Floquet chiral edge states in graphene (Supplementary material)

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Supplementary information on the numerics. Here we supply further details on the numerical calculations reported in the main text. The model used for the numerical results reported in Figs. 2-3 of the manuscript is a nearest neighbors π-orbitals (tight-binding) model as is standard for graphene (see for example [1–3]):

$$\mathcal{H}_e = \sum_i E_i\, c_i^\dagger c_i - \sum_{\langle i,j\rangle} [\gamma_{ij} c_i^\dagger c_j + \text{h.c.}], \qquad (1)$$

where $c_i^\dagger$ and c_i are the electronic creation and annihilation operators at the π-orbital on site i, with energy E_i, and $\gamma_{ij} = \gamma_0 = 2.7$ eV is the nearest-neighbors carbon-carbon hopping matrix element [4].

The interaction with the laser at normal incidence on the graphene sheet is described through a time-dependent phase in the hopping amplitudes as in [5–7],

$$\gamma_{ij} = \gamma_0 \exp\left(\mathrm{i}\frac{2\pi}{\Phi_0}\int_{\boldsymbol{r}_j}^{\boldsymbol{r}_i} \boldsymbol{A}(t)\cdot \mathrm{d}\boldsymbol{\ell}\right), \qquad (2)$$

where Φ_0 is the magnetic flux quantum and $\boldsymbol{A}$ is the vector potential which is related to the electric field $\boldsymbol{E}$ through $\boldsymbol{E} = -(1/c)\,\partial\boldsymbol{A}/\partial t$.

The general scheme based on Floquet theory [8–10] described in the text can then be used to compute the Floquet spectrum, the average density of states and the conductance [8, 11] (see also Chapter 6 of [3]). The calculation in Fig. 1 corresponds to a k.p calculation with a model as the one mentioned in the main text. In the spectral calculations shown in Fig. 2, the tight-binding model in the presence of radiation is solved and the full spectrum obtained.

To compute the transport properties one considers a setup where only the sample is being irradiated while the electrodes are not. From the matrix form of $\hat{\mathcal{H}}_F$ we can compute the associated Floquet-Green functions which can be related to the transmission probabilities between the different channels. Assuming that the sample is connected to semi-infinite electrodes where thermalization takes place, a coherent calculation gives the time-averaged current [8].

In the case of the results presented in Figure 3, to numerically show the chirality of the edge states we need to *locally* probe the transport. To such end, we imagine a situation where local probes are attached to specific sites s_1 and s_2. s_1 is located along the the line labeled with L in the inset of Fig. 3a (marked in red) while s_2 is labeled along the line labeled with R. The layers L and R are a distance d along the y direction apart from each other. The sample comprises a region eight times larger than d and included the area depicted in the insets of Fig. 3. The ribbon is infinite in both directions and only the sample area is being irradiated. Then, within Floquet's theory [8–10] and by assuming probes weakly connected to s_1 and s_2 one can compute the total transmission probabilities $T_{s_1\to s_2}$ and $T_{s_2\to s_1}$ from the Green's functions as in [6, 8]. In the limit of weakly coupled probes the specific model taken for them does not influence the results shown in Fig. 3. A crucial assumption for this formalism to be valid is that the leads are non-irradiated, thereby allowing for the asymptotic occupations in the leads to be well defined.

In the calculations involving different types of disorder (Fig. 3 c-f), the disorder is included only in the region between L and R.

[1] R. Saito, G. Dresselhaus, and M. Dresselhaus, *Physical Properties of Carbon Nanotubes* (Imperial College Press, London, 1998).
[2] J.-C. Charlier, X. Blase, and S. Roche, Rev. Mod. Phys. **79**, 677 (2007).
[3] L. E. F. Foa Torres, S. Roche, and J. C. Charlier, *Introduction to Graphene-Based Nanomaterials: From Electronic Structure to Quantum Transport* (Cambridge University Press, 2014).
[4] S. M.-M. Dubois, Z. Zanolli, X. Declerck, and J.-C. Charlier, The European Physical Journal B **72**, 1 (2009).
[5] T. Oka and H. Aoki, Phys. Rev. B **79**, 081406 (2009).
[6] H. L. Calvo, H. M. Pastawski, S. Roche, and L. E. F. Foa Torres, Appl. Phys. Lett. **98**, 232103 (2011).
[7] H. L. Calvo, P. M. Perez-Piskunow, S. Roche, and L. E. F. Foa Torres, Appl. Phys. Lett. **101**, 253506 (2012).
[8] S. Kohler, J. Lehmann, and P. Hänggi, Physics Reports **406**, 379 (2005).
[9] G. Platero and R. Aguado, Physics Reports **395**, 1 (2004).
[10] M. Moskalets and M. Büttiker, Phys. Rev. B **66**, 205320 (2002).
[11] S. Camalet, J. Lehmann, S. Kohler, and P. Hänggi,

Phys. Rev. Lett. **90**, 210602 (2003).