Arbeitsgruppe Quantentheorie und Vielteilchensysteme

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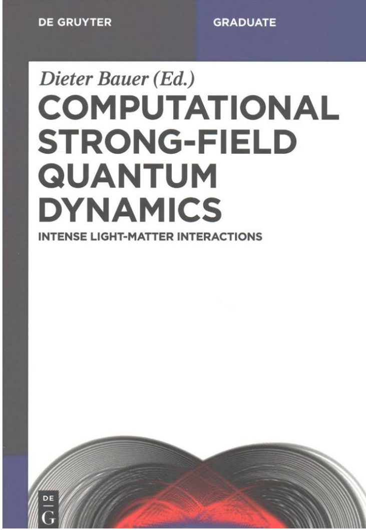
Vorstellung von möglichen BSc-Arbeitsthemen, 13.01.2022

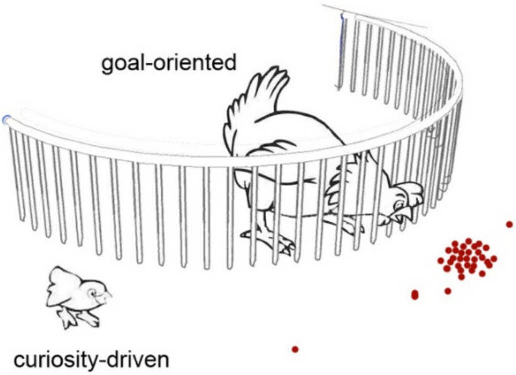
Gruppe 2019

Quantensysteme — geschüttelt und gerührt

- **Theorie und Simulation**
- **Quantendynamik jenseits von Störungstheorie**
- **Lasergetriebene Quantendynamik**
- **Vielteilchen-Quantensysteme**
- **Topologische Effekte**



Warum das Ganze?



Aus Th. Hänschs Nobel-Vortrag 2005

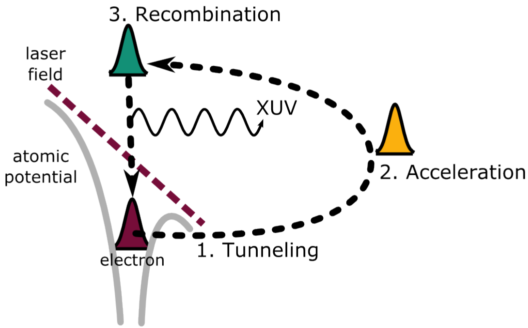
- Abbildung von Struktur und Dynamik im “Einzelschuss”
- Neuartige Strahlungsquellen
- Teilchenbeschleunigung
- Ultraschnelle, lichtgetriebene Elektronik

⋮

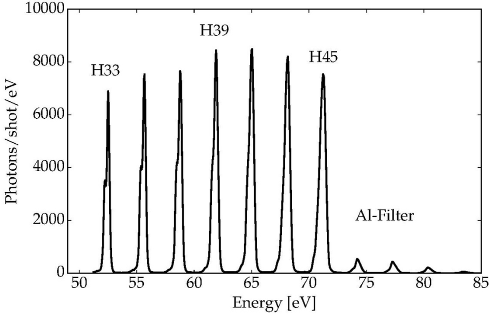
- Neue theoretische Ansätze und Simulationsmethoden

Erzeugung hoher Harmonische

Von der Wikipediaseite zu *High Harmonic Generation*:

