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Determining the Transverse Mode that Produces Frequency Combs in Microresonators

Logan Courtright, Zhen Qi, Thomas F. Carruthers, and Curtis R. Menyuk

CSEE Department

University of Maryland, Baltimore County

Baltimore, USA

Corresponding Author: lcourt1@umbc.edu

Tanvir Mahmood, Sang-Yeon Cho, James P. Cahill, and Weimin Zhou

US Army Research Laboratory

Adelphi, USA

Abstract—It has been difficult to use the measured dispersion data to determine which transverse mode is the best to use for producing optical frequency combs in microresonators. We propose a simulation method to do so.

Keywords—microresonator, frequency combs, transverse modes

I. INTRODUCTION

Over the past two decades, microresonator-generated optical frequency combs have developed into an important emerging technology, with potential applications in metrology and a wide range of other fields [1,2]. The frequency combs can be generated by coupling continuous-wave laser light into a high- Q microresonator with Kerr nonlinearity to create single solitons, as shown schematically in Figure 1. During the coupling process, there will be a specific transverse mode inside the microresonator that is used to generate the soliton that we will call the coupling mode. A persistent problem in the literature is that the coupling mode being used and its polarization are not identified, which limits the reproducibility of the experimental results. Here, we present a method to determine the coupling mode using published dispersion data and geometric device parameters, accounting for small fabrication or measurement variations. The goal is to help design and characterize microresonator combs. In this work, we focus on the numerical modeling of high- Q microresonators reported in two experimental works [3,4].

For a single transverse mode in a single polarization, the resonance frequency of the longitudinal modes can be written using a Taylor expansion as $\omega_\mu = \omega_0 + \mu D_1 + \mu^2 D_2/2 + \dots$, where ω_0 is the frequency of some central azimuthal mode μ_0 and μ is the relative mode number. We define the integrated dispersion $D_{\text{int}}(\mu) = \omega_\mu - \omega_0 - \mu D_1 = \mu^2 D_2/2 + \dots$, which is commonly used to characterize the modal dispersion. Both papers use the central frequency $\lambda_0 = 1550$ nm, and we consider a frequency range $\Delta\lambda = 30$ nm for [3] and $\Delta\lambda = 20$ nm for [4] to analyze their results. To allow for fabrication variations, we study microresonators with a 10% variation from the reported geometric parameters, focusing in particular on the radius and thickness. The central parameter values are radius = 1.5 mm with thickness = 8 μm for [3], and radius = 100 μm with thickness = 700 nm for [4].

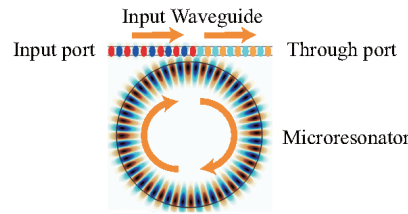


Fig. 1: Schematic illustration of the microresonator system

II. RESULTS

In our approach, we use COMSOL Multiphysics© to find the transverse mode profile. At the central parameter values, we calculate $D_{\text{int}}(\mu)$ using 20 points over the wavelength range. We found that $D_{\text{int}}(\mu)$ was dominated by the parabolic term, D_2 , for the central parameters corresponding to [3] and [4]. Since the parameters are swept over a relatively small range, we assume that for all parameter values that we consider $D_{\text{int}}(\mu)$ will still be dominated by the parabolic term, which we have verified in selected cases. So, for parameter values other than the central values, we use only 3 points over the wavelength range for faster calculations. We start by examining the first-radial-order TE mode, denoted TE1. This mode and all other modes here are first-vertical-order modes. Figures 2(a) and (b) show the simulation results at the central geometric parameters versus the experimental results. Upon observing the differences, we vary the parameters with a 10% fabrication variation. Figures 2(c) and (d) show how $D_{\text{int}}(\mu)$ changes over the parameter range, where we plot the maximum $D_{\text{int}}(\mu)$. Next, we examine the TM mode and then increase the radial mode order as needed. We find that the dispersion profile for the second-radial-order TE mode, denoted TE2, is the closest match to [3], as shown

in Figs. 2(e) and 2(g), while the second-radial-order TM mode, denoted TM2, is the closest match to [4], as shown in Figs. 2(f) and 2(h). In [4], it is indicated that the TE1 mode was used for comb generation, in contradiction with our demonstration that the TM2 mode most closely matches their published dispersion profile. This may occur if different modes were used to show their dispersion and comb generation results.

