewrite $R_{mn}^{a,b}(\mathbf{k})$ as

$$R_{mn}^{a,b}(\mathbf{k}) = - \lim_{q_a \rightarrow 0} \partial_{q_a} \text{Im} \ln \langle m, \mathbf{k} | m, \mathbf{k} + \mathbf{q}_a \rangle \langle m, \mathbf{k} + \mathbf{q}_a | r^b | n, \mathbf{k} + \mathbf{q}_a \rangle \langle n, \mathbf{k} + \mathbf{q}_a | n, \mathbf{k} \rangle \langle n, \mathbf{k} | r^b | m, \mathbf{k} \rangle. \quad (8)$$

We then arrive at the Wilson loop representation of shift vector $R_{mn}^{a,b}(\mathbf{k})$ as

$$R_{mn}^{a,b}(\mathbf{k}) = - \lim_{q_a \rightarrow 0} \partial_{q_a} \text{Im} \ln [W_{mn}(\mathbf{k}, \mathbf{q}_a, r^b, r^b)] = - \lim_{q_a \rightarrow 0} \partial_{q_a} \arg [W_{mn}(\mathbf{k}, \mathbf{q}_a, r^b, r^b)], \quad (9)$$

where $W_{mn}(\mathbf{k}, \mathbf{q}_a, r^b, r^b)$ denotes general absorption on a Wilson loop,

$$W_{mn}(\mathbf{k}, \mathbf{q}_a, r^b, r^b) \equiv \langle m, \mathbf{k} | m, \mathbf{k} + \mathbf{q}_a \rangle \langle m, \mathbf{k} + \mathbf{q}_a | r^b | n, \mathbf{k} + \mathbf{q}_a \rangle \langle n, \mathbf{k} + \mathbf{q}_a | n, \mathbf{k} \rangle \langle n, \mathbf{k} | r^b | m, \mathbf{k} \rangle, \quad (10)$$

$W_{mn}(\mathbf{k}, \mathbf{q}_a = 0, r^b, r^b) = r_{mn}^b(\mathbf{k}) r_{nm}^b(\mathbf{k})$ yields linear absorption strength at \mathbf{k} through direct interband transition. The Wilson loop can be generalized to

$$W_{mn}(\mathbf{k}, \mathbf{q}, r^a, r^b) = \langle m, \mathbf{k} | m, \mathbf{k} + \mathbf{q} \rangle \langle m, \mathbf{k} + \mathbf{q} | r^a | n, \mathbf{k} + \mathbf{q} \rangle \langle n, \mathbf{k} + \mathbf{q} | n, \mathbf{k} \rangle \langle n, \mathbf{k} | r^b | m, \mathbf{k} \rangle. \quad (11)$$

Herein, the interband Berry curvature contributing to nonlinear injection current¹⁰ can also be represented by the Wilson loop

$$\Omega_{mn}^{ab}(\mathbf{k}) = 2 \text{Im} W_{mn}(\mathbf{k}, \mathbf{q} = 0, r^a, r^b). \quad (12)$$

In fact, $W_{mn}(\mathbf{k}, \mathbf{q} = \mathbf{0}, r^a, r^b)$ defined on the Wilson loop is identical to quantum geometric tensor, and its real and imaginary part gives the symmetric quantum metric g_{mn}^{ab} and antisymmetric Berry curvature Ω_{mn}^{ab} at finite crystal momentum \mathbf{k} , respectively.

We can further rewrite the shift current conductivity tensor using the Wilson loop representation as

$$\begin{aligned}
\sigma^{abb}(\omega) &= -\frac{\pi e^3}{\hbar^2} \int \frac{d\mathbf{k}}{(2\pi)^d} \sum_{nm} f_{nm} R_{mn}^{a,b}(\mathbf{k}) r_{nm}^b r_{mn}^b \delta(\omega_{nm} - \omega) \\
&= \frac{\pi e^3}{\hbar^2} \int \frac{d\mathbf{k}}{(2\pi)^d} \sum_{nm} f_{nm} \lim_{q_a \rightarrow 0} \partial_{q_a} \text{Im} \ln[W_{mn}(\mathbf{k}, \mathbf{q}_a, r^b, r^b)] W_{mn}(\mathbf{k}, 0, r^b, r^b) \delta(\omega_{nm} - \omega) \\
&= \frac{\pi e^3}{\hbar^2} \int \frac{d\mathbf{k}}{(2\pi)^d} \sum_{nm} f_{nm} \text{Im} \lim_{q_a \rightarrow 0} \partial_{q_a} W_{mn}(\mathbf{k}, \mathbf{q}_a, r^b, r^b) \delta(\omega_{nm} - \omega).
\end{aligned} \tag{13}$$

We then obtain

$$\sigma^{abb}(\omega) = \frac{\pi e^3}{\hbar^2} \int \frac{d\mathbf{k}}{(2\pi)^d} \sum_{nm} f_{nm} \lim_{q_a \rightarrow 0} \frac{1}{q_a} \text{Im} W_{mn}(\mathbf{k}, \mathbf{q}_a, r^b, r^b) \delta(\omega_{nm} - \omega). \tag{14}$$

The above equation is a new formula for the shift current, which is only dependent on the imaginary part of the Wilson loop. This formula avoids the ambiguity in the definition of the argument around optical zeros and band degeneracies. The Wilson loop representation of Berry curvature and geometrical shift vector are illustrated in Figs. 1a and 1b. In fact, the Wilson loop approach provides an equivalent expression as the Young-Rappe formula¹⁹, which involves a more complicated Wilson loop, including indirect optical transition matrix elements as shown in Supplementary Figure 1.

