Exploiting Ultralow Loss Multimode Waveguides for Broadband Frequency Combs

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Low propagation loss in high confinement waveguides is critical for chip-based nonlinear photonics applications. Sophisticated fabrication processes which yield sub-nm roughness are generally needed to reduce scattering points at the waveguide interfaces to achieve ultralow propagation loss. Here, ultralow propagation loss is shown by shaping the mode using a highly multimode structure to reduce its overlap with the waveguide interfaces, thus relaxing the fabrication processing requirements.

Microresonators with intrinsic quality factors (Q) of 31.8 ± 4.4 million are experimentally demonstrated. Although the microresonators support ten transverse modes only the fundamental mode is excited and no higher order modes are observed when using nonlinear adiabatic bends. A record-low threshold pump power of 73 µW for parametric oscillation is measured and a broadband, almost octave spanning single-soliton frequency comb without any signatures of higher order modes in the spectrum spanning from 1097 to 2040 nm (126 THz) is generated in the multimode microresonator. This work provides a design method that can be applied to different material platforms to achieve and use ultrahigh-Q multimode microresonators.

2. Results and Discussion

Here, we show low propagation loss in high confinement waveguides by shaping the mode using a highly multimode structure to reduce its overlap with the waveguide interfaces, thus relaxing the need to physically reduce the scattering points via fabrication processes. We show a design of a highly multimode microresonator that minimizes the interaction between the fundamental mode and excited higher order modes to prevent the increase of threshold for nonlinear processes. Our design ensures propagation solely in the fundamental mode by preventing the excitation of higher order modes, in contrast to previous designs that ensure propagation solely in the fundamental mode by eliminating the excited higher order modes using loss. Weakly tapered gap together with a narrow bus waveguide in low confinement waveguide is studied to increase fundamental mode coupling, but it relies on very large bending radius and big footprint. Our microresonator consists of a highly multimode waveguide with a bending radius that changes nonlinearly along the circumference from a large value (900 µm) in the coupling section to a small value (80 µm) in the bend (see Figure 1a). The large value in the coupling section ensures efficient coupling and excitation of only the fundamental mode, whereas the small value allows fundamental mode propagation with a small effective bending radius. We engineer the microresonator by leveraging nonlinear functions for minimizing rapid changes in curvature, which have been well studied in mathematics and applied in photonics. We design the bending radius to change nonlinearly to ensure adiabaticity while maintaining a small footprint. For comparison, a design with a bending radius that changes linearly—using the same slope as the one in the coupling section of the nonlinear case to ensure adiabaticity—would require a ten times larger footprint. We choose the hyperbolic tangent (tanh) function for changing the bending radius as our nonlinear function to provide a high degree of adiabaticity with simple design implementation and a compact footprint. This tanh
Figure 1. a) Schematic of our microresonators with adiabatic bends design. The bending radius is 900 μm in the coupling section and then gradually reduces to 80 μm in the sharpest bend. Inset shows the transverse electric (TE) modes supported by the waveguide and only the fundamental mode is excited in the adiabatic bends design. b) FDTD simulations of the adiabatic bends design (top) and the conventional ring resonator with constant bending radius (bottom). Note that higher order modes are excited in the constant bending radius ring and not in our adiabatic bends design. c) Simulations of normalized mode excitations for adiabatic bend and conventional bend with constant bending radius of 131 μm as a function of wavelength.

We design a microresonator that supports ten transverse modes while ensuring that ≈95% of the input power circulating in the resonator is in the fundamental mode when using nonlinear adiabatic bends. The microresonator shown in Figure 1a has a free spectral range (FSR) of 174 GHz and is based on a waveguide with a cross section of 730 nm x 2600 nm which supports ten modes (transverse electric (TE) modes, shown in Figure 1a inset). The bus waveguide consists of the same cross section and to ensure that only the fundamental mode is launched into the microresonator, it is terminated with an inverse taper. In Figure 1b, we show the full 3D finite-difference time-domain (FDTD) simulations (Lumerical FDTD) of the coupling section. In Figure 1c, we show the normalized power in each mode normalized by the total power coupled from the bus waveguide to the resonator. The simulations show that at 1550 nm in our resonator design the power in the higher order modes is almost 7 dB lower than that in the conventional resonator with a constant bending radius.

