# Study on quantum optical phenomena of graphene under the high-intensity magnetic field drive

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**Abstract.** Driven by the high-intensity magnetic field, graphene demonstrate special optical properties, which have become an important research issue in the field of quantum optics. This paper studies the graphene quantum optical phenomena under the high-intensity magnetic field drive. First, the energy band structure of graphene in a high-intensity magnetic field is analyzed. Second, optical phenomena, including coherent optical phenomena and nonlinear optical phenomena, of graphene driven by the high-intensity magnetic field are examined. Finally, several realization approaches are put forward.

## 1 Introduction

Graphene is an allotrope of carbon in the form of a two-dimensional, atomic-scale, hexagonal lattice in which one atom forms each vertex. After, Geim et al. successfully prepared the monolayer graphene, research of two-dimensional materials represented by graphene has drawn wide attention from the academic field. Many scholars have observed unique optical properties and electronic properties of graphene in a high-intensity magnetic field. Its structure is similar to the heterostructure of the quantum well, and its trapezoid energy band structure can realize interaction between light and other materials. Therefore, graphene is a photoelectric material with huge potential.

## 2 Graphene energy band structure under the high-intensity magnetic field drive

2.1 Graphene energy band structure

The monolayer graphene materials have a hexagonal lattice structure. Their electronic energy band, when driven by the high-intensity magnetic field, changes. When a high-intensity magnetic field passes through graphene, the continuous energy band starts splitting to form the discrete-state Landau energy level structure. A "4×4" matrix can be used to represent its Hamiltonian. To solve the Hamiltonian, the coupling effect between K and K' is ignored. The equation, H0Ψ=δΨ, is adopted to solve the function. In essence, Hamiltonian is the wave vector representing the quantum number in the n and y direction. The coefficient is Cn, and the magnetic field is l. The self-energy and frequency can be obtained through calculation. The quantum number is set to be an integer, namely n=±1, ±2, … The negative and positive value is corresponding to the electron or electron hole. Before the high-intensity magnetic field drive is imposed, the graphene Landau energy level is reflected as the linear electronic dispersion relation. After imposing of the high-intensity magnetic field drive, the neighboring Landau energy level undergoes transition, and the frequency is located within the frequency band between the intermediate infrared and the THz [1].

2.2 In-band transition selection rule

When a typical optical field enters the discrete energy level, graphene and the optical field interact with each other. The vector potential is added to the momentum operator, π, to obtain the Hamiltonian reflecting the interaction between the optical field and the material. In other words, Hint=vFσ$\frac{e}{c}$Aopt. The Hamiltonian and the vector potential are in direct proportion to each other. Therefore, graphene possess the linear dispersion relation, but Hamiltonian does not rely on the momentum operator, and

is linearly correlated with the Pauli operator. Thus, the Landau energy level optical transition in the graphene system can be represented using quantum mechanics. Since the wave function, $\varphi_n$, features a complete orthogonal function system, only when |ni|-1=|nj| or |ni|=|nj|-1, its optical transition formula has the untrivial solution. Therefore, the in-band transition selection rule can be written as $\triangle$|n|=±1, where the levorotation polarized optical transition is $\triangle$|n|=+1 and the dextrorotation polarized optical transition is $\triangle$|n|=-1 [2].

## 3 Quantum optical phenomena of graphene under the high-intensity magnetic field drive

3.1 Coherent optical phenomena

The coherent optical phenomenon is the outcome of the magnetic field interacting with certain material. It is a research focus of quantum optics. The coherent optical phenomenon is usually accompanied by the quantum interference. Take the electromagnetic induced transparency for example. The characteristics of the coherent optical phenomenon is shown in Table 1.

Table 1. Characteristics of the electromagnetic induced transparency

| Phenomenon | Abbreviation | Characteristics | Generation medium |
|---|---|---|---|
| Electromagnetic induced transparency | EIT | A coherent optical phenomenon, optical group velocity slow-down and no flip laser | Atoms and semiconductor materials |

Relevant research suggests that the Landau energy level graphene in the discrete state can also generate similar coherent optical phenomena. Besides, its optical devices and applications have a greater advantage. This helps usher in a new approach for optical research of two-dimensional materials. At present, the pulse coherent control and the Terahertz test are primarily adopted to examine the coherent optical effects.

(1) Terahertz test

Terahertz or THz is located at a special position of the electromagnetic spectrum, so it demonstrates many unique characteristics. See Table 2.

Table 2. Unique characteristics of Terahertz frequency band

| Frequency band | Characteristics | Limitations | Applications |
|---|---|---|---|
| THz | Perceptivity, safety, instantaneity, and broadband | Easy to be absorbed by the atmospheric water molecules | Lay a solid foundation for application of the THz technology to graphene materials. |

Driven by a high-intensity magnetic field, graphene materials will develop the energy-band structure of the THz frequency band. Therefore, the THz technology can be applied to the graphene material research. However, the THz technology is different from the traditional THz technology in that the latter mainly makes use of the low-frequency oscillator for frequency conversion and nonlinear frequency doubling, but application of the THz technology to graphene material detection is based on quantum interference. The destructive interference of the quantum can be utilized to generate different optical phenomena.