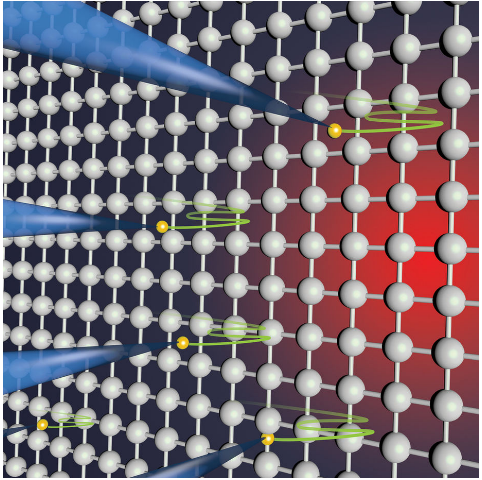


Three-step model beim Atom



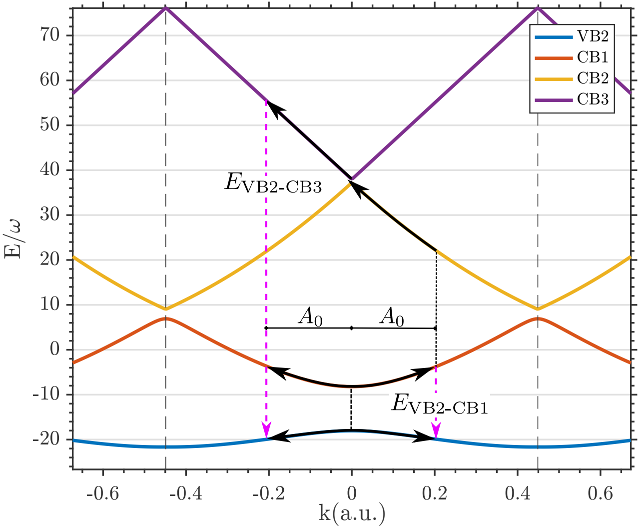
High harmonic spectrum

Erzeugung hoher Harmonischer im Festkörper

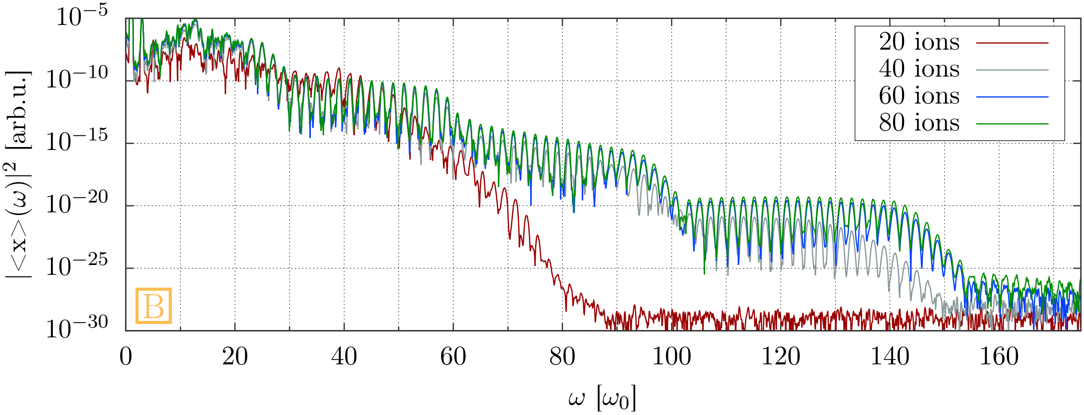


G. Vampa, D.M. Villeneuve, Nature Physics 11, 529 (2015)

Beispiel: Erzeugung hoher Harmonischer in einer linearen Kette



Erzeugung hoher Harmonischer in einer linearen Kette



Kenneth K. Hansen, T. Deffge, D. Bauer, Phys. Rev. A 96, 053418 (2017)

Topologie

Ortsraum

- Gauss-Bonnet

$$\int \mathrm{d}^2 r \begin{pmatrix}\text{Gauss}\\ \text{Krüm-}\\ \text{mung}\end{pmatrix} = 4\pi(1 - \#\text{Löcher})$$