We show experimentally that intrinsic quality factors ($Q$) of 31.8 ± 4.4 million are achieved by propagating a single mode in the highly multimode microresonators. To test these devices, we use a lensed fiber to launch a laser source through a fiber polarization controller into the inverse nanotaper input of our chip and use a collimating lens to collect the transmitted light from the inverse nanotaper output of our chip. In Figure 2a, we show the measured transmission spectrum and the measured average intrinsic linewidth is 6.1 MHz ± 0.9 MHz, corresponding to an intrinsic $Q$ of 31.8 ± 4.4 million and a propagation loss of less than 1 dB m$^{-1}$. The histogram of intrinsic linewidths in Figure 2b shows that the low propagation loss is consistent across multiple FSRs and four different fabricated samples. To compare our designed resonator with a conventional resonator having a constant bending radius, we fabricate both types of structures on the same wafer. By choosing a constant bending radius of 131 μm, we ensure that both structures exhibit the same FSR. In Figure 2c, we show the measured normalized transmission spectra for the two structures. While for the microresonator with constant radius the transmission dips at multiple frequencies, indicating the presence of higher order mode excitation and propagation,[25] for the microresonator with nonlinear adiabatic bends the transmission dips only at every FSR, indicating the lack of higher order modes. The measured integrated dispersion of our microresonator is shown in the Supporting Information. Note that in our experiment, the maximum intensity variation of the background is about 4%, which is therefore the sensitivity limit of higher order mode measurement. We also show the $Q$ and a histogram of linewidths measured using resonators with a smaller width as comparison in Figure 3. The resonators have a height of 730 nm and a width of 1.5 μm. We choose this width since it provides anomalous group-velocity dispersion (GVD) and is a typical dimension for Kerr frequency comb generation.[26] We show a normalized transmission spectrum of a resonance with an intrinsic $Q$ of 13.8 million and a histogram of intrinsic linewidths measured with several samples. The average intrinsic linewidth is 13.9 MHz ± 1.0 MHz. The $Q$’s are significantly
Figure 2. a) Normalized transmission spectrum of a resonance with an intrinsic Q of 32.8 million. b) Histogram of intrinsic linewidths measured with several samples. The average intrinsic linewidth is 6.1 MHz ± 0.9 MHz. c) Schematic of a microresonator with adiabatic bend design (top left). Measured normalized transmission spectrum with no higher order mode observed (bottom left). Schematic of microresonators with constant bending radius design (top right). Measured normalized transmission spectrum with clear signatures of higher order modes (bottom right). The inset shows the higher order modes resonance dips in between one FSR of the fundamental mode. Note that both microresonators have the same FSR and similar footprint.

Figure 3. a) Normalized transmission spectrum of a resonance with an intrinsic Q of 13.8 million for resonators with 1.5 µm widths. b) Histogram of intrinsic linewidths measured with several samples. The average intrinsic linewidth is 13.9 MHz ± 1.0 MHz.
increased with the highly multimode microresonators, which indicates the effectiveness of our approach. The propagation loss for a single mode waveguide with similar fabrication process can also be found in ref. [27]. We measure a record-low pump power threshold of 73 $\mu$W for parametric oscillation using the multimode microresonator and generate a broadband, almost octave spanning single soliton frequency comb without any fingerprint of higher order modes, spanning from 1097 to 2040 nm (126 THz) with an FSR of 174 GHz. We measure the output power in the first generated four-wave-mixing sideband for different pump powers to determine the pump power threshold for parametric oscillation. The measured first sideband power for a pump wavelength around 1560 nm is shown in Figure 4a and an example of the initial state of parametric oscillation with pump power of 73 $\mu$W is shown in Figure 4b. To measure the generated combs, we use two optical spectrum analyzers (OSAs) to acquire the spectrum due to the limited wavelength range of a single OSA. In Figure 5a, we show a broadband frequency comb spectrum generated with the microresonator before phase-locking and in Figure 5b, we show frequency comb single soliton spectrum generated with the microresonator close to octave spanning and phase-locked using the microheater thermal tuning method discussed in ref. [28].