Gauge invariance is guaranteed on each local Wilson loop in the discretized Brillouin zone. Under an arbitrary local gauge transformation $u_n(\mathbf{k}) \rightarrow e^{i\phi_n(\mathbf{k})} u_n(\mathbf{k})$ or $|n, \mathbf{k}\rangle \rightarrow e^{i\phi_n(\mathbf{k})} |n, \mathbf{k}\rangle$, Berry connections transform as

$$\mathcal{A}'_m(\mathbf{k}) = \mathcal{A}_m(\mathbf{k}) - \partial_{\mathbf{k}} \phi_m(\mathbf{k}), \tag{15}$$

$$\mathbf{r}'_{mn}(\mathbf{k}) = e^{i(\phi_n(\mathbf{k}) - \phi_m(\mathbf{k}))} \mathbf{r}_{mn}(\mathbf{k}). \tag{16}$$

Shift vector is clearly gauge-invariant

$$R'^{a,b}_{mn}(\mathbf{k}) = R^{a,b}_{mn}(\mathbf{k}) - \partial_{k_a}(\phi_n(\mathbf{k})) - \phi_m(\mathbf{k}) - \partial_{k_a} \phi_m(\mathbf{k}) + \partial_{k_a} \phi_n(\mathbf{k}) = R^{a,b}_{mn}(\mathbf{k}). \tag{17}$$

Consistently, the gauge transformation of quantum geometric tensor $W_{mn}(\mathbf{k}, \mathbf{q}, \mathbf{r}, \mathbf{r})$ on the Wilson loop is given by

$$\begin{aligned}
W'_{mn}(\mathbf{k}, \mathbf{q}, \mathbf{r}, \mathbf{r}) &= -\langle m, \mathbf{k} | m, \mathbf{k} + \mathbf{q} \rangle e^{i(\phi_m(\mathbf{k}+\mathbf{q}) - \phi_m(\mathbf{k}))} \langle m, \mathbf{k} + \mathbf{q} | \mathbf{r} | n, \mathbf{k} + \mathbf{q} \rangle e^{i(\phi_n(\mathbf{k}+\mathbf{q}) - \phi_m(\mathbf{k}+\mathbf{q}))} \\
&\quad \langle n, \mathbf{k} + \mathbf{q} | n, \mathbf{k} \rangle e^{i(\phi_n(\mathbf{k}) - \phi_n(\mathbf{k}+\mathbf{q}))} \langle n, \mathbf{k} | \mathbf{r} | m, \mathbf{k} \rangle e^{i(\phi_m(\mathbf{k}) - \phi_n(\mathbf{k}))} \\
&= -\langle m, \mathbf{k} | m, \mathbf{k} + \mathbf{q} \rangle \langle m, \mathbf{k} + \mathbf{q} | \mathbf{r} | n, \mathbf{k} + \mathbf{q} \rangle \langle n, \mathbf{k} + \mathbf{q} | n, \mathbf{k} \rangle \langle n, \mathbf{k} | \mathbf{r} | m, \mathbf{k} \rangle = W_{mn}(\mathbf{k}, \mathbf{q}, \mathbf{r}, \mathbf{r}).
\end{aligned} \tag{18}$$

Hence, quantum geometric tensor $W_{mn}(\mathbf{k}, \mathbf{q}, \mathbf{r}, \mathbf{r})$ is also gauge invariant. Figure 1c shows the geometrical Berry curvature and shift vector using a two-band model. The geometrical meaning of the shift vector in Wilson loop representation is illustrated in Fig. 1d, which clearly shows it is related to the difference of the real-space charge center or spontaneous polarization for the valence and conduction bands upon direct optical transition. It is also known that the geometrical shift vector contributes to nonreciprocal Landau-Zener tunneling²⁸.

Rice-Mele model of one-dimensional ferroelectric system

To demonstrate the generalized Wilson loop approach, we first use the one-dimensional Rice-Mele (RM) model of ferroelectric systems with broken inversion symmetry. The tight-binding Hamiltonian is illustrated in Fig. 2a, which is given by

$$H_{\text{RM}} = \sum_i \left[\left(\frac{t}{2} + (-1)^i \frac{\delta_t}{2} \right) (c_i^\dagger c_{i+1} + h.c.) + (-1)^i \Delta_t c_i^\dagger c_{i+1} \right], \quad (19)$$

where t is the hopping parameter and δ_t denotes the dimerization of the chain related to the distortion with respect to the centrosymmetric structure with $t_i = \frac{t}{2} + (-1)^i \frac{\delta_t}{2}$. Δ_t is the staggered on-site potential between two sites. c_i^\dagger and c_i are the fermion creation and annihilation operator, respectively. The inversion symmetry is broken when $\delta_t \neq 0$ and $\Delta_t \neq 0$. It leads to the following Bloch Hamiltonian

$$H_{\text{RM}} = \sum_{j=x,y,z} d_j \sigma_j = t \sigma_x \cos\left(\frac{ka}{2}\right) - \delta_t \sigma_y \sin\left(\frac{ka}{2}\right) + \Delta_t \sigma_z. \quad (20)$$

where a is the lattice parameter. We use the following parameters for GeS, which yields a bandgap of 1.9 eV⁹, $t = -1.0$ eV, $\delta_t = -0.83$ eV, and $\Delta_t = -0.45$ eV. The shift vector of the two-band RM model²⁹ has an analytical solution,

$$R_{cv} = \frac{\Delta_t a t \delta_t}{2E} \left\{ \frac{(\delta_t^2 - t^2)[4E^2 \cos ka + (t^2 - \delta_t^2) \sin^2 ka]}{\Delta_t^2 (\delta_t^2 - t^2) \sin^2 ka + 4t^2 \delta_t^2 E^2} - \frac{1}{E^2 - \Delta_t^2} \right\}, \quad (21)$$

The conduction and valence band energies $E_{v,c}$, as shown in Fig. 2b, are given by

$$E_{v,c} = \pm E = \pm \sqrt{t^2 \cos^2 \frac{ka}{2} + \delta_t^2 \sin^2 \frac{ka}{2} + \Delta_t^2}. \quad (22)$$