III. CONCLUSIONS

In conclusion, we have demonstrated a method to determine the transverse mode and its polarization from published dispersion data, assuming a reasonable variation of the device geometric parameters. This approach can be used as a starting point to optimize the coupling geometry and to guide design of future microresonator combs. Additionally, fabrication errors are inevitable and our approach makes it possible to effectively identify the variations by taking advantage of the dispersion profile. Future work will include expanding the parameter space to identify trends that can serve as design rules for different microresonator geometries.

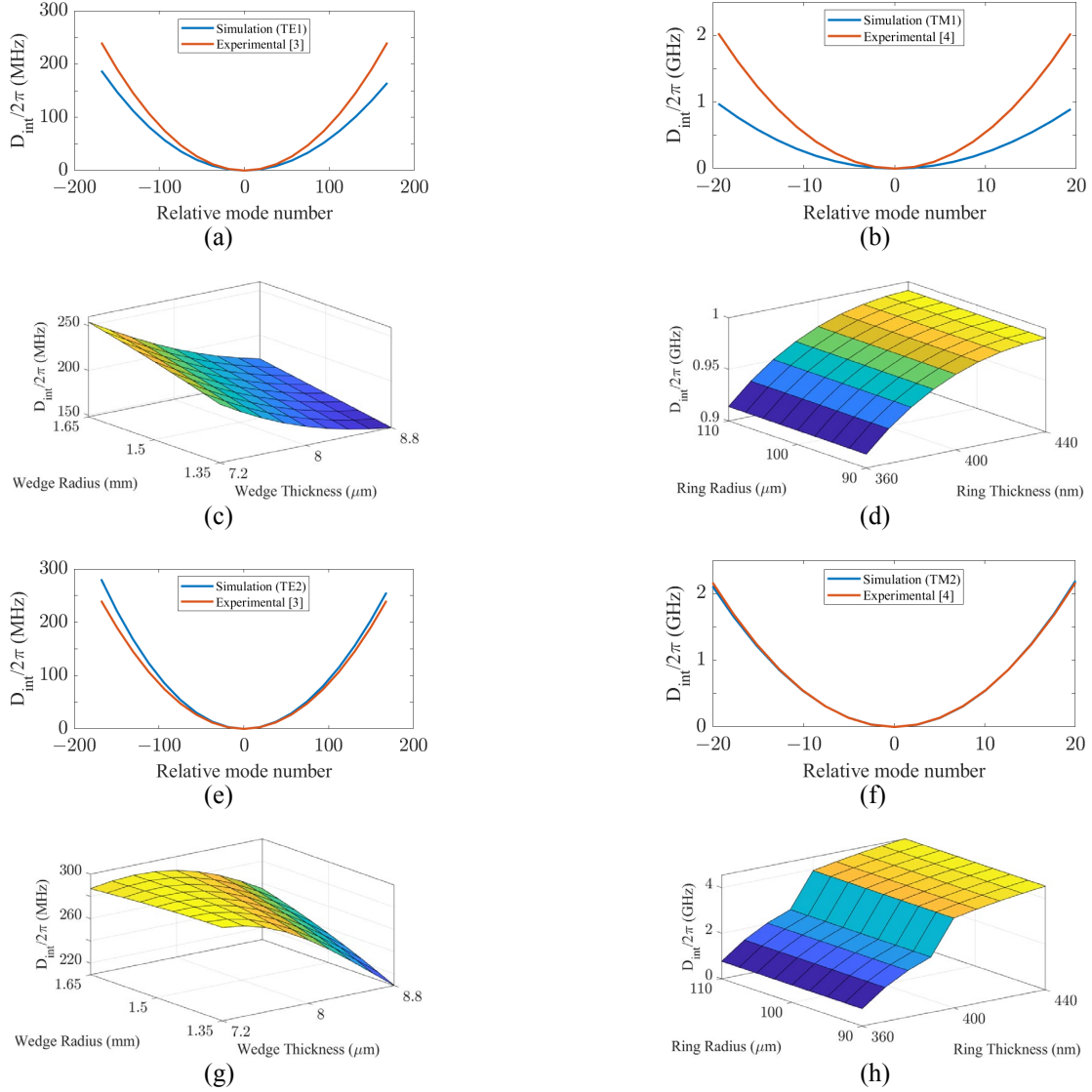


Fig. 2: Integrated dispersion comparison of the TE1 mode for [3]. (b) Integrated dispersion comparison of the TE1 mode for [4]. (c) Parameter space variation for (a). (d) Parameter space variation for (b). (e-h) Corresponding integrated dispersion figures for the matching modes: TE2 mode for [3] and TM2 mode for [4].

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