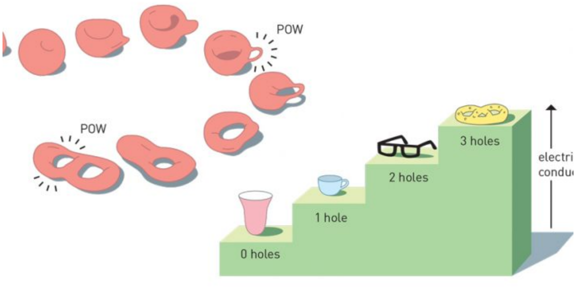


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

Impulsraum

- Chern

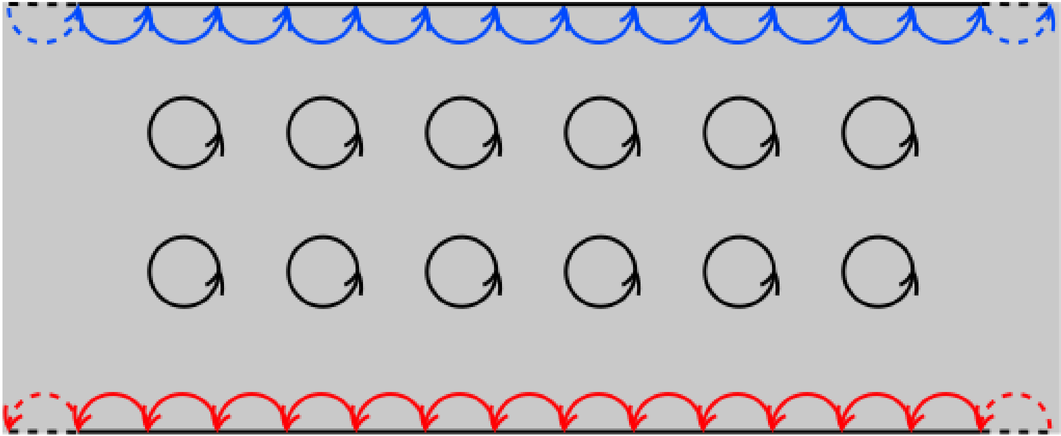
$$\int \mathrm{d}^2 k \begin{pmatrix}\text{Berry}\\ \text{Krüm-}\\ \text{mung}\end{pmatrix} = 2\pi \times \#\text{Chern}$$

- Zak

$$\oint \mathrm{d}k \begin{pmatrix}\text{Berry}\\ \text{connec-}\\ \text{tion}\end{pmatrix} = \text{Zak-Phase}$$

- Chern oder Zak $\neq 0$
  $\Longrightarrow$ topologisch geschützte Randzustände

Hall-Effekt



Was passiert, wenn man solch topologische Systeme mit dem Laser antreibt?

Was passiert, wenn man solch topologische Systeme mit dem Laser antreibt?

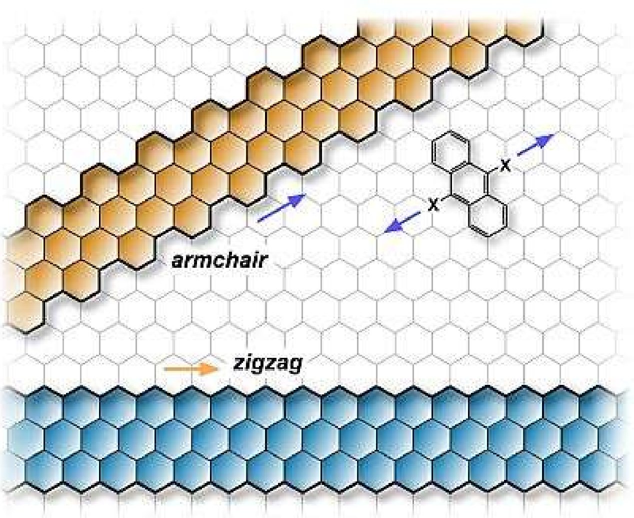
Wie bewegen sich die Teilchen?

Was passiert, wenn man solch topologische Systeme mit dem Laser antreibt?

Wie bewegen sich die Teilchen?

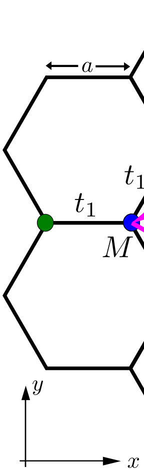
Welches Licht wird abgestrahlt?

