Development of polariton-based PT symmetric laser that converts loss into gain

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We have successfully developed a parity-time reversal symmetry (PT symmetry) laser using highly interactive quantum particles in a regular hexagonal semiconductor rod structure and found that improvement of luminous performance as loss increases. To this end, the interaction between the different modes in a single hexagonal microcavity is directly controlled by using exciton-polaritons, which has a high interaction unlike light. In a single resonator with hexagonal symmetry, two optical modes with the same energy and paths in the form of upward and downward triangles exist without interaction. By using exciton-polaritons instead of light, however, direct interaction between the two modes is possible through excitons. Of these, only the downward triangular mode was combined with a substrate grooved in the shape of a bow tie so that the amount of loss could be continuously adjusted. Through this, the unusual result that the energy required for operation becomes smaller as the loss increases was observed at room temperature and the cause was systematically investigated. This is a counterintuitive result that the energy required for operation increases as the loss is greater. It overcomes the complexity and limitations of the existing PT symmetric system using light and uses only a single semiconductor microcavity to develop a PT symmetric laser based on polariton system for the first time. The PT symmetric laser developed through this research is expected to be widely used for high-efficiency laser devices and quantum optical devices.

1. Background (objectives)

In any physical system, loss has been recognized as an object that should be minimized or eliminated. For example, if there is loss in a laser system that requires gain, the threshold energy required for operation increases, so the loss should be reduced as much as possible. However, if the concept of parity-time reversal (PT) symmetry and breaking existing in quantum mechanics is applied to photonic systems through mathematical similarity, a unique photonic system that can use losses in a beneficial direction for operation becomes possible.
In order to implement a PT symmetric system based on only photons, the following strict conditions must be satisfied. Since photons basically do not interact with each other, two or more spatially separated photonic components must be fabricated to mediate the coupling. In this case, in order to match the eigenenergy, two structures must be identically fabricated without error, and a complex control process is required in which loss and gain are individually adjusted for each photonic component.
On the other hand, if suitable conditions are established for photons to stay for a long time in a direct-bandgap semiconductor rather than in a vacuum or a dielectric, exciton-polaritons which has the characteristics of both excitons and photons can be created. The exciton-polaritons can interact with each other due to the material properties of the exciton, and the Bose-Einstein condensation can be realized. The exciton-polariton formation temperature is determined by the exciton binding energy, and since excitons are easily dissociated by thermal energy in most semiconductor materials, a cryogenic experimental environment was an essential element. However, in the case of group III-nitride semiconductors, since the exciton binding energy is greater than the thermal energy at room temperature, the exciton-polaritons can be stably formed even at room temperature.

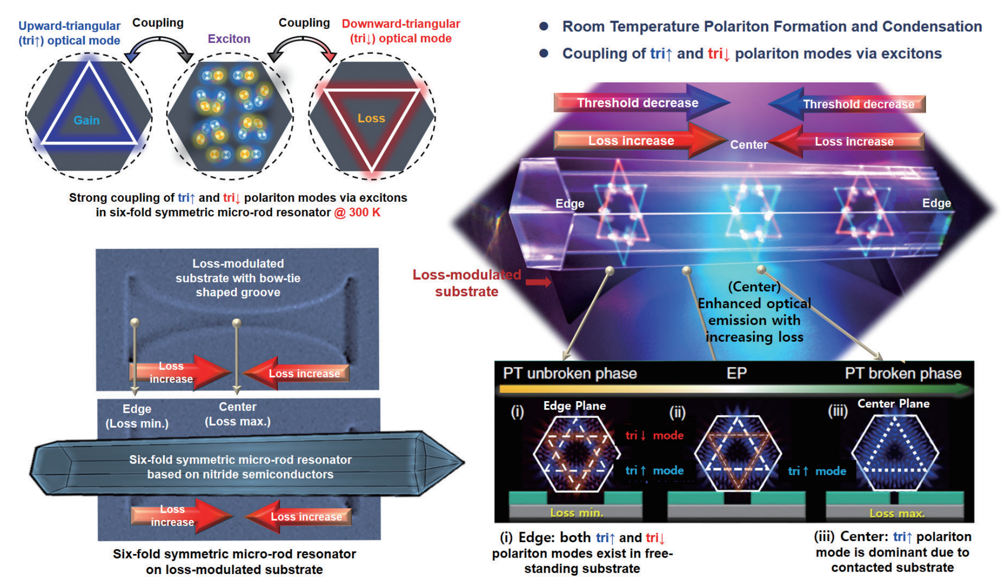
2. Contents

In this work, we used the exciton-polaritons that can interact with each other unlike the conventional PT symmetric systems using non-interacting photons, and we devised a unique method to directly control the interaction between the different degenerate eigenmodes within a single hexagonal microrod resonator.
If nitride semiconductors having a hexagonal (Wurtzite) crystal structure are used, a microrod structure having a cross-section having regular hexagonal symmetry can be grown. In the resonator having a six-fold hexagonal cross-section, two eigenmodes with the same energy, i.e., upward and downward triangular optical modes, exist inside the resonator without interaction. When exciton-polaritons are formed in the hexagonal microrod structure made of nitride semiconductors, we anticipated that direct interaction between the two triangular modes would be possible through excitons.
The hexagonal microrod resonator was placed on a loss-modulated substrate with a bow-tie shaped groove, so that the degree of loss can be continuously adjusted only for the downward triangular mode without affecting the upward triangular mode. The unusual result that the threshold energy required for the Bose-Einstein condensation becomes smaller as the lose caused by the substrate increases was observed at room temperature and the origin was systematically investigated.

3. Expected effect

This is a result contrary to the general intuition that the energy required for operation increases as the loss is greater. Our result overcomes the complexity and limitations of the existing PT symmetric system using only photons, and is meaningful to implement the PT symmetric system using exciton-polaritons with only single micro resonator. A system to which such PT symmetry is applied provides an important platform that makes it possible to use loss to gain as a result. It can be applied not only to photonic devices such as optical sensors, but also to new concept devices such as irreversible devices that can control the direction of light or superfluid-based integrated circuit quantum photonic devices.

Figure.
Polariton-Based PT Symmetric System in a Single Microrod Resonator



Research outcomes

Paper "Room-temperature polaritonic non-Hermitian system with single microcavity", H. G. Song, M. Choi, K. Y. Woo, C. H. Park, and Y. H. Cho*, Nature Photonics 15, 582 (2021). [Impact Factor = 38.771]- Introduced in Phys.org, K-Light (Optical Society of Korea), Physics and Advanced Technology (The Korean Physical Society), etc.

"Tailoring the potential landscape of room-temperature single-mode whispering gallery polariton condensate", H. G. Song, S. Choi, C. H. Park, S. H. Gong, C. Lee, M. S. Kwon, D. G. Choi, K. Y. Woo, and Y. H. Cho*, Optica 6, 1313 (2019). [IF = 11.104]

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