One-way transport in laser-illuminated bilayer graphene: A Floquet isolator

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We explore the Floquet band-structure and electronic transport in laser-illuminated bilayer graphene. By using a bias voltage perpendicular to the graphene bilayer we show how to get one-way charge and valley transport among two unbiased leads. In contrast to quantum pumping, our proposal uses a different mechanism based on generating a non-reciprocal bandstructure with a built-in directionality. The Floquet states at one edge of a graphene layer become hybridized with the continuum on the other layer, and so the resulting bandstructure allows for one-way transport as in an isolator. Our proof-of-concept may serve as a building block for devices exploiting one-way states.

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I. INTRODUCTION

The advent of graphene1–4 as well as the new family of two-dimensional (2D) materials and their heterostructures5 has provided us with an outstanding playground for testing quantum transport concepts and ideas, from devices exploiting quantum interference6–8 to schemes harnessing the valley degree of freedom9. In spite of the rapid progress, controlling or steering the flow of charge, spin and valley currents across a device or material has remained as a main challenge. A promising control path is achieving one-way transport, a situation where the current (of charge, valley or spin) can flow among two electrodes in one direction only. An example is the recent realization of non-reciprocal supercurrent flow in a carbon nanotube10. An even more challenging path is seeking for one-way transport in an isolator configuration. The isolator concept is borrowed from photonics11 and is used here for a setup where transport is possible only from lead L to lead R but not in the opposite direction while the reflection at lead L vanishes (Fig. 1 (a)). As the scattering matrix associated to the two terminals in an isolator is non-unitary, achieving an isolator for electrons might seem impossible at first sight, but, as will become clear later, this is not the case.

Here we show a proof-of-concept for an electronic isolator obtained by shining a laser on bilayer graphene. A previous study12 predicted a scheme for realizing this effect for charge (spin) transport on a biased bilayer graphene by including a Haldane (spin-orbit) term. In spite of the difficulty to realize a Haldane term13 in a condensed matter experiment, our results show that laser illumination can take a similar role and use it to produce a targetted non-reciprocity. This proposal is, to the best of our knowledge, the first one for an electronic/valley isolator using a time-dependent field. By offering a proof of concept, our work thus paves the way for new optoelectronic devices.

In the following we deepen on the isolator concept and provide further motivation to this work before turning to our model and the results.

The isolator concept in optics. In optics, a device allowing light to pass in one direction but blocking it in the opposite one is called an isolator11. It is of great use in photonics where reflections that may, for example, reveal information to an observer intercepting the signal, are undesired. Moreover, in an isolator, other effects such as spurious interferences and light rerouting can be lessened if not eliminated. Theoretically, it requires at least two single-mode terminals connected

![Figure 1. (color online) (a) Scheme of the simplest ideal isolator (as discussed in Ref. 11) where single moded wires are connected to a sample. The scattering matrix is skewed and transmission occurs only from left to right. (b) Scheme of the setup considered in this work to obtain an isolator effect: A laser illuminated graphene sample connected to left and right electrodes, an inhomogenous region with monolayer and bilayer graphene, and a third electrode on top. The bilayer area is biased perpendicularly to the graphene plane.](http://example.com/figure1.png)
to the device in such a way that transmission can occur from one terminal to the other, but vanishes in the reciprocal direction. As noted in Ref. 11, the isolator has either to perfectly block the transmission in one direction or divert it to a third terminal. Thus the scattering matrix that represents an isolator must be asymmetric. For a two terminal system having a single channel on each terminal an isolator would be as shown in Fig. 1(a).

Opportunities and challenges for the isolator concept in electronics. An isolator-like effect is also desirable in other contexts such as for example in electronics where directional transport is useful for logical applications, yet, to the best of our knowledge, it is still missing from the toolkit of quantum devices. The first challenge is immediately apparent: in typical electronic devices the scattering matrix is warranted to be unitary and as such a skewed matrix like the one mentioned earlier is not possible. Notwithstanding, this is not an obstacle if we consider a system with a third electrode intended solely to reroute or divert the charges propagating in one direction. The effective scattering matrix for the two terminal system may indeed be skewed in such case without violating unitarity. But even when these issues can be circumvented by adding a third physical terminal, it remains the challenge on how to get a perfectly non-reciprocal system, one where transmission from L to R is one and zero from R to L.

If we think of systems hosting perfectly transmitting and robust states, the first that comes to mind is a sample hosting chiral states like in the quantum Hall regime. But this also occurs in others non-equilibrium situations such as in the case of graphene irradiated with a laser, where Floquet chiral edge states emerge in the spectrum. Since the bandstructure in such systems is recyclo, to get an isolator-like behavior one would need to supress transport through the states propagating along one of the edges. However this is prevented by the bulk-boundary correspondence, thereby requiring a scheme to circumvent it.