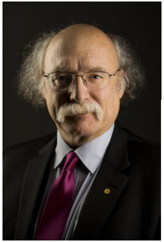
Paradebeispiel: “Graphenartige” Systeme

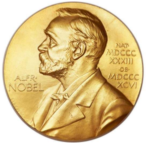


www.phys.org

Haldane model





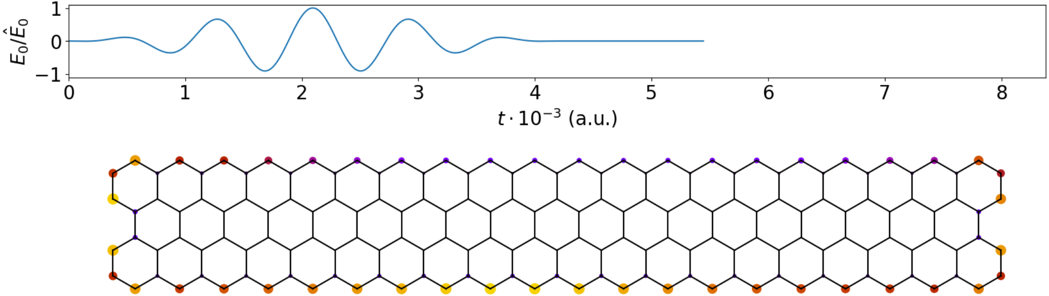


F. D. M. Haldane, Phys. Rev. Lett. 61, 2015 (1988)

A finite “Haldanite”-flake in a laser field

Lin. pol., $\omega = 0.0075$, $E_0 = 0.05\,\omega$, 5-cycle $\sin^2$, $t_1 = 0.1$, $M = 0.01$, $t_2 = 0.025i$

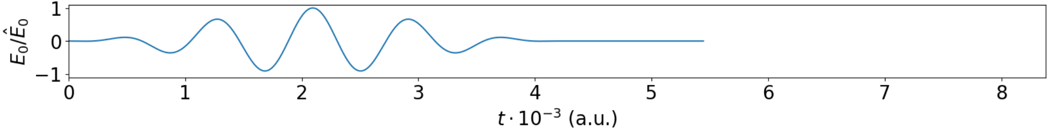
Tight-binding, highest occupied state (edge state)

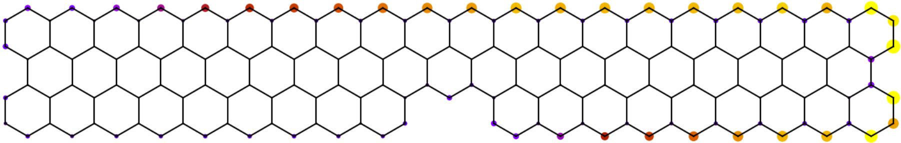


A finite perturbed “Haldanite”-flake in a laser field

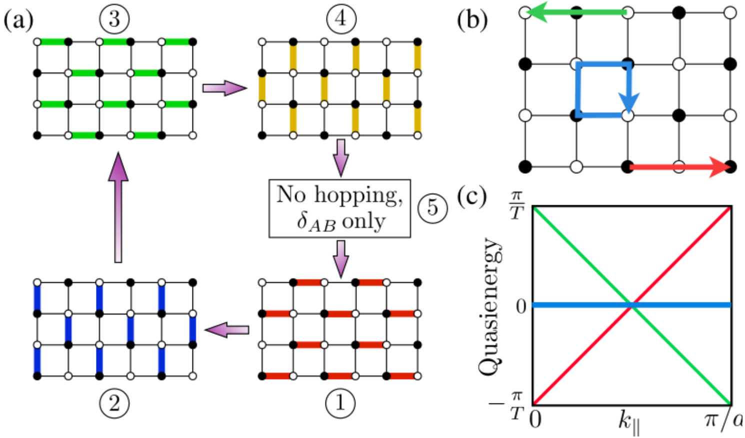
Lin. pol., $\omega = 0.0075$, $E_0 = 0.05\,\omega$, 5-cycle $\sin^2$, $t_1 = 0.1$, $M = 0.01$, $t_2 = 0.025\mathrm{i}$

Tight-binding, highest occupied state (edge state)





Kontrollierte Quantenmaterie durch "Floquet engineering"



Rudner *et al.*, Phys. Rev. X 3, 031005 (2013).