It is clear that the shift vector is reversed when δ_t or Δ_t changes sign, enabling ferroelectric-driven shift photocurrent switching¹⁰. This is also verified by Wilson loop approach as shown in Fig. 2d. Numerically, the shift vector and shift current conductivity are usually calculated by the sum rule with mass or diamagnetic term for tight-binding model. The generalized derivative of interband Berry connection for shift vector and shift current can be expressed by using the sum rule as^{7,30}

$$r_{nm;b}^a = \frac{i}{\hbar \omega_{nm}} \left[i r_{nm}^a \Delta_{nm}^b + i r_{nm}^b \Delta_{nm}^a - \hbar \sum_{p \neq n,m} (r_{np}^a r_{pm}^b \omega_{np} - r_{np}^b r_{pm}^a \omega_{pm}) - w_{nm}^{ab} \right], \quad (23)$$

where $\Delta_{nm}^b = v_n^b - v_m^b$ is the group velocity difference and $\hbar \omega_{nm} = \hbar \omega_n - \hbar \omega_m$ is the band energy difference. The mass term $w_{nm}^{ab} = \langle n | \partial_{k_a} \partial_{k_b} H | m \rangle$ cannot be neglected for the tight-binding model because the interband Berry connection is not gauge-covariant and its generalized derivative in the Hamiltonian gauge involves the second-order derivative of Hamiltonian³¹. In two-band RM model with $m = 1, n = 2$, the shift vector using the sum rule at optical nonzero \mathbf{k} -points (*i.e.* $|r_{nm}^b r_{mn}^b| \neq 0$) reads

$$R_{nm}^{a,b} \equiv \frac{\text{Im } r_{nm;a}^b r_{mn}^b}{|r_{nm}^b r_{mn}^b|} = \frac{\text{Re } w_{nm}^{ba} r_{mn}^b}{|r_{nm}^b r_{mn}^b| \hbar \omega_{mn}}. \quad (24)$$

It shows that the shift vector and shift current are vanishing in two-band RM model without considering the mass term. The calculated shift vector and shift current conductivity with an effective area of 9.37 Å² by different methods are shown in Figs. 2c and 2d. The results demonstrate that the shift vector and the

shift current calculated by the Wilson loop approach are in excellent agreement with the analytical solution and the sum-over-states approach.

Wannier tight-binding model of monolayer GeS

Next, we demonstrate the Wilson loop method for real materials with a symmetrized Wannier tight-binding Hamiltonian. The details of the first-principles calculations and the constructions of symmetrized Wannier tight-binding Hamiltonian are described in Methods. Taking the ferroelectric monolayer GeS as an example, it has a C_{2v} point group with a mirror plane \mathcal{M}_x perpendicular to the x -axis. The crystal structure and band structure of monolayer GeS are shown in Figs. 3a and 3b, respectively. From group theory analysis, the components $\sigma^{xxx}(\omega)$ and $\sigma^{xyy}(\omega)$ vanish under linearly polarized light with in-plane polarization, which was verified in our calculation. Here, we focus on $\sigma^{yyy}(\omega)$ and the corresponding shift vector $R_{cv}^{y,y}$. Figure 3c shows \mathbf{k} -resolved shift vector $R_{cv}^{y,y}$ between the top valence band and the bottom conduction band across the bandgap. The shift vector away from optical zeros can be ~ 10 Å, much larger than its lattice constant. This is very different from spontaneous electric polarization vector constrained within the lattice constant. Berry curvature of the top valence band is also calculated by the Wilson loop approach as shown in Fig. 3d. Given the mirror symmetry \mathcal{M}_x , we have verified the symmetry properties $R_{cv}^{y,y}(\mathbf{k}_x, \mathbf{k}_y) = R_{cv}^{y,y}(-\mathbf{k}_x, \mathbf{k}_y)$ and $\Omega_v^z(\mathbf{k}_x, \mathbf{k}_y) = -\Omega_v^z(-\mathbf{k}_x, \mathbf{k}_y)$. A Berry curvature dipole along x direction is generated which can induce a similar ferroelectric nonlinear Hall effect³²⁻³⁴ in monolayer GeS. The intraband Berry curvature of the bottom conduction band and the interband Berry curvature across the gap are presented in Supplementary Figure 2.

Figure 4a shows the calculated frequency-dependent shift current conductivity $\sigma^{yyy}(\omega)$. To convert the sheet conductivity σ^{2D} to bulk conductivity σ^{3D} , we set the effective thickness l to be 2.56 Å by $\sigma^{3D} = \sigma^{2D}/l$. We have verified the identity $W_{mn}(\mathbf{k}, \mathbf{q} = 0, r^b, r^b) = r_{mn}^b r_{nm}^b$. The k -resolved absorption strength between the top valence band and the bottom conduction band is shown in Fig. 4b. The white region indicates optical zeros and has no contribution to shift current conductivity. To investigate the origin of large responses, we calculate the k -resolved shift current strength $I_{mn}^{a,b}(\mathbf{k}, \omega)$ at $\omega = 2.0$ and $\omega = 2.8$ eV using the Wilson loop approach, defined as

$$I_{mn}^{a,b}(\mathbf{k}, \omega) = \lim_{q_a \rightarrow 0} \frac{1}{q_a} \text{Im} W_{mn}(\mathbf{k}, \mathbf{q}_a, r^b, r^b) \delta(\omega_{nm} - \omega). \quad (25)$$

The results are shown in Figs. 4c and 4d. The convergence was checked with respect to the number of bands and \mathbf{k} -point sampling in the first Brillouin zone, as shown in Supplementary Figure 3, for shift conductivity. In addition, frequency-dependent $\sigma^{yxx}(\omega)$ for monolayer GeS is shown in Supplementary Figure 4. Furthermore, we performed similar calculations with the Wilson loop approach for a different 2D materials monolayer WS₂, and the results are shown in Supplementary Figure 5. Our results clearly demonstrate that the generalized Wilson loop approach is not only efficient and generally applicable to both effective models and realistic materials, but also avoids the summation over a large number of intermediate valence and conduction bands, making it valuable for computing nonlinear optical responses.