This work. Here we offer a proof-of-concept where an isolator effect is obtained in a laser-illuminated graphene bilayer. The proposed system has two ‘active’ electrodes connected to one of the layers (which form the isolator) and a third electrode connected to the other layer which is used for diverting unwanted reflections (see scheme in Fig. 1(b)). As it will become clear later on, since driving has a crucial role as it promotes the non-reciprocity for the electronic/valley transport, we call this device a Floquet isolator.

We should also comment on the difference with the large body of previous works aimed at obtaining directional charge transport using time-dependent fields. This includes, notably, the phenomenon called quantum pumping, the use of time-dependent potentials to steer transport and obtain a dc current at zero bias or even against an external bias voltage. In the open regime quantum pumping usually relies on quantum interference and has been extensively studied for both the adiabatic and non-adiabatic cases. The proposal in this paper is different from those in different aspects. First, in our case the directionality is built-in the electronic structure of the system, and second, the scattering matrix for a quantum pump does not generally have a perfect directionality as in an isolator.

Finally, there is also one interesting previous study where optical non-reciprocity is produced through electrical driving, this is the converse of our proposal where non-reciprocity in charge or valley transport is produced through laser illumination. Another recent work aiming at tailoring non-reciprocity but in interacting systems is Ref. 36. In our case we use laser illumination and take non-reciprocity to the extreme of producing an almost perfect isolator.

II. HAMILTONIAN MODEL AND FLOQUET SOLUTION SCHEME

To motivate our discussion we consider a simple Hamiltonian for the electronic excitations in bilayer graphene:

\[ \mathcal{H} = \sum_i E_i c_i^\dagger c_i - \sum_{\langle i,j \rangle} \gamma_{ij} c_i^\dagger c_j + \mathcal{H}_{\perp}, \]

where \( c_i^\dagger \) and \( c_i \) are the electronic creation and annihilation operators at the \( \pi \)-orbital on site \( i \) (which can be A-type or B-type, A_1 and B_1 for the lower layer and A_2 and B_2 for the upper one). The second summation runs over nearest-neighbors, and the associated hopping matrix elements \( \gamma_{ij} \) are taken all equal to \( \gamma_0 = 2.7 \text{ eV} \), which is considered as the unit of energy hereafter. To model a bias voltage applied perpendicularly to the graphene bilayer we include a shift of the site energies on the lower (\( E_i = E_{01} - \Delta/2 \)) and upper (\( E_i = E_{01} + \Delta/2 \)) layers. Without loss of generality we take \( E_{01} = 0 \). We consider a bilayer graphene with Bernal stacking (see Fig. 2(c)). In our model we consider the hopping matrix elements between A_1 and B_2 sites, \( \gamma_1 \), which is included in the \( \mathcal{H}_{\perp} \) of the Hamiltonian.

It has been shown that laser-illuminated graphene monolayers and bilayers may host chiral edge states if the laser parameters are appropriately chosen. These Floquet chiral edge states will be the ‘substrate’ on which we will base our proposal.

Here, we consider a sample irradiated with a circularly polarized laser perpendicular to the bilayer. This is incorporated in the Hamiltonian through the Peierls substitution as a time dependent phase in the nearest-neighbors matrix elements:

\[ \gamma_{ij}(t) = \gamma_0 \exp \left( i \frac{2\pi}{\Phi_0} \int_{r_j}^{r_i} \mathbf{A}(t) \, dr \right). \]

where \( \mathbf{A}(t) \) is the vector potential of the radiation and \( \Phi_0 \) the magnetic flux quantum. As it can be noticed, \( \gamma(t) \) depends on the position of the two nearest-neighbors sites under consideration. Then, since the radiation is perpendicular to the graphene plane, the alteration of \( \gamma_1 \) can be despised. Particularly, the vector potential associated with a circularly polarized monochromatic plane wave in the \( z \)-direction (perpendicular to the graphene sheet) is \( \mathbf{A}(t) = \)
III  GENERATING A NON-RECYPROCAL FLOQUET BANDSTRUCTURE WITH UNBALANCED CHIRAL EDGE STATES

To design an isolator device we take advantage of the chiral edge states found in irradiated graphene\(^{18,41,47}\) and look for a way of annihilating one of those. Specifically, we aim to generate a non-reciprocal bandstructure with unbalanced chiral states where directional transport can be achieved.

In references \(^{41}\) and \(^{47}\), the authors have shown that when illuminating a graphene monolayer with a laser, a gap at zero energy opens in the dispersion relation (besides others at energies which are integer multiples of the laser frequency and half the laser frequency), and chiral states propagating along the edges emerge.

If we take the interlayer coupling of the bilayer graphene sample to be zero, then applying a perpendicular bias leads to a bandstructure that is equivalent to that of two laser-illuminated monolayers but shifted in energy (as shown in Fig. 2(a)). Notably, on each monolayer one observes the opening of a gap around the Dirac point and edge states bridging them. When the interlayer coupling is turned on, one gets the results shown in figure 2(b). Besides a valley asymmetry due to the breaking of inversion symmetry, we see that the edge states bridging the laser-induced gap seem to remain almost intact.