Can be implemented in optical waveguides or with cold atoms

Methodik

- **Analytische Modellierungen** (tight-binding, Semiklassik, Floquet)
- **Numerische Simulationen** (Lösen der zeitabhängigen Schrödinger-Gleichung)
- **Zusammenarbeit mit experimentellen Gruppen**

nature physics LETTERS
https://doi.org/10.1038/s41567-021-01275-3
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OPEN

Nonlinear second-order photonic topological insulators

Marco S. Kirsch[1,6], Yiqi Zhang[2,6], Mark Kremer[1], Lukas J. Maczewsky[1], Sergey K. Ivanov[3,4], Yaroslav V. Kartashov[3,5], Lluis Torner[5], Dieter Bauer[1], Alexander Szameit[1] ✉ and Matthias Heinrich[1]

Higher-order topological insulators are a novel topological phase beyond the framework of conventional bulk-boundary correspondence[1,2]. In these peculiar systems, the topologically non-trivial boundary modes are characterized by a co-dimension of at least two[3,4]. Despite several promising preliminary considerations regarding the impact of nonlinearity in such systems[5,6], the flourishing field of experimental higher-order topological insulator research has thus far been confined to the linear evolution of topological states. As such, the observation of the interplay between nonlinearity and the dynamics of higher-order topological phases in conservative systems remains elusive. Here we experimentally demonstrate nonlinear higher-order topological corner states. Our photonic platform enables us to observe nonlinear topological corner states as well as the formation of solitons in such topological structures. Our work paves the way towards the exploration of topological properties of matter in the nonlinear regime, and may herald a new class of compact devices that harnesses the intriguing features of topology in an on-demand fashion.

Despite a number of promising preliminary theoretical considerations[6,22,23], several experimental studies in dissipative HOTI systems[24–26], as well as the recently demonstrated potential of harnessing tightly localized HOTI corner states for the enhancement of nonlinear processes such as third-harmonic generation[27], there is only one experimental study at hand, where the evidence of switching into the HOTI phase under the nonlinear action of a homogeneous global pump was reported in electronic circuits[5]. Importantly, to date, research into the wave dynamics of photonic HOTIs in conservative optical systems has been confined to strictly linear conditions, and their extension in the presence of nonlinear self-action has yet to be explored. Yet, even these first glimpses into the nonlinear regime raise various intriguing fundamental questions. In particular, as the concept of band topology has thus far been considered to be inherently tied to linear systems, the generalization to nonlinear systems is by no means straightforward. Since topological properties can indeed persist in the presence of nonlinearity[28], and may even be established by it[29,30], does the same hold true for HOTIs?

In this work, we experimentally explore the nonlinear dynamics of light in photonic HOTIs based on the kagome geometry (Fig. 1b).

PHYSICAL REVIEW A 102, 053112 (2020)

Intense-laser-driven electron dynamics and high-order harmonic generation in solids including topological effects

Daniel Moos, Christoph Jürß, and Dieter Bauer
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(Received 24 July 2020; revised 30 October 2020; accepted 5 November 2020; published 23 November 2020)

A theory for laser-driven electron dynamics and high-harmonic generation in bulk solids with two lattice sites per unit cell of arbitrary dimension is formulated. In tight-binding approximation, such solids can be described by 2×2 Bloch Hamiltonians. Our theory is able to fully capture topological effects in high-harmonic generation by such systems because no simplifications beyond tight-binding, dipole approximation, and negligible depletion of the valence band are made. An explicit, analytical expression for the electron velocity is given. Exemplarily, the theory is applied to the Su-Schrieffer-Heeger chain and the Haldane model in strong laser fields.

DOI: 10.1103/PhysRevA.102.053112

PHYSICAL REVIEW LETTERS 120, 177401 (2018)

High-Harmonic Generation in Solids with and without Topological Edge States

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Institute of Physics, University of Rostock, 18051 Rostock, Germany
Kenneth K. Hansen
Department of Physics and Astronomy, Aarhus University, DK-8000, Denmark

(Received 12 November 2017; revised manuscript received 26 January 2018; published 24 April 2018)

High-harmonic generation in the two topological phases of a finite, one-dimensional, periodic structure is investigated using a self-consistent time-dependent density functional theory approach. For harmonic photon energies smaller than the band gap, the harmonic yield is found to differ by up to 14 orders of magnitude for the two topological phases. This giant topological effect is explained by the degree of destructive interference in the harmonic emission of all valence-band (and edge-state) electrons, which strongly depends on whether or not topological edge states are present. The combination of strong-field laser physics with topological condensed matter opens up new possibilities to electronically control strong-field-based light or particle sources or—conversely—to steer by all optical means topological electronics.