It should be noted that the geometrical shift vector at optical zeros cannot be calculated using the sum-over-states approach. Furthermore, while the large shift vector at optical zeros has no contribution to shift current response with vertical transitions, it can contribute to the shift current response when taking into account the photon-drag effect²¹ involving indirect transitions or strong electron-phonon coupling effect. Our demonstration of geometrical shift vector in real materials will allow for theoretical investigations of a wide range of geometric effects induced by quantum geometric potential.

Discussion

A common challenge with a perturbation theory for nonlinear optical responses in the length gauge is the treatment of the position operator \mathbf{r} for the extended Bloch states. The intraband part of the position operator is represented by $\langle m, \mathbf{k} | \mathbf{r}_i | n, \mathbf{k}' \rangle = \delta_{mn} (\delta(\mathbf{k} - \mathbf{k}') \mathcal{A}(\mathbf{k}) + i \partial_{\mathbf{k}} \delta(\mathbf{k} - \mathbf{k}'))$. The real-space coordinate \mathbf{r} of the wave packet made from the Bloch wave functions is represented by $\mathbf{r}_i = i \partial_{\mathbf{k}} - \mathcal{A}(\mathbf{k})$. Nonlinear optical responses involve the matrix element of the commutator $\langle m, \mathbf{k} | [\mathbf{r}_i, \mathcal{O}] | n, \mathbf{k}' \rangle = i \delta(\mathbf{k} - \mathbf{k}') \mathcal{O}_{mn;\mathbf{k}}$, where the covariance derivative $\mathcal{O}_{mn;\mathbf{k}} \equiv \partial_{\mathbf{k}} \mathcal{O}_{mn} - i \mathcal{O}_{mn} (\mathcal{A}_m(\mathbf{k}) - \mathcal{A}_n(\mathbf{k}))$ plays a central role in many other nonlinear responses. The derivation of the commutator relation can be found in Supplemental Information. For example, the generalized derivative of dipole matrix element is written as

$$(r_{nm}^a)_{;\mathbf{k}^b} \equiv \partial_b(r_{nm}^a) - i(\xi_{nn}^b - \xi_{mm}^b)r_{nm}^a = -i[-\partial_b(\phi_{nm}^a) + (\xi_{nn}^b - \xi_{mm}^b)]r_{nm}^a = iR_{mn}^{a,b}r_{nm}^a, \quad (26)$$

which is a key physical quantity for second harmonic generation⁷. Hence, the Wilson loop approach developed here can be readily applied to other nonlinear optical effects such as second and third harmonic generation and linear and quadratic electro-optic effect.

The spin-orbit interaction is weak in monolayer GeS, thus it is not considered in the present calculations. Nevertheless, the expression can be easily extended to include spin-orbit coupling, and generalized to the degenerate and near degenerate case by considering band sets and the appropriate operator for selecting sub-blocks. Furthermore, although all the calculations in this work are performed within the independent particle approximation, the Wilson loop approach can also be developed to include many-body effect.

In summary, we presented a gauge-invariant generalized approach for efficient and direct calculations of nonlinear optical responses with pure Wilson loop representation. This generalized Wilson loop method avoids the cumbersome issues of the commonly used sum-over-states approach, and allows for easy implementation and efficient calculation. The Wilson loop representation provides an elegant geometric interpretation of nonlinear optical processes and responses based on quantum geometric tensors and quantum geometric potentials responsible for shift current and Landau-Zener tunneling. The generalized Wilson loop method developed here can be readily applied to study other nonlinear optical responses such as second and third harmonic generation, linear and quadratic electro-optic effect, as well as magnetic injection current and magnetic shift current³⁵.

Methods

First-principles calculations of atomistic and electronic structure. First-principles calculations for structural relaxation and quasiatomic Wannier functions were performed using density-functional theory^{36,37} as implemented in the Vienna Ab initio Simulation Package (VASP)³⁸ with the projector-augmented wave method for treating core electrons³⁹. We employed the generalized-gradient approximation of exchange-correlation functional in the Perdew-Burke-Ernzerhof form⁴⁰, a plane-wave basis with an energy cutoff of 400 eV, and a Monkhorst-Pack k -point sampling of $10 \times 10 \times 1$ for the Brillouin zone integration.

Generalized Wilson loop approach of shift current using first-principles tight-binding Hamiltonian. To compute the Wilson loop related quantities, we first construct quasiatomic Wannier functions and symmetrized first-principles tight-binding Hamiltonian from Kohn-Sham wavefunctions and eigenvalues under the maximal similarity measure with respect to pseudoatomic orbitals^{41,42}. Total 16 quasiatomic Wannier functions were obtained for monolayer GeS. Using the developed tight-binding Hamiltonian we then compute Berry curvature, shift vector and shift current using a dense k -point sampling of $200 \times 200 \times 1$. Sokhotski-Plemelj theorem is employed for the Dirac delta function integration with a small imaginary smearing factor η of 0.02 eV. We checked the convergence of shift current conductivity tensor with respect to the number of bands and the k -point sampling (see Supplementary Figure 4).

