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Coupling of a Notched Ring Microresonator to a Straight Input Waveguide

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Abstract: We describe a notched AlGaAs ring microresonator design that minimizes the overlap between the TE and TM modes. We use coupled mode theory to study the coupling between the microresonator and a straight input waveguide. © 2023 The Author(s)

Microresonator-generated optical frequency combs have matured as a technology over the past two decades [1, 2]. Microresonator frequency combs are created by coupling light from an input waveguide into a single transverse mode of the microresonator with a high quality factor Q , as shown schematically in Fig. 1a. Microresonators fabricated from AlGaAs have attracted significant attention in recent years, primarily due to the large nonlinear coefficient of AlGaAs and its high refractive index [3]. However, the dispersion profile of AlGaAs resonators typically suffers from significant unwanted distortion due to avoided mode crossings generated from TE–TM transverse mode coupling [4]. This coupling occurs because of the large spatial overlap of the TE and TM transverse modes [4]. If large enough or close enough to the pumped mode, the distortion from avoided crossings can negatively affect the generation and stability of solitons [5]. Previous approaches to reducing the intracavity mode coupling have involved filtering out the TM mode in different ways, such as using a filtered waveguide to couple to the microresonator [4, 6]. In prior work, we used particle swarm optimization (PSO) to develop a notched ring microresonator design that significantly reduces the intracavity overlap of the fundamental TE and TM modes, as shown in Fig. 1b [7]. Although the design achieves significant mode separation, the fundamental TE mode, shown in Fig. 1(c), is significantly deformed, which could potentially affect the coupling between this mode and the fundamental TE mode in the input waveguide. In this work, we used coupled-mode theory [8] to calculate the coupling Q between the notched design and the input waveguide in order to find the impact of this design change on the loaded Q of the fundamental mode of interest. We studied a range of input waveguide geometries and coupling distances to determine the optimal combination of those parameters for coupling to the notched design.

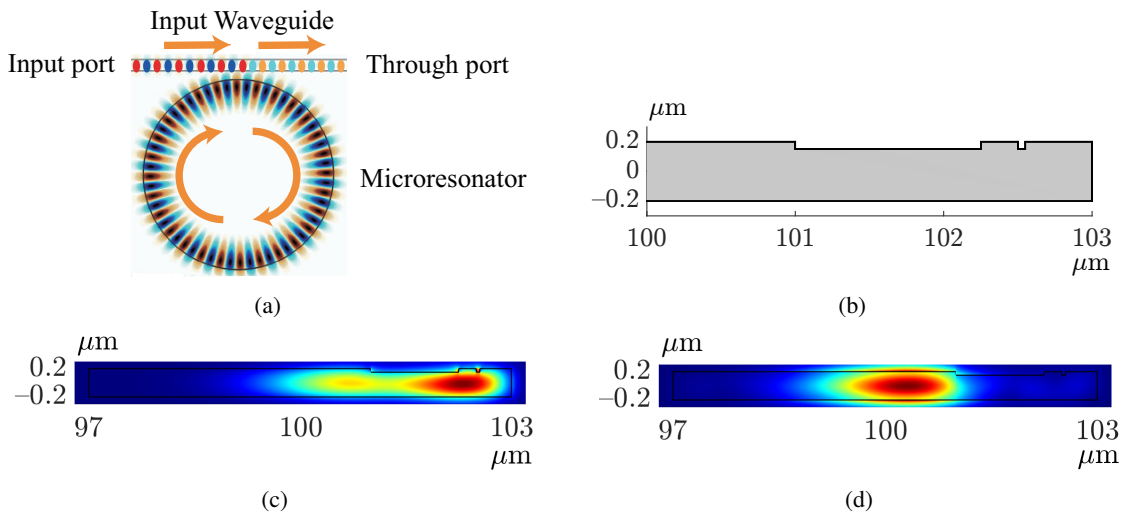


Fig. 1: (a) Schematic illustration of the microresonator system. (b) Outer-half cross-section of the PSO-developed notched ring resonator design. The ring parameters are: Ring Width = $6\ \mu\text{m}$, Ring Thickness = $0.400\ \mu\text{m}$, and Ring Radius = $100\ \mu\text{m}$. The ring extends from an inner radius of $97\ \mu\text{m}$ to an outer radius of $103\ \mu\text{m}$. (c-d) Transverse electric field magnitude of the fundamental (c) TE and (d) TM modes in the notched ring resonator.