DOI: 10.1103/PhysRevLett.120.177401

RESEARCH

TOPOLOGICAL OPTICS

Nonlinearity-induced photonic topological insulator

Lukas J. Maczewsky[1], Matthias Heinrich[1], Mark Kremer[1], Sergey K. Ivanov[2,3], Max Ehrhardt[1], Franklin Martinez[1], Yaroslav V. Kartashov[3,4], Vladimir V. Konotop[5,6], Lluis Torner[4,7], Dieter Bauer[1], Alexander Szameit[1]*

A hallmark feature of topological insulators is robust edge transport that is impervious to scattering at defects and lattice disorder. We demonstrate a topological system, using a photonic platform, in which the existence of the topological phase is brought about by optical nonlinearity. The lattice structure remains topologically trivial in the linear regime, but as the optical power is increased above a certain power threshold, the system is driven into the topologically nontrivial regime. This transition is marked by the transient emergence of a protected unidirectional transport channel along the edge of the structure. Our work studies topological properties of matter in the nonlinear regime, providing a possible route for the development of compact devices that harness topological features in an on-demand fashion.

drive the system into a topologically nontrivial phase and promote the formation of nonlinear chiral edge states.

The underlying principle can be understood by considering two interacting waveguides that form a directional coupler (Fig. 1B). Whereas such a coupler composed of identical waveguides exhibits the characteristic sinusoidal intensity oscillation and the associated periodic full-power transfer between the waveguides, introducing a detuning between their effective refractive indices forces a certain fraction of light to remain in the initially excited guide at all times. In the linear regime, the maximum reached in the second waveguide therefore remains well below the total input power. However, when launching high-power light into the lower-index guide, a positive

PHYSICAL REVIEW A 99, 053402 (2019)

Robustness of topologically sensitive harmonic generation in laser-driven linear chains

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Institute of Physics, University of Rostock, 18051 Rostock, Germany

(Received 5 January 2019; published 1 May 2019)

A many-order-of-magnitude difference in the harmonic yield from the two topological phases of finite, dimerizing linear chains in laser fields has recently been observed in all-electron time-dependent density-functional simulations [Bauer and Hansen, Phys. Rev. Lett. **120**, 177401 (2018)]. In this work, we explore the robustness of the effect concerning the length of the chains, a continuous transition between the two topological phases, and disorder. A high robustness of both the degeneracy of the edge states in the topologically nontrivial phase as well as of the pronounced destructive interference, causing a dip in the harmonic spectra, in the topologically trivial phase is observed.

DOI: 10.1103/PhysRevA.99.053402

Eur. Phys. J. Spec. Top.
https://doi.org/10.1140/epjs/s11734-021-00188-9
THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS
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Regular Article

High-harmonic spectra of hexagonal nanoribbons from real-space time-dependent Schrödinger calculations

Helena Drüeke[a] and Dieter Bauer[b]
University of Rostock, Rostock, Germany

Received 18 January 2021 / Accepted 31 May 2021

Abstract High-harmonic spectroscopy is a promising candidate for imaging electronic structures and dynamics in condensed matter by all-optical means and with unprecedented temporal resolution. We investigate harmonic spectra from finite, hexagonal nanoribbons, such as graphene and hexagonal boron nitride, in armchair and zig-zag configuration. The symmetry of the system explains the existence and intensity of the emitted harmonics.

1 Introduction

High-harmonic generation (HHG) has been first observed in gases [1,2]. Its non-perturbative nature, featuring a plateau of almost constant high-harmonic yield, was subsequently explained by the three-step model [3,4]: An electron is removed from the atom, propagates under the external field's influence, and recombines with the atom. The orbital energies of electrons in atoms do not depend on momentum, and the electron's dispersion relation in the continuum is shaped parabolically. Therefore, electrons in the ground state or free electrons emit no harmonics. Only transitions between bound states or recombination from continuum states back to bound states lead to harmonic

laser light with graphene got into the focus of interest for its prospects to steer electrons at will on ultrafast time scales [21–24].

