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Suppression of avoided resonance crossing in microresonators

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Kerr frequency comb generation in microresonators is enabled by notable developments in fabrication technology and novel nonlinear material platforms. However, even in a low loss and highly nonlinear microresonator, the avoided resonance crossing may hamper reliable frequency comb generation. We present a method to suppress the avoided resonance crossing induced by polarization mode coupling. Our approach employs a filter waveguide coupled to a microring resonator for selective filtering of the TM$_{00}$ mode while keeping the operational TE$_{00}$ mode with low loss. We experimentally demonstrate an avoided-crossing-suppressed microresonator in the AlGaAs-on-insulator platform. © 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

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Microresonator-based Kerr frequency combs [1] have garnered a great deal of interest in the past decade, driven by various integrated photonic applications [2–5] that require an energy-efficient, small-footprint, broadband, and coherent optical source on a chip. In the aim of improving the energy efficiency of frequency comb generation, a wide range of nonlinear photonic material platforms (e.g., Si$_3$N$_4$ [6,7], SiC [8], AlN [9], LiNbO$_3$ [10], GaP [11], AlGaAs [12,13]) have been investigated in search of a higher Kerr nonlinearity, and fabrication technology improvements [14,15] have enabled higher quality factors