Symmetrization of the tight-binding Hamiltonian. The construction of Wannier functions for the crystalline does not preserve space group symmetries. To avoid the artificial symmetry breaking, we performed symmetrization of the tight-binding Hamiltonian. The Hamiltonian is invariant under symmetry operation g in the group G

$$\forall g \in G: H(\mathbf{k}) = D_{\mathbf{k}}(g)H(g^{-1}\mathbf{k})D_{\mathbf{k}}(g^{-1}), \quad (27)$$

$$D_{\mathbf{k}}(g) = e^{i\mathbf{t}_g \cdot \mathbf{k}} D(g), \quad (28)$$

where $D_{\mathbf{k}}(g)$ is \mathbf{k} -dependent representation of the symmetry and \mathbf{t}_g is the translation vector of the symmetry. We define the symmetrized Hamiltonian using the group average

$$\tilde{H}(\mathbf{k}) = \frac{1}{|G|} \sum_{g \in G} D_{\mathbf{k}}(g)H(g^{-1}\mathbf{k})D_{\mathbf{k}}(g^{-1}). \quad (29)$$

To apply the group average to above tight-binding Hamiltonian with all crystalline symmetry constraints in real space, we rewrite the hopping matrices⁴³

$$\tilde{H}_{ij}(\mathbf{R}) = \frac{1}{|G|} \sum_{g \in G} D_{il}(g)H_{lm} \left(S_g^{-1}(\mathbf{R} - \mathbf{T}_{ij}^{ml}) \right) D_{mj}(g^{-1}), \quad (30)$$

where S_g is the real space rotation matrix and $\mathbf{T}_{ij}^{ml} = S_g(\mathbf{r}_m - \mathbf{r}_l) - \mathbf{r}_j - \mathbf{r}_i$, \mathbf{r}_i is the position of the localized orbitals in the unit cell. Band structure of monolayer GeS with and without symmetrization of the Hamiltonian is shown in Supplementary Figure 6.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

This work was supported by the National Science Foundation under Award #DMR-1753054 and #DMR-2103842, and by an Office of Naval Research MURI through grant #N00014-17-1-2661.

Author contributions

X.Q. conceived the project. X.Q. and J.L. supervised the project. H.W. and X.Q. developed the formula. H.W. developed first-principles code for Wilson loop method and carried out the calculations. H.W. and X.Q. wrote the manuscript with the help of others. All authors conducted theoretical analysis and analyzed the results.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available.

References

- 1 Thomson, R., Leburn, C. & Reid, D. *Ultrafast Nonlinear Optics*. (Springer, 2013).
- 2 von Baltz, R. & Kraut, W. Theory of the bulk photovoltaic effect in pure crystals. *Phys. Rev. B* **23**, 5590-5596 (1981).
- 3 Evans, C. L. & Xie, X. S. Coherent anti-Stokes Raman scattering microscopy: chemical imaging for biology and medicine. *Annu. Rev. Anal. Chem.* **1**, 883-909 (2008).
- 4 Yanik, M. F., Fan, S., Soljačić, M. & Joannopoulos, J. D. All-optical transistor action with bistable switching in a photonic crystal cross-waveguide geometry. *Opt. Lett.* **28**, 2506-2508 (2003).
- 5 Kwiat, P. G., Waks, E., White, A. G., Appelbaum, I. & Eberhard, P. H. Ultrabright source of polarization-entangled photons. *Phys. Rev. A* **60**, R773-R776 (1999).
- 6 Sturman, P. J. & Fridkin, V. M. *Photovoltaic and Photo-refractive Effects in Noncentrosymmetric Materials*. Vol. 8 (CRC Press, 1992).
- 7 Sipe, J. E. & Shkrebtii, A. I. Second-order optical response in semiconductors. *Phys. Rev. B* **61**, 5337-5352 (2000).
- 8 Nastos, F. & Sipe, J. Optical rectification and shift currents in GaAs and GaP response: Below and above the band gap. *Physical Review B* **74**, 035201 (2006).
- 9 Rangel, T. *et al.* Large Bulk Photovoltaic Effect and Spontaneous Polarization of Single-Layer Monochalcogenides. *Physical review letters* **119**, 067402 (2017).
- 10 Wang, H. & Qian, X. Ferrocity-driven nonlinear photocurrent switching in time-reversal invariant ferroic materials. *Sci. Adv.* **5**, eaav9743 (2019).
- 11 Wang, X., Yates, J. R., Souza, I. & Vanderbilt, D. Ab initio calculation of the anomalous Hall conductivity by Wannier interpolation. *Physical Review B* **74**, 195118 (2006).
- 12 Ibañez-Azpiroz, J., Tsirkin, S. S. & Souza, I. Ab initio calculation of the shift photocurrent by Wannier interpolation. *Physical Review B* **97**, 245143 (2018).
- 13 Wilson, K. G. Confinement of quarks. *Physical review D* **10**, 2445 (1974).
- 14 Thouless, D. J., Kohmoto, M., Nightingale, M. P. & den Nijs, M. Quantized Hall conductance in a two-dimensional periodic potential. *Physical review letters* **49**, 405 (1982).
- 15 Nagaosa, N., Sinova, J., Onoda, S., MacDonald, A. H. & Ong, N. P. Anomalous Hall effect. *Rev. Mod. Phys.* **82**, 1539-1592 (2010).
- 16 Sinova, J. *et al.* Universal intrinsic spin Hall effect. *Physical review letters* **92**, 126603 (2004).
- 17 Kane, C. L. & Mele, E. J. Quantum spin Hall effect in graphene. *Physical review letters* **95**, 226801 (2005).
- 18 Bernevig, B. A., Hughes, T. L. & Zhang, S.-C. Quantum spin Hall effect and topological phase transition in HgTe quantum wells. *science* **314**, 1757-1761 (2006).
- 19 Young, S. M. & Rappe, A. M. First Principles Calculation of the Shift Current Photovoltaic Effect in Ferroelectrics. *Physical Review Letters* **109**, 116601 (2012).
- 20 King-Smith, R. & Vanderbilt, D. Theory of polarization of crystalline solids. *Phys. Rev. B* **47**, 1651 (1993).
- 21 Shi, L.-k., Zhang, D., Chang, K. & Song, J. C. W. Geometric Photon-Drag Effect and Nonlinear Shift Current in Centrosymmetric Crystals. *Physical Review Letters* **126**, 197402 (2021).
- 22 Zhao, M.-s. & Chen, J.-l. Adiabatic condition and quantum geometric potential. *Physical Review A* **77**, 062114 (2008).
- 23 Ahn, J., Guo, G.-Y. & Nagaosa, N. Low-frequency divergence and quantum geometry of the bulk photovoltaic effect in topological semimetals. *Physical Review X* **10**, 041041 (2020).
- 24 Holder, T., Kaplan, D. & Yan, B. Consequences of time-reversal-symmetry breaking in the light-matter interaction: Berry curvature, quantum metric, and diabatic motion. *Phys. Rev. Research* **2**, 033100 (2020).
- 25 Provost, J. & Vallee, G. Riemannian structure on manifolds of quantum states. *Communications in Mathematical Physics* **76**, 289-301 (1980).
- 26 Resta, R. The insulating state of matter: a geometrical theory. *The European Physical Journal B* **79**, 121-137 (2011).
- 27 Fukui, T., Hatsugai, Y. & Suzuki, H. Chern numbers in discretized Brillouin zone: efficient method of computing (spin) Hall conductances. *Journal of the Physical Society of Japan* **74**, 1674-1677 (2005).
- 28 Kitamura, S., Nagaosa, N. & Morimoto, T. Nonreciprocal Landau-Zener tunneling. *Communications Physics* **3**, 63 (2020).
- 29 Fregoso, B. M., Morimoto, T. & Moore, J. E. Quantitative relationship between polarization differences and the zone-averaged shift photocurrent. *Physical Review B* **96**, 075421 (2017).