In this article, we investigate the harmonic spectra emitted by hexagonal nanoribbons in two different edge configurations, armchair (Sect. 3) and zig-zag (Sect. 4). We performed our calculations using a real-space time-dependent Schrödinger solver (as described in Sect. 2). The results of this publication validate the tight-binding approach in [25].

2 Methods

PHYSICAL REVIEW A 102, 043105 (2020)

Helicity flip of high-order harmonic photons in Haldane nanoribbons

Christoph Jürß and Dieter Bauer
Institute of Physics, University of Rostock, 18051 Rostock, Germany

(Received 29 June 2020; accepted 9 September 2020; published 13 October 2020)

Recent studies in high-harmonic spectroscopy of condensed matter mainly focused on the bulk of the system under consideration. In this work we investigate the response of thin, hexagonal nanoribbons to an intense laser pulse that is linearly polarized along the ribbon. Such nanoribbons are prime examples of two-dimensional systems that are bulklike in one direction and finite in the other direction. Despite the atomically thin scale in the direction perpendicular to the linearly polarized driving laser field, the emitted harmonics are elliptically polarized if an alternating onsite potential and Haldane hopping is taken into account. For given hoppings, we find a sudden change of the helicity for a certain harmonic order. The origin of this flip is traced back to phase differences between the components of Bloch states.

DOI: 10.1103/PhysRevA.102.043105

PHYSICAL REVIEW B 99, 195428 (2019)

High-harmonic generation in Su-Schrieffer-Heeger chains

Christoph Jürß and Dieter Bauer
Institute of Physics, University of Rostock, 18051 Rostock, Germany

(Received 11 February 2019; revised manuscript received 17 April 2019; published 15 May 2019)

Su-Schrieffer-Heeger (SSH) chains are the simplest model systems that display topological edge states. We calculate high-harmonic spectra of SSH chains that are coupled to an external laser field of a frequency much smaller than the band gap. We find huge differences between the harmonic yield for the two topological phases, similar to recent results obtained with more demanding time-dependent density functional calculations [D. Bauer and K. K. Hansen, Phys. Rev. Lett. **120**, 177401 (2018)]. This shows that the tight-binding SSH model captures the essential topological aspects of the laser-chain interaction (while higher harmonics involving higher bands or screening in the metal phase are absent). We study the robustness of the topological difference with respect to disorder, a continuous phase transition in position space, and on-site potentials. Further, we address the question of whether the edges need to be illuminated by the laser for the huge difference in the harmonic spectra to be present.

DOI: 10.1103/PhysRevB.99.195428

Eur. Phys. J. D (2021) 75:190
https://doi.org/10.1140/epjd/s10053-021-00201-9
THE EUROPEAN PHYSICAL JOURNAL D
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Regular Article - Ultraintense and Ultrashort Laser Fields

Edge-state influence on high-order harmonic generation in topological nanoribbons

Christoph Jürß[1,a] and Dieter Bauer[1,b]
[1] Institute of Physics, University of Rostock, 18051 Rostock, Germany

Received 26 March 2021 / Accepted 14 June 2021 / Published online 29 June 2021

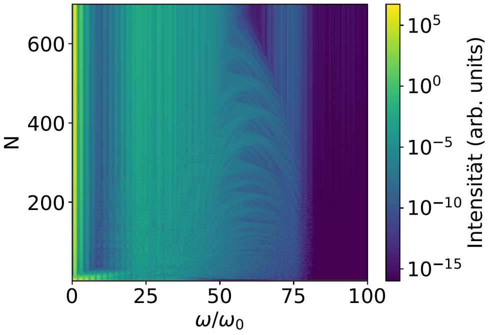
Abstract. The high-order harmonic generation in finite topological nanoribbons is investigated using a tight-binding approximation. The narrow, two-dimensional ribbons consist of hexagonal structures. A topological phase transition is defined by a sudden change of the topological invariant. In the bulk, this kind of phase transition might occur if an existing band gap closes and reopens again. Through the bulk-boundary correspondence, this is related to the emergence of topologically protected edge states in the respective finite systems. For the finite ribbons studied in this work, the variation of the tight-binding parameters leads to the emergence of two edge states after the closing of the band gap. The energies of those edge states as functions of the tight-binding parameters display crossings and avoided crossings, which influence the high-harmonic spectra.

