論 文 の 内 容 の 要 旨

論文題目　　Study on the cavity optomagnonics
（共振器オプトマグノニクスの研究）

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Enhancement of interaction between light and matter has been intensely studied using optical cavities, in which the light field is build up more than thousands of times. For example, an atom inside a microwave Fabry-Perot resonator is controlled by the cavity photons in a quantum regime, which flourished as a cavity quantum electrodynamics [1]. By using a solid-state artificial atom, the dispersive quantum bit readout has been implemented using a resonator [2]. High-quality optical resonators have also enabled researchers to manipulate mechanical motions of an object involved in them, which is the activity called the cavity optomechanics [3]. These have enabled the coherent control over the internal states of the atoms and the vibration quanta of the mechanical oscillator, leading to the realization of the material-based quantum information and communication technologies. Here we introduce another object, the macroscopic spin excitation or magnon, as an object to be optically controlled. Since the realization of the strong coupling between a superconducting qubit and a uniform magnon [4], the optical control of the magnon is also of certain interest in the scope of the construction of the quantum network.

In general, the interaction between light and magnon in a material is weak due to the fact that the interaction is mediated by the spin-orbit interaction of electrons in a material. Therefore, the relatively strong electromagnetic field is required to observe the interaction. For instance, the magnon-induced Brillouin scattering has been studied using ultrashort, intense optical pulses [5,6]. As an alternative way to enhance the magnon-light interaction, we propose to use an optical cavity. In particular, optical whispering gallery modes (WGMs) hosted in an axially symmetric sample is used, which have favorable features of a high quality factor and a small mode volume. Study on the Brillouin scattering of light in the WGMs by magnons, which we call cavity optomagnonics, is a new system involving light and magnon, and will serve as a new platform for chiral photonics, opto-spintronics and opto-magnonics.

We implement such a system by a sphere made of single-crystal yttrium iron garnet (YIG) which is a ferrimagnetic insulator transparent for 1.5 μm-wavelength light. The magnetostatic modes in a YIG sphere, the Walker modes, are well known as being long-lived. On the other hand, the WGMs in a ferromagnetic sphere have not been observed. The WGMs in a YIG sphere with diameter of around 1 mm are for the first time observed in this study. The Brillouin scattering of WGM light by the uniform magnon mode, the Kittel mode, is revealed to show rich behaviors such as the Stokes/anti-Stokes scattering asymmetry and the nonreciprocity. These behaviors are explained by the unique polarization property of WGMs. The Brillouin scattering is further investigated by varying the applied magnetic field, where we found the strong modification of the scattering strength owing to the densities of states of the WGMs. The Brillouin scatterings by the general, non-uniform Walker modes are also observed, and show nontrivial behavior due to the coupling among other Walker modes. A theoretical treatment of the Brillouin scatterings involving WGMs and some families of the Walker modes is developed and compared with the experiments. We find that in the cavity optomagnonics, the spin and orbital angular momentum conservation are the key features.

We now elaborate on the details of the research mentioned above. First, the WGMs in a YIG sphere are investigated for the first time. The experimental apparatuses for coupling light into WGMs in a YIG sphere via a tapered optical nanofiber, as well as a silicon prism are designed and constructed. The former shows a large coupling but also some difficulty in determining the polarization coupled to WGM. The latter is inferior in terms of the coupling to WGMs, however, the ambiguity of the coupled polarization is removed. The observed spectra for two different polarizations exhibit the intrinsic frequency shift due to the geometrical birefringence. The observed frequency shift and the free spectral range are in agreement with the theoretical prediction. In addition, from the theoretical perspective, we analyze the polarization of WGMs which depends on the position and the circulation direction. Orbital angular momenta of the WGMs are also considered, which, together with the polarization properties, are revealed to be crucial in studying the Brillouin scattering

Next, we examine the Walker modes in a YIG sphere by sending microwaves to a loop coil near the sphere and measure the reflected power. Walker-mode frequencies depending on the static magnetic field strength for the cases of the relatively homogeneous and inhomogeneous magnetic fields applied respectively by cylindrical and ring-shaped magnets. It is found that even in the case of the inhomogeneous magnetic field with ring-shaped magnets, several observed Walker modes can be identified in comparison to the case of the homogeneous field produced by the cylindrical magnets. For the analysis of the Brillouin scattering, the orbital angular momenta of Walker modes, which is to be conserved together with those of WGMs, are important but have not explicitly given so far. We extracted them from the well-known expressions of the transverse magnetization distributions of the Walker modes.

We then study the Brillouin scattering of WGMs by Walker mode. We first focus on the Kittel mode, the uniform magnon mode which does not possess orbital angular momentum. In the Brillouin scattering of WGM by the Kittel mode, the pronounced nonreciprocity and the Stokes/anti-Stokes scattering asymmetry are observed and interpreted in terms of the spin and orbital angular momentum conservation. The variation of the scattering strength is observed by changing the Kittel-mode frequency using an electromagnetic coil and the maximum is found when the density of states of the WGM fully supports the scattered light.

With these series of experiments, a theory of the Brillouin scattering of light in WGMs by Walker modes including the Kittel mode is constructed. According to the theoretical framework, the general, non-uniform Walker modes show different conditions on the scattering process. The differences arise from the finite orbital angular momentum of the Walker mode. We attempt to experimentally observe the difference of the behavior of the Brillouin scattering caused by various Walker modes. In general, the experimentally observed behavior does not simply agree with the theory, probably due to the coupling among various Walker modes. For a specific Walker mode, the nonreciprocal nature of the Brillouin scattering is present but significantly different from the one by the Kittel mode. This is, however, qualitatively consistent with the theory we developed.

In conclusion, we investigated the system of cavity optomagnonics, where the Brillouin scattering interconnects the WGMs and Walker modes hosted inside a YIG sphere. We developed a theory of the Brillouin scattering involving WGMs and Walker modes, which imposes spin and orbital angular momentum conservation on the system. For the Kittel mode, the nonreciprocity, the Stokes/anti-Stokes asymmetry and the scattering strength depending on the magnetic field were observed as consequences of the angular momentum conservation and the presence of the optical WGM resonances. For higher-order Walker modes, the coupling among Walker modes makes the behavior so rich that the theory cannot be simply applied, whereas the mode seemingly not so much affected by others shows qualitatively consistent behavior with the theory. For the latter, the orbital angular momentum conservation is observed.

This system will be further investigated for the higher-order Walker modes aiming at enhancing the Brillouin scattering of light in WGMs. Among other modes the surface spin wave modes are expected to have stronger light-magnon interaction due to smaller mode volume, which may lead to the quantum-level, optical control of the magnon. Our work will be a nexus between quantum optics and spintronics and open up a new testbed for the research such as the chiral photonics, opto-spintronics and optomagnonics.

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