A more compelling feature is hidden in this dispersion relation but can be revealed when coloring it according to the polarization (greater than 95\%). The origin of this polarization is the radiation itself (which is responsible of the appearance of the chiral edge states) and it is also favored by the presence of the perpendicular bias.

However, the most significative characteristic exposed in figures 2(d) and (g) is the existence of a region of energy where the (weight of the) chiral edge state vanishes. This disappearance is originated in the hybridization between the edge states in one layer and the continuum on the other one in the...
DIRAC ELECTRONIC STATE IN A BILAYER GRAPHENE SAMPLE

IV. TRANSPORT PROPERTIES, ONE-WAY CHARGE TRANSPORT AND ISOLATOR EFFECT

Illuminating the bilayer graphene sample with a circularly polarized laser breaks the time reversal symmetry. The same result is attained on the inversion symmetry due to the external bias. Hence, the right-left symmetry is broken in our system. However, this cannot be exploited when connecting only two leads to the sample. The unitary of the $2 \times 2$ scattering matrix implies that the transmission from the left lead to the right one is equal to the transmission in the opposite direction. To elude this obstacle in the search of a Floquet isolator, a third monolayer graphene lead is incorporated by attaching it to the upper layer of the sample (see schemes on Fig. 3(a) and (b)). The unitary is now compulsory for the new $3 \times 3$ scattering matrix, whereas the effective $2 \times 2$ scattering matrix can be asymmetric allowing us to profit from the non-reciprocity of the dispersion relation.

In figure 3(a) we show the left to right and right to left transmission probabilities for the irradiated bilayer graphene sample. The chosen range of energy corresponds to the one at which one of the chiral edge states vanishes in the dispersion relation (Fig. 2(d) and (g)). We assumed that the thermalization process occurs in the leads as is usual in Floquet scattering theory.37,48 The figure shows how the non-reciprocity of the band structure is reflected as a directional asymmetry in the transmissions.

Comparing our results to the ones of an ideal isolator (fig. 1), we can notice that they differ in the $T_{R \rightarrow L}$ which is not perfectly zero though $T_{L \rightarrow R}$ is almost one. Two main factors contribute to this small $T_{L \rightarrow R}$: a) the unavoidable interface between illuminated and non-illuminated areas which may lead to additional scattering (and which indeed produces a reflection filtering all but one transmission channel), b) the abrupt change from the bilayer sample to the graphene monolayer leads. Nonetheless, the directionality is still evident.

Ideally, an electronic isolator should be robust to disorder and roughness. This implies that its properties (like the directional asymmetry), shall not be modified by details such as edge ending or roughness, or the presence of defects. However, to produce the isolator-like behavior we relied on the sublattice polarization of the Floquet chiral states (see Fig. 2(d)-(g)) which allows for the upper layer to introduce a selective ‘environment’ to the lower one thanks to the stacking order. Hence, the non-reciprocity might be jeopardized by a small distortion of the physical system. In order to circumvent this problem, we devised a different setup. Specifically, we considered a monolayer graphene sample in which only one half is covered by a second layer, as shown in the scheme in Fig. 3(b). Thus, the upper layer can only be effective in...
V. SUMMARY AND FINAL REMARKS.

Isolators, devices where transmission occurs in one direction and is suppressed on the opposite one, have been missing from the toolkit of available devices in electronics. Here we present a demonstration of this effect for the case of a laser-illuminated graphene bilayer. Laser illumination allows to introduce an effective Haldane-like term\textsuperscript{13} which together with the inversion symmetry breaking, produced by an electric field perpendicular to the graphene bilayer, allows for a non-reciprocal bandstructure which is exploited to produce an isolator effect.

Our starting point in this paper are the Floquet topological states produced by laser illumination on graphene. By exploiting the sublattice polarization of these edge states in zigzag-terminated samples, together with its stacking order (Bernal), we achieve a selective ‘switch-off’ of those at one of the edges. Although this configuration is fragile against small changes in the device geometry (termination, stacking order, etc.), when covering a single edge of the system the results become much more promising: the directionality now improves with edge roughness and disorder, it is anti-fragile.\textsuperscript{49} This implies that, rather than being merely resilient to disorder, the effect actually improves or gets better with it.

By offering a proof of concept, our work thus paves the way for new optoelectronic devices exploiting the one-wayness of the topological states for more efficient transport of energy, charge or spin. We hope that these results could stimulate the search of new ways of tailoring and harnessing non-reciprocity in electronic systems both theoretically and experimentally.

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Author contributions. LEFFT, VDL and ESM developed the concept. LEFFT and VDL designed the study. VDL wrote a code and obtained the numerical results shown here, LEFFT verified the main results. VDL and LEFFT wrote the manuscript and prepared the figures. The text was discussed and agreed by all the authors.

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