1 Introduction

atomic elements such as in hexagonal boron nitride (h-BN), for instance,

Interferenzeffekte bei Hoher-Harmonischen-Erzeugung in Su-Schrieffer-Heeger-Ketten

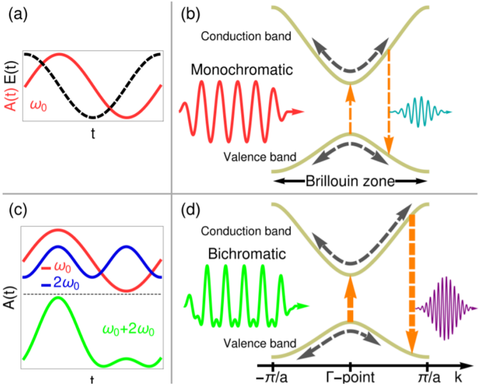
- In HHG-Spektren von SSH-Ketten zeigen sich — abhängig von der Länge der Ketten — Interferenzstrukturen
- Welche Zustände sind dafür verantwortlich? Erklärung mittels Bandstruktur?
- Im Idealfall analytische Erklärung möglich
- Numerikanteil: 50–80%
- Betreuung: Christoph Jürß



Vincent Burgtorf, Bachelorarbeit 2020

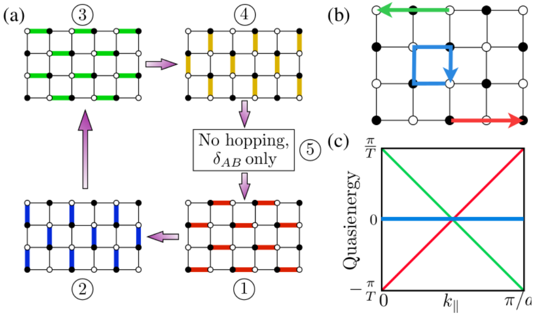
Two-color high-harmonic generation in doped semiconductors

- Understand the electronic properties of semi-conductors with and without impurities
- Understand electronic motion in two-color laser pulses
- Calculate HHG and study the effect of the impurities and the two colors
- Code available, can be modified; writing code from scratch is also possible
- Numerics: $\geq$ 70%
- Supervision: Francisco Navarrete



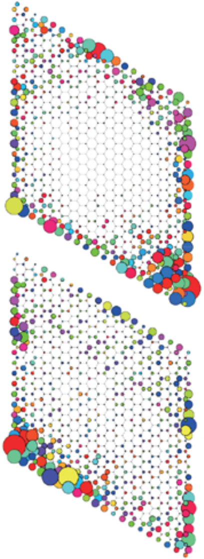
Quantendynamik von wechselwirkenden Teilchen in Floquet-topologischen Isolatoren

- Floquet-System wie in Rudner *et al.*, Phys. Rev. X 3, 031005 (2013), aber mit zwei wechselwirkenden Teilchen
- Analyse der Zustände und deren Abhängigkeit von der Art der Wechselwirkung
- Giebt es immer noch topologisch geschützten Transport?
- Numerikanteil: $\geq$ 50%
- Betreuung: Helena Drüeke



Der Bott-Index als topologische Invariante

- Chern number definiert für Bänder
- Topologische Invariante für endliche oder ungeordnete Systeme?
- Aus der Mathematik: Bott-Index
- Verstehe die zugrundeliegende Theorie und berechne den Bott-Index für physikalisch relevante Systeme
- Numerikanteil: 20%
- Betreuung: Dieter Bauer



Wang et al., Phys. Rev. Lett. 125, 217202

Weitere Informationen

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