The weak probe field and the strong THz field vertically enter the graphene materials, respectively, to build an in-band transition path and to form an interactive environment between the light field and the material. The path is similar to the three-level energy position, and can generate the electromagnetic induced transparency (EIT). By solving the steady-state density matrix function, the system polarizability can be obtained. The propagation law of the probe field in the graphene medium adheres to the Maxwell equation. In the probe field transmission spectrum, if the THz field does not

exist, the optical resonance happens and gets absorbed. Under the strong THz field effect, narrow, transparent windows appear between the absorption peaks. This is because the graphene in-band transition causes quantum interference of the transition path. Consequently, the probe field is not absorbed, but passes through the graphene materials. Therefore, the probe field can be adopted to analyze whether the THz field exists.

(2) Impulse coherent control

The impulse coherent control is a method of quantum optics. It makes use of a beam of the control field impulse to adjust the probe field impulse accordingly. Adoption of this method can help realize controlling light with light and creating an all-optical switch. Advantages and characteristics of the all-optical switch are presented in Table 3.

Table 3. Advantages and characteristics of the all-optical switch

| Type | Advantages | Characteristics | Applications |
|---|---|---|---|
| All-optical switch | Resolve defects with the electronic switch in terms of the broadband limitation, high power consumption and crosstalk. | Stable and super-fast. | Research of atoms, semiconductors and optical fiber materials. |

Harris et al. first proposed the all-optical switch realization plan in the four-energy-level atom system. Yan et al. proved feasibility of the plan by putting it into practice. Besides, Wu et al. discussed the all-optical switch realization plan in the heterostructure of the solid quantum well using the Fano interference effect. In this paper, an all-optical switch realization plan featuring impulse two-way control and a three-energy-level graphene energy-band structure is put forth. The strong coupling effect between THz and Landau energy level is employed to regulate the medium's absorption of the probe field via adjustment of the impulse intensity and exchange of the interference position between the THz field and the probing field. The square-wave pulse is used to simulate the process to realize switching of the THz field and the probe field along with passage of time.

3.2 Nonlinear optical phenomenon

As a major branch of nonlinear physics, nonlinear optics mainly studies changing rules of the dielectric polarization along with the optical field frequency, amplitude and phase. Table 4 shows the content and applications of the nonlinear optical effect.

Table 4. Research content of nonlinear optics

| Effect | Subject category | Major content | Applications |
|---|---|---|---|
| Nonlinear optical effect | Nonlinear physics | Optical solitons, enhanced nonlinearity, mixing process, excited Raman scattering, etc. | Laser technology, optical communication, electronic instrument, etc. |

Scholars committed to studying nonlinear optical effects have been long searching a steady solid-state nonlinear material nonlinear optical effect research. The special photoelectric properties of graphene have a great potential to tap in terms of their applications. The main nonlinear optical effects of graphene are presented in Table 5.

Table 5. Several nonlinear effects of graphene

| Nonlinear optical effects | Properties & Characteristics | Role of graphene & Realization path |
|---|---|---|
| Enhanced optical nonlinearity | Graphene not driven by a high-intensity magnetic field possesses nonlinear optical properties, and can provide a stronger optical nonlinearity. | Make use of the third-order mixed frequency effect signal intensity to measure degree of nonlinearity. |
| Optical solitons | A special optical impulse, whose velocity, shape, and amplitude can maintain the same in the nonlinear medium. | Monolayer graphene supports the spatial optical soliton propagation. |
| Four-wave mixing | Interaction between the nonlinear medium and the three beams of different frequencies generate the fourth coherent propagation. | The maximal efficiency of the four-wave mixing in the graphene system far exceeds the mixed frequency efficiency of other systems, and has a strong adjustability. |
| Super-Raman scattering | Inelastic scattering generated by atomic and molecular vibration and rotation. | The EIT and the Raman scattering in the graphene system compete with each other. The EIT can be employed to control Raman scattering. |

## 4 Conclusions

To sum up, graphene materials show favorable electronic properties and optical properties. To study their quantum optical phenomena under the high-intensity magnetic field drive can help associate the quantum optical phenomena with the nonlinear optical phenomena, thus providing broader application prospects for graphene materials. This research can also inspire further applications of the coherent optical and nonlinear optical phenomena of graphene materials.

## References

[1] Poumirol J M, Liu P Q, Slipchenko T M, et al. Electrically controlled terahertz magneto-optical phenomena in continuous and patterned graphene.[J]. Nature Communications, 2017, 8:14626.

[2] Thomas A G R, Ridgers C P, Bulanov S S, et al. Strong Radiation-Damping Effects in a Gamma-Ray Source Generated by the Interaction of a High-Intensity Laser with a Wakefield-Accelerated Electron Beam[J]. Physical Review X, 2012, 2(4):3209-3219.

[3] Lima C P, Lima F M S, Fonseca A L A, et al. Magnetic field effect on the laser-driven density of states for electrons in a cylindrical quantum wire: transition from one-dimensional to zero-dimensional behavior[J]. New Journal of Physics, 2011, 13(7):073005.

[4] Borisova T D, Blagoveshchenskaya N F, Kalishin A S, et al. Phenomena in the High-Latitude Ionospheric F, Region Induced by a HF Heater Wave at Frequencies Near the Fourth Electron Gyroharmonic[J]. Radiophysics & Quantum Electronics, 2014, 57(1):1-19.