**Abstract of Doctoral Dissertation**

# Non-reciprocity of magnon excitations in non-centrosymmetric magnets

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Macroscopic responses observed in solids have always been supported by the symmetry breaking in a state of matter. For example, piezoelectricity and natural optical activity emerge in spatial-inversion symmetry (SIS) broken materials. Time- reversal symmetry (TRS) breaking induces the Hall effect and Faraday effect. It turned out recently that there is a class of systems that require the breaking of both SIS and TRS in materials. The breakthrough is provided by the discovery of the magnetically induced ferroelectrics (multiferroics). Several developments followed such as magnetoelectric effect, a variation of the magnetization induced by the electric field and the electric polarization controlled by the magnetic field. The breaking of both SIS and TRS also affects the dynamics of elementary excitations; the energy and decay rate of wave vector $+k$ become not equivalent to those of $-k$. This phenomenon is non-reciprocity. The non-reciprocity is nontrivial, because the origin is intrinsic interactions appearing only in both SIS and TRS broken materials such as the spin-orbit interaction. This thesis is devoted to the non-reciprocal phenomena relevant to magnon excitation.

We have demonstrated the non-reciprocity of the microwave and the magnon propagations in the non-centrosymmetric magnets. We have obtained the new knowledge about the non-reciprocal microwave response related to magnon excitations as follows.

1. Magnon non-reciprocally propagates along the magnetization in a bulk ferromagnet with chiral crystal structure. This non-reciprocity can be explained by the asymmetric magnon dispersion owing to the Dzyaloshinskii-Moriya interaction which is only finite in the system with simultaneous breaking of time-reversal symmetry and space-inversion symmetry.
2. The non-reciprocity derived from the Dzyaloshinskii-Moriya interaction in a chiral ferromagnet is clearly discriminated from the non-reciprocities originated from the Damon-Eshbach mode. This is because the former propagates parallel to the direction of the magnetic field, whereas the latter propagates perpendicular to the direction of the magnetic field.
3. The multiferroic helimagnet $Ba_2Mg_2Fe_{12}O_{22}$ has the conical magnon excitation in the microwave region. In the microwave region, the type-II multiferroics $Ba_2Mg_2Fe_{12}O_{22}$ shows the optical magnetoelectric effect. In addition, the amplitude and the sign of the non-reciprocity of microwave can be controlled by the poling electric field.
4. The multiferroic antiferromagnet $Ba_2MnGe_2O_7$ has the conventional antiferromagnetic magnon modes with easy plane anisotropy in the microwave region. The fitting of experimentally observed magnetic field dependence of these modes to the theoretical equation provides the exchange interaction constant and the magnetic anisotropy of $Ba_2MnGe_2O_7$. We observed the microwave non-reciprocity of one of the magnon modes. The microwave non-reciprocity is quantitatively explained by using the spin wave theory, the Kubo formula, and the metal ligand hybridization mechanism.