In the system that we consider, both the resonator and the waveguide are made from an $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ core that guides light, and are surrounded by an SiO_2 cladding. The fields of the modes inside both structures decay almost exponentially outside the waveguides in which they propagate, forming evanescent fields. Coupling is due to the overlap of each of these evanescent fields with the core field of the other device, which can be described by an overlap integral Γ given as [8]

$$\Gamma(\omega, l) = \frac{\omega}{4} \int_S (\epsilon_{\text{wg}} - \epsilon_{\text{R}}) \mathbf{E}_{\text{R}}^* \cdot \mathbf{E}_{\text{wg}} d\mathbf{r} dz,$$

where r and z are the radial and vertical directions from the center of the resonator, ω is the angular frequency of the resonator mode, $\mathbf{E}_{\text{R, wg}}$ is the normalized electric field of the resonator and waveguide mode, respectively, and $\epsilon_{\text{R, wg}}$ is the dielectric permittivity of the resonator and the waveguide, respectively. Once calculated, the overlap integral is used to calculate the power coupling coefficient between the resonator and waveguide modes, from which the extrinsic quality factor value Q_{ext} is obtained [8].

Pumping efficiency is maximized at critical coupling, when the extrinsic quality factor Q_{ext} and the intrinsic quality factor Q_{int} equal each other; this is the approximate experimental target. In this work, we calculate Q_{ext} using a parameter space of three geometric parameters: input waveguide thickness, input waveguide width, and distance between the input waveguide and resonator. We then compare Q_{ext} to Q_{int} to find the parameter combination that minimizes the metric $(Q_{\text{ext}} - Q_{\text{int}})^2$. Since the parameter space is small, direct computation can be used instead of optimization techniques.

For the results reported here, we assumed $Q_{\text{int}} = 2 \times 10^6$, which is a typical experimental value [3]. We varied the input waveguide width and thickness from 300 nm to 800 nm and the coupling distance from 100 nm to 1000 nm. The coupling distance that gave the extrinsic Q that minimized $(Q_{\text{ext}} - Q_{\text{int}})^2$ was selected as the optimal coupling distance. Below, two figures are shown to represent this data. Figure 2(a) is a 3D mesh plot that shows the input waveguide thickness and input waveguide width in the x - y plane versus the optimal coupling distance along the z -axis. Figure 2(b) shows three slices of the 3D plot, where the input waveguide thickness has been chosen to approximately equal 400 nm, the same thickness as the ring resonator, and also showing the effect of a slight variation from 375 nm to 425 nm. From these plots, we observe that the optimal coupling only changes slightly over the parameter range that we considered, indicating that it is insensitive to small fabrication variations. We note that the distortion of the fundamental TE mode led to no difficulty in the coupling to the input waveguide.

In conclusion, we have used coupled mode theory to study the coupling of a novel notched ring resonator design. Future work will include studying new resonator designs, such as rings with inner side wall modulation.

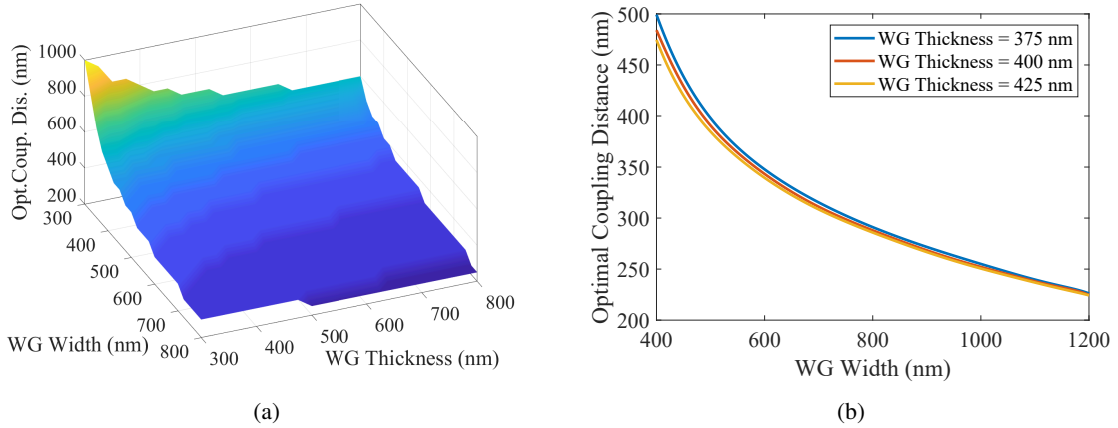


Fig. 2: (a) Optimal coupling distance plotted against the input waveguide cross section parameters. (b) Optimal coupling distance versus input waveguide width for three different input waveguide thicknesses.

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