Topology optimization of dielectric ring resonators in application on laser resonators and optical sensors

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Abstract

Micro-ring resonators have tremendous potential in optics with applications to low threshold microcavity lasers and optical sensors. The optical modes, set up in these devices by emissions from input light, form circular continuous closed beams governed by internal reflections along the boundary of the resonator. The circular mode shape is called a whispering-gallery (WG) mode. Optical resonators exploiting WG modes have been attaining high levels in the important typical-performance criteria for resonators, that is, high Q factor which measures the inverse of the decay rate of the energy and low mode volume which signifies the spatial confinement of the light. As the same with the laser resonators, its application on the optical sensor for nano-scale objects such as molecules or virus is also extensively studied.

In designing novel devices with existing dielectric materials under a specified emission wavelength, device shape must be paramount. The search for novel device geometry can be assisted by accurate numerical performance analysis using FEM. In particular, due to the circular shape of the device and the optical mode, axisymmetric models are effective at simulating the WG resonance mode in ring resonators. Using FEM, simple geometric parametric studies have been performed for disc shapes and toroidal shapes. However, a detailed search for an ideal device shape remains an open problem. Moreover, since varying the device shape varies the resulting WG mode order and emission wavelength, a detailed search for an optimal shape is quite challenging for a specified wavelength. Thus, integrating existing parametrical studies and detailed shape optimization provides a means to develop high performance devices that would be available for a wide variety of uses. Topology optimization has contributed to optimal designs in novel wave propagation devices in photonics. In the approach, the designed devices are represented as distributions of the dielectric material or metal in the analysis model. By updating the distribution by the gradient-based optimization method, the generated distribution represents the shape of devices that attain specific performance criteria.

In this research, we study FEM-based topology optimization for WG micro-ring resonators. The systematic procedure helps to find optimal device shapes with fixed design performance given a prescribed emission wavelength and WG resonance mode. The analysis domains and the equations of state for the WG mode ring resonators are first considered. As the performance criteria for the laser resonator, the Q factor and mode volume are considered. On the other hand, the electric field intensity is considered as the one for the optical sensor. They are formulated as objective functions. The emission wavelength is treated as an equality constraint in order to specify it to a certain value. The proposed geometrical optimization is implemented as a distribution optimization of the dielectric material using the SIMP method of topology optimization. The optimization algorithm is constructed based on the two-stage FEM analysis, sensitivity analysis for each objective function and density function constraint, and SLP with a phase field method. Finally, numerical examples are provided as a validation of the proposed methodology.