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学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称 博士（工学） 氏名 望月 健

学 位 論 文 題 名

Topological Phenomena in Quantum Walks owing to Peculiarity of Floquet and/or Open Systems
(フロケ系や開放系に特有の性質に起因する量子ウォークのトポロジカルな現象)

Exploration of topological phases has made significant progress in the research field of condensed matter physics. Energy band structures of systems are characterized by integers called topological numbers, and phases with the non-zero topological numbers are referred to as nontrivial topological phases. Topological features persist in various physical settings irrespective of details of the systems, since only symmetries and dimensions have effects on whether non-trivial topological phases can exist or not. The topology of energy band structures results in emergence of topologically protected edge states which localize at boundaries of systems, which is referred to as the bulk-edge correspondence. From the viewpoint of topological phases and bulk-edge correspondence, known phenomena have been re-interpreted and novel phenomena have been predicted theoretically. For instances, the integer quantum hall effect was interpreted in terms of a non-trivial topological phase characterized by the Chern number and resulting chiral edge states, and theoretical work on topological phases characterized by binary numbers led to the discovery of topological insulators with helical edge states.

While physics of symmetry protected topological phases was firstly explored in electronic systems historically as mentioned above, the concept can be applied to photonic systems. A quantum walk is one of such photonic systems in which non-trivial topological phases can emerge. Quantum walks have advantages for exploring topological phases in comparison to electronic systems, that symmetries and topological numbers are easily manipulated and real-space observation of topologically protected edge states is possible. Owing to these features, various topological phases and resulting edge states of quantum walks have been explored. Quantum walks are often referred to as simulators of topological phases in electronic systems, since many topological phases of gapped energy bands in quantum walks can be understood from the analogy to electronic systems described by time-independent Hamiltonians. However, abilities of such simulations of topological phenomena by quantum walks are much inferior to usual computers. While simulating or mimicing topological phases of electronic systems in photonic systems may lead to useful optical devices, such studies do not generate theoretically novel results. Then, what is the meaning of studying topological phases in quantum walks? The answer is that exploration of topological phenomena peculiar to quantum walks only has significance, without analogy to conventional electronic systems. In order to study topological phenomena unique to quantum walks, we focus on the following three distinct features of quantum walks from conventional electronic systems and/or other photonic systems. First, gain-loss effects of light can be manipulated in quantum walks. Since the intensity of light is not conserved in such dynamics, novel phenomena can occur without analogy to closed systems. Second, nonlinear effects can be induced in quantum walks based on the feed-forward controls using loss effects of light. The nonlinear effects affect the dynamics

of quantum walks and can cause peculiar phenomena. Third, quantum walks have discrete periodicity in time direction. Such systems which are called periodically driven system (Floquet systems) should have distinct features from static systems due to the periodicity. In this doctoral thesis, we clarify novel topological phenomena stemming from these peculiar features; gain-loss effect of light, nonlinearity, and discrete periodicity in time direction.

Chapters 1, 2, and 3 are devoted to introduction of basic knowledge and backgrounds about topological phases and quantum walks. In Chap. 1, we give an introduction and motivations of this doctoral thesis. In Chap. 2, we explain topological phases of static systems, focusing on the winding number which is a kind of topological numbers. In Chap. 3, we give the explanation on how to describe the dynamics and topological phases of quantum walks. Main results of our work are presented in Chaps. 4, 5, and 6.

In Chap. 4, derivation of topological numbers and confirmation of the bulk-edge correspondence are given in chiral symmetric open Floquet systems. While topological numbers in closed Floquet systems were well known, there were no adequate discussion on topological numbers in open Floquet systems. However, a formula for topological numbers had been used in open Floquet systems, without microscopic foundation. Then, we derive topological numbers in open Floquet systems based on chiral symmetry. In addition, using the derived formula, the bulk-edge correspondence is confirmed in a photonic quantum walk with gain and/or loss. Our work gives the microscopic foundation of the topological numbers for the first time, which had been used in open Floquet systems.

In Chap. 5, it is clarified that discrete periodicity in time can lead to novel bifurcations in nonlinear Floquet systems. In a nonlinear quantum walk, it was expected that a topological edge state always becomes a stable attractor. However, discrete periodicity in time was ignored, which is a unique feature of quantum walks. We explore effects of such uniqueness on the stability of edge states in nonlinear quantum walks. As a result, it is found that edge states can be unstable due to discrete periodicity in time. Moreover, based on discussions about spectral radius and spectral norm, bifurcation points are obtained analytically, which is generally difficult in other nonlinear systems. Our analytical procedure can be applied to general Floquet nonlinear systems.

In Chap. 6, we discuss non-trivial topological phases protected by a unique symmetry to Floquet systems. In 2017, symmetry peculiar to Floquet systems was proposed, which is called time-glide symmetry. We find that quantum walks can have topological phases protected by time-glide symmetry. This is done by obtaining topological numbers which originate from time-glide symmetry and constructing a concrete model in which non-trivial topological phases exist. In addition, how to detect topological edge states in experiments is discussed. In the model, there also appear flat bands owing to chiral symmetry, which is firstly discussed in quantum walks by our work.

Chapter 7 gives the significance and outlook of our work, about peculiar topological phenomena in quantum walks, which stem from gain-loss effects, nonlinearity, and/or discrete periodicity in time.