- 30 Cook, A. M., Fregoso, B. M., De Juan, F., Coh, S. & Moore, J. E. Design principles for shift current photovoltaics. *Nat. Commun.* **8**, 14176 (2017).
- 31 Wang, C. *et al.* First-principles calculation of nonlinear optical responses by Wannier interpolation. *Phys. Rev. B* **96**, 115147 (2017).
- 32 Sodemann, I. & Fu, L. Quantum Nonlinear Hall Effect Induced by Berry Curvature Dipole in Time-Reversal Invariant Materials. *Physical Review Letters* **115**, 216806 (2015).
- 33 Wang, H. & Qian, X. Ferroelectric nonlinear anomalous Hall effect in few-layer WTe₂. *npj Computational Materials* **5**, 119 (2019).
- 34 Xiao, J. *et al.* Berry curvature memory through electrically driven stacking transitions. *Nature Physics* **16**, 1028–1034 (2020).
- 35 Wang, H. & Qian, X. Electrically and magnetically switchable nonlinear photocurrent in PT-symmetric magnetic topological quantum materials. *npj Computational Materials* **6**, 199 (2020).
- 36 Hohenberg, P. & Kohn, W. Inhomogeneous electron gas. *Phys. Rev. B* **136**, B864-B871 (1964).
- 37 Kohn, W. & Sham, L. J. Self-consistent equations including exchange and correlation effects. *Physical review* **140**, A1133 (1965).
- 38 Kresse, G. & Furthmüller, J. Efficient iterative schemes for *ab initio* total-energy calculations using a plane-wave basis set. *Physical Review B* **54**, 11169-11186 (1996).
- 39 Blöchl, P. E. Projector augmented-wave method. *Physical Review B* **50**, 17953-17979 (1994).
- 40 Perdew, J. P., Burke, K. & Ernzerhof, M. Generalized gradient approximation made simple. *Phys. Rev. Lett.* **77**, 3865-3868 (1996).
- 41 Mostofi, A. A. *et al.* wannier90: A tool for obtaining maximally-localised Wannier functions. *Comput. Phys. Commun.* **178**, 685-699 (2008).
- 42 Qian, X. *et al.* Quasiatomic orbitals for *ab initio* tight-binding analysis. *Phys. Rev. B* **78**, 245112 (2008).
- 43 Gresch, D. *et al.* Automated construction of symmetrized Wannier-like tight-binding models from *ab initio* calculations. *Physical Review Materials* **2**, 103805 (2018).

