Mode selection control in microring resonators

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Abstract. We present numerical simulations of a novel microring resonator geometry, based on subwavelength hollow core defects inside the resonator cavity in order to study its influence on mode structure. The microring resonator has 9 μm outer diameter and 5 μm inner diameter, subwavelength defects are round shaped and have 100 nm diameter. Results allowed us to formulate basic approaches for controlling mode structure of ring microresonators.

1. Introduction

The rapid growth of information flows leads to the need of continuous improvement of instruments and devices for its processing, storage and transmission. The advent of WDM channels, allowing information packets pass simultaneously on dozens of carrier frequencies using a single path, principally increased competitive solutions based on optical transmission and processing of information. Thus, Photonic Integrated Circuits (PICs) have been subject to extensive research over the last years [1,2]. A key component in many PICs is the optical resonator. Various types of resonators were demonstrated, including, for example, microring resonators (MRR) [3,4], Photonic Crystals (PhCs) cavities [5], Bragg resonators, Fabry-Perot resonators, microdisk resonators, vertical-external-cavity surface-emitting-laser (VECSEL) [6] etc. The potential applications for such resonators include laser sources, modulators, filters, sensors, optical delay lines, nonlinear optics and more.

MRRs used in PIC applications typically have small ring thickness and therefore support only whispering gallery modes (WGMs), but in general microring resonators sustain higher order radial modes. The mode structure changes of microring lasers caused by focused ion beam (FIB) milling of pits and grooves were demonstrated [7]. However, the information about proper positioning and selecting proper size, shape and number of defects is absent. Thus, we conducted more detailed research on possibility of mode selection control via subwavelength defects.

2. Perforated microring resonators

Recently it was shown that microring resonators with couple of microns (ranging from less than 2 μm up to 12 μm) diameter containing active region can sustain laser generation [8,9]. We obtained a number of micro-photoluminescence spectra of GaAs microring resonators with active region based on InAs QD. We found that MRR with 9 μm outer diameter and 5 μm inner diameter exhibits the best performance (among our set). So in this paper we considered MRR of this size. The simulations were performed using finite element method (FEM) in COMSOL Multiphysics software. While the full three-dimensional simulations are necessary for determining parameters of the device, as intended for
use in real world applications, two-dimensional simulations can also provide some insight into the structure of the resonator and its performance. Also as the geometry of the structure becomes complicated, with finer details, a smaller grid step size is required. Thus, simulations of a structure with fine details in 3D become time-consuming. Only a single microring resonator problem can be fully reduced from 3D to 2D calculations – this is possible due to axial symmetry of the problem. In this paper all results come from 2D simulations, except mode analysis in a single microring resonator stated above. The ring consists of material with refractive index \( n_1 = 3.43 \) (corresponding to refractive index of GaAs on ~1.2 \( \mu \)m wavelength). The ambient media has refractive index \( n_0 =1 \).

For further investigation we obtained eigenmodes of the MRR and chose 3 modes with different radial order numbers – WGM, 2\(^{nd}\) and 3\(^{rd}\) radial modes. For example, the light intensity distribution of the 3\(^{rd}\) order radial mode is shown in the figure 1.

![Figure 1. 3\(^{rd}\) order radial mode in the MRR.](image)

2.1. Microring resonator with single defect

The size of the light intensity maximums of the modes averaged in 100 nm, so one should expect that defects of this size would be critical for light propagation in the MRR. Indeed, bigger defects will cause diffraction and the anticipated effect will not be local, on the other hand smaller ones have negligible influence. In comparison with the light wavelength in the material (~340 nm), the defects are subwavelength-sized. The simplest modification of the MRR is a single subwavelength hollow core defect of 100 nm diameter positioned in the maximum of the light intensity of the mode. The light intensity distribution of the 3\(^{rd}\) order radial mode in the locally perforated MRR is shown in the figure 2. The defect affects the mode in such a way, that maximums of the light intensity redistribute from defect area to the edge of the MRR. But this influence is not enough to remove this mode from eigenmode spectrum of the MRR. Also this defect doesn’t affect WGM and 2\(^{nd}\) order mode because it’s located relatively far from their maximums. Of course, radial mode has axial symmetry, and it can be rotated in such a way that defect falls in between maximums of the light intensity distribution, but it will be noted that in real world applications the symmetry is violated.
2.2. Microring resonator with several defects

The next straightforward step is to add one more defect. But our simulations have shown that only equilateral triangle configuration of 3 subwavelength defects is sufficient to suppress 3\textsuperscript{rd} radial mode and removes it from eigenmode spectrum. Figure 3 shows the light intensity distribution calculated on the frequency corresponding to the chosen 3\textsuperscript{rd} radial mode.

![Figure 3. The light intensity distribution in the perforated MRR.](image)

1\textsuperscript{st}, all 3 defects fall into maximums of the light intensity distribution, 2\textsuperscript{nd} huge number of the light intensity maximums filling the entire volume of the MRR.
Both these facts result in removing the 3rd radial mode from the eigenmode spectrum, and it is in the agreement with the results of solving eigenvalue problem. This approach can be tuned to remove any other mode just by placing defects in the proper position corresponding to maximum of the light intensity of mode.

2.3. Add-drop filter

All the previous results were obtained for MRR alone, but in real world applications input and output of light are required. It is achieved by placing planar waveguides in the vicinity of MRR, so the light can exhibit tunneling back and forth. By varying the tunneling gap one can tune the Q-factor of the system. In integrated optics this system is known as add-drop filter. It should be noted that the addition of waveguides to MRR brakes the axial symmetry of the system and “fixes” MRR modes, so the previous considerations of placing defects in intensity maximums were correct (in the system MRR-waveguide mode is bound to the gap).

We simulated add-drop filter consisting of the MRR (diameter of 9 μm) and 2 planar waveguides placed opposite from each other. Waveguides have 300 nm thickness and the same material properties as MRR, the gap between waveguide and MRR is 100 nm. The principal scheme is shown in the figure 4 (a).

![Figure 4](image.png)

**Figure 4.** (a) Scheme of the add-drop filter. (b) Transmission spectrum of the add-drop filter. Numbers in brackets \((M,N)\) indicate azimuthal \(M\) order and radial \(N\) order of a mode.

The calculated spectrum of the system is shown in the figure 4 (b). Black solid line corresponds to MRR without any defects. In this case 4 modes of different orders are excited. Red dashed line corresponds to MRR with 3 defects placed in equilateral triangle configuration. In that case the WGM still excites, but the 2nd order radial mode exhibits partial suppression, while the 3rd order mode is totally suppressed as was expected. Also 2nd order radial mode exhibits blue shift due to change in effective refractive index for this mode caused by defects. According to the principle of reciprocity, these results also can be used in the case of microring laser coupled with waveguides.
3. Conclusion
As a result we formulate basic principles of controlling mode spectrum of MRR via subwavelength hollow core defects: size of a defect should match spatial size of light intensity maximum of the chosen mode and not exceed $\lambda_{\text{mat}}/4$, defect should be positioned in light intensity maximum of the chosen mode for maximum influence. Also we state that configuration of 3 defects is sufficient for suppressing different MRR modes.

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