The fit to a single soliton state with a spectral sech$^2$ envelope is shown (in purple) in Figure 5b and matches well with our experimental results. The comb spectra do not exhibit the typical defects that indicate the presence of higher order modes, such as missing lines or dips. Note that in Figure 5b the spectrum exhibits dips (at 1350 and 1850 nm, for example) only at the frequencies corresponding to the narrow wavelength division multiplexing (WDM) used to filter the pump to increase the dynamic range of the OSA for the phase-locked comb. Our demonstration of broadband frequency combs shows our ability to engineer the dispersion despite the large waveguide dimensions. The simulated GVD parameter as a function of the microresonator width, with a fixed height of 730 nm for the fundamental TE mode and a pump wavelength of 1550 nm, is shown in Figure 5c. The dispersion in these wide structures is robust to fabrication variations and the shaded area indicates the anomalous GVD region needed for broadband soliton combs.

For our experiment, we choose 2600 nm width (marked with the red star), because it minimizes the overlap between propagating mode and scattering points at the waveguide interfaces while providing small anomalous GVD favorable for broadband comb generation,[29,30] In addition, GVD in these wide structures is more robust to fabrication variations as illustrated by results from simulation in the Supporting Information.

3. Conclusion

In conclusion, we show that a highly multimode microresonator can be used to achieve ultralow propagation loss (<1 dB m$^{-1}$) using as-deposited films, in contrast to previous demonstrations, where Damascene processing or CMP of the films are needed.[15–17] Our fabrication method to achieve ultralow propagation loss (<1 dB m$^{-1}$) is based solely on subtractive processing without Damascene or CMP, and it also eliminates the requirement of tens of hours of high-temperature resist reflow. Our method of using highly multimode structures to achieve ultralow propagation loss can be applied not only to Si$_3$N$_4$ but also to different material platforms,[31–41] where developing optimized processes to achieve smooth interfaces is more challenging. Our method of using highly multimode structures to achieve ultralow propagation loss eliminates the requirement for CMP and can be applied not only to Si$_3$N$_4$ but also to different material platforms,[15–41] where developing optimized processes to achieve smooth interfaces is more challenging. In principle, these highly multimode structures could be further combined with sophisticated optimized fabrication processes to achieve extremely low propagation loss. High coupling ideality is crucial for microresonators with small FSRs, which can be achieved by increasing the coupling length.[42] However, coupling to higher-order modes is also increased. We show high coupling ideality and low higher-order modes excitation can be achieved simultaneously using our nonlinear adiabatic design method. Our method is more beneficial for microresonators with small FSRs where drawbacks of mode crossings may be appreciable. For small FSRs, the cavity length is sufficiently large to ensure the coupling region is suitably long and the radius changes adiabatically. For larger FSRs, sharper bends are needed due
to the limited cavity length which could affect the dispersion and increase loss. Utilizing the nonlinear adiabatic design to efficiently excite and propagate only the fundamental mode increases flexibility in the waveguide design while ensuring ultralow propagation loss as well as dispersion engineering. The generated unlocked, smooth, and broadband comb with small line spacing could be useful for applications that do not require low phase noise, such as optical coherence tomography, whereas the generated phase-locked comb could benefit applications that rely on microresonators such as spectroscopy, metrology, astronomy, high-speed communications, and on-chip optical clocks.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

frequency combs, microresonators, multimode, nonlinear optics, soliton, ultralow loss

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