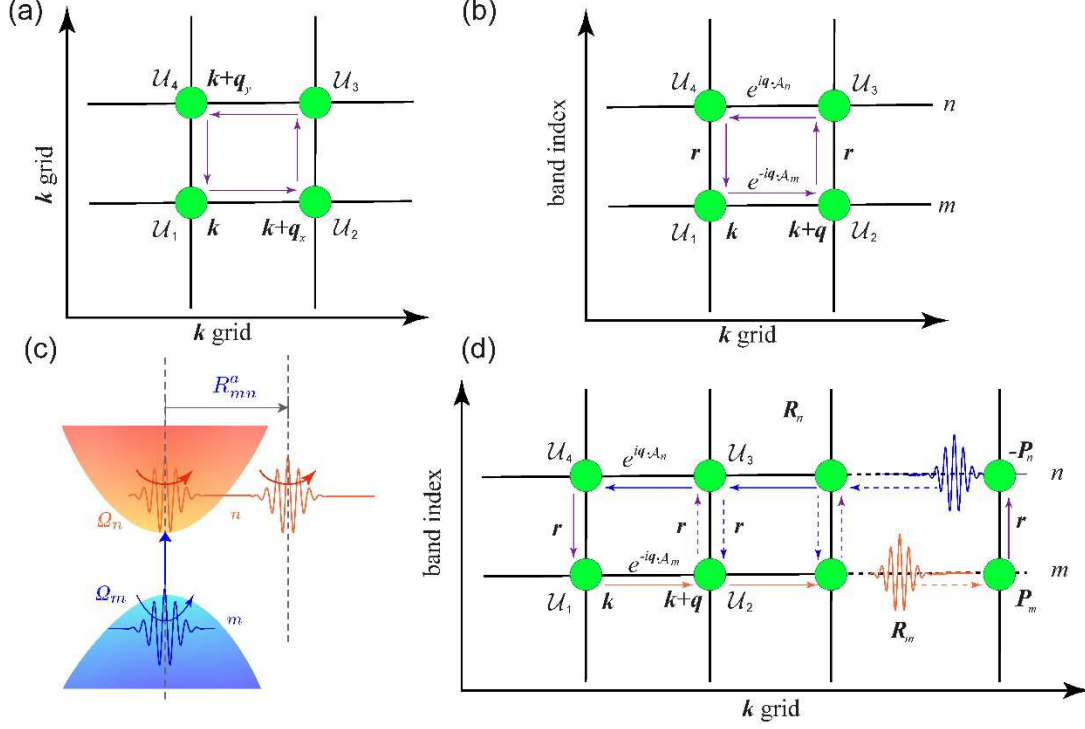


Fig. 1 Wilson loop approach of the Berry curvature and geometrical shift vector. **a** Berry curvature $\Omega^z(\mathbf{k})$ represented by the overlap matrix elements between Bloch wavefunctions \mathcal{U} at neighboring \mathbf{k} -points. The Wilson loop is $W_n(\mathbf{k}) = \langle \mathcal{U}_1 | \mathcal{U}_2 \rangle \langle \mathcal{U}_2 | \mathcal{U}_3 \rangle \langle \mathcal{U}_3 | \mathcal{U}_4 \rangle \langle \mathcal{U}_4 | \mathcal{U}_1 \rangle$. **b** Shift vector $\mathbf{R}_{mn}(\mathbf{k})$ along \mathbf{q} between band m and n represented by Bloch wavefunctions \mathcal{U} at neighboring \mathbf{k} -points and transition matrix elements \mathbf{r}_{mn} . The Wilson loop for shift vector $W_{mn}(\mathbf{k}) = \langle \mathcal{U}_1 | \mathcal{U}_2 \rangle \langle \mathcal{U}_2 | \mathbf{r} | \mathcal{U}_3 \rangle \langle \mathcal{U}_3 | \mathcal{U}_4 \rangle \langle \mathcal{U}_4 | \mathbf{r} | \mathcal{U}_1 \rangle$ is associated with the interband transition. **c,d** Physical meaning of shift vector. The integral of the Wilson loops results in the polarization difference between two bands upon optical transition and the relative shift of the charge center of wave packet involving a pair of states.

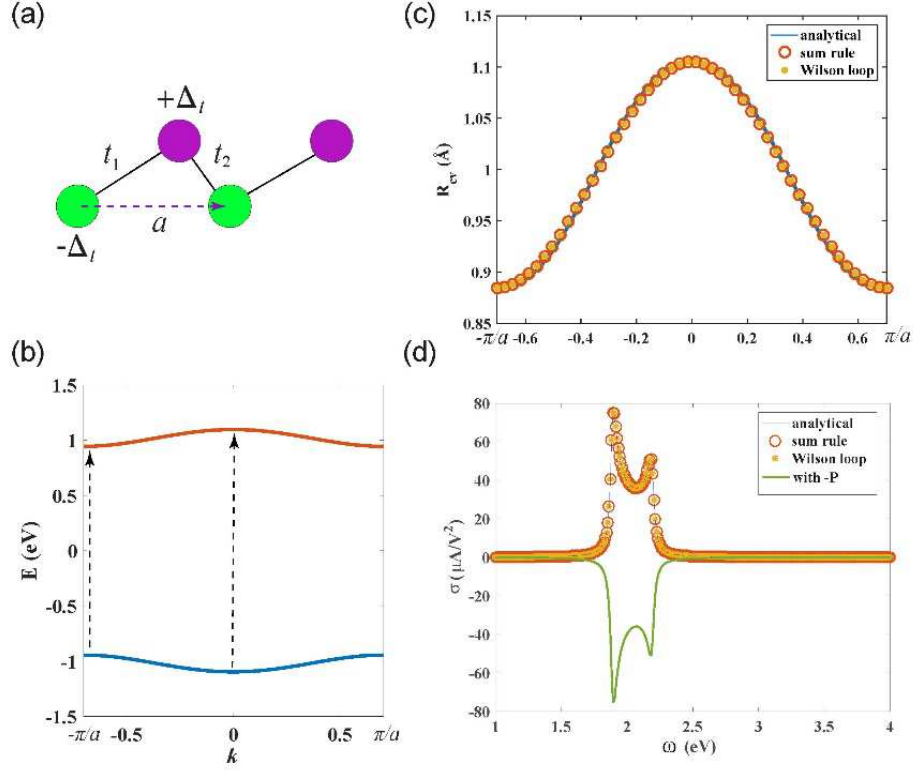


Fig. 2 Band structure, shift current, and shift vector for noncentrosymmetric Rice-Mele model. **a** Two-band Rice-Mele tight-binding model of one-dimensional polarized chain with two sites in each unit cell. **b** Energy dispersion of the conduction and valence bands. The arrows denote the optical transition in the edge and center of the first Brillouin zone. **c** Shift vector calculated by three different methods, including the analytical solution, the sum rule with the mass term, and the Wilson loop approach. **d** Shift current calculated by the analytical method, the sum rule with mass term, and the Wilson loop approach. “-P” denotes the 1D Rice-Mele model with reversed polarization. The two peaks are related to the optical transitions indicated as two arrows in **b**.

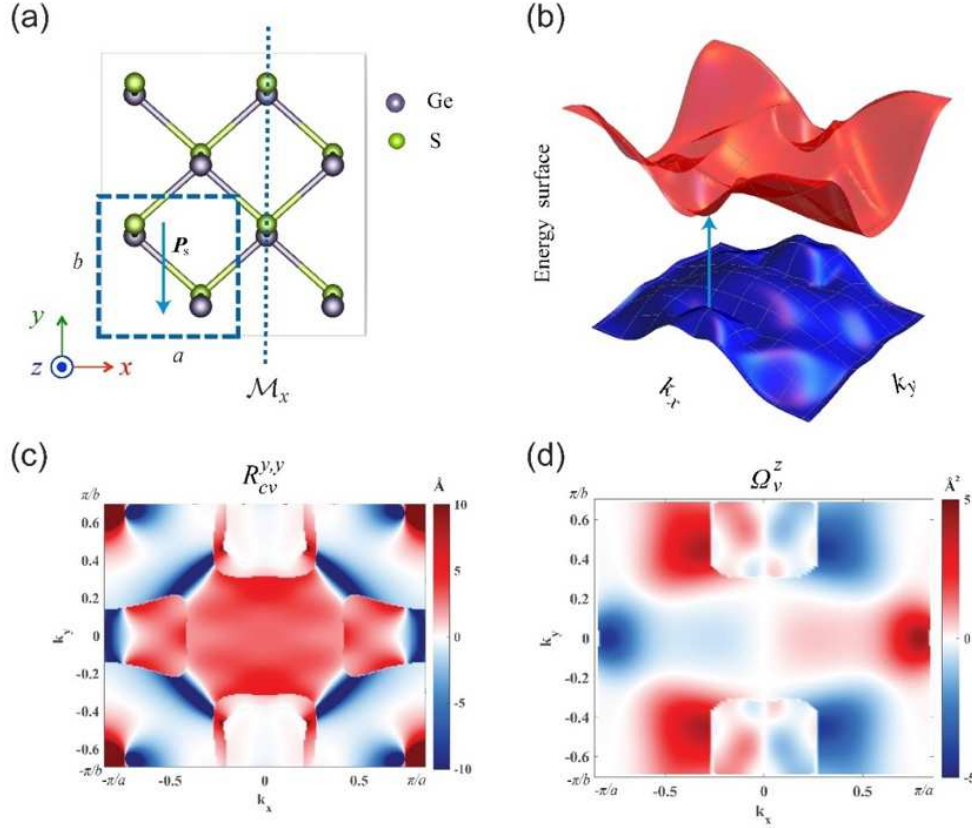


Fig. 3 Crystal structure, band structure, shift vector, and Berry curvature of monolayer GeS. a Crystal structure of ferroelectric monolayer GeS with noncentrosymmetric C_{2v} point group. **b** Valence and conduction band energy surfaces across the bandgap. **c** k -resolved shift vector across the bandgap in the first Brillouin zone. **d** k -resolved Berry curvature of the top valence band in the first Brillouin zone.

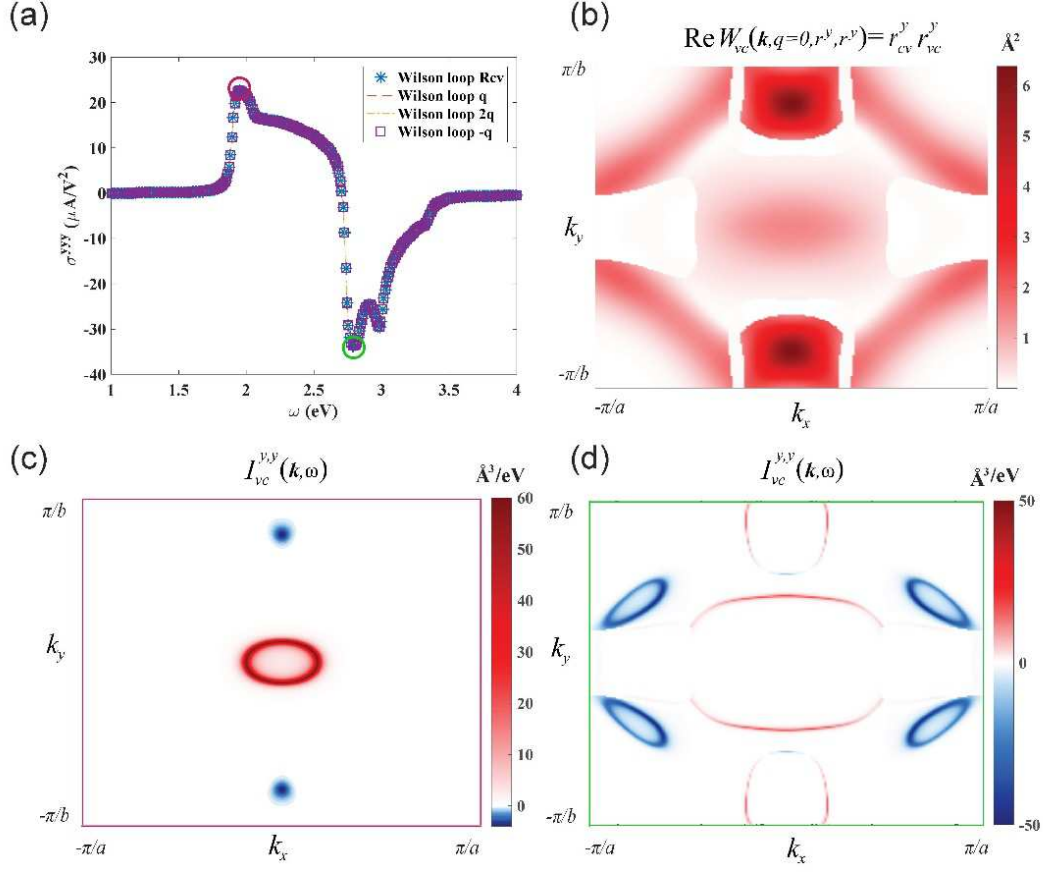


Fig. 4 Shift current conductivity and the k -space distribution of the related quantities in monolayer GeS. **a** Calculated shift current conductivity $\sigma^{yyy}(\omega)$ by the Wilson loop approach with two bands across the gap. R_{cv} denotes the original shift vector formula and $q, 2q, -q$ represent the formula using the imaginary part of Wilson loop $W_{mn}(\mathbf{k}, \mathbf{q}, \mathbf{r}, \mathbf{r})$ with different q values. **b** k -resolved absorption strength $r_{cv}^y r_{vc}^y$ corresponding to quantum metric g_{cv}^{yy} in the first Brillouin zone. **c,d** k -resolved shift current strength $I_{vc}^{y,y}(\mathbf{k}, \omega)$ at $\omega = 2.0$ and $\omega = 2.8$ eV using the Wilson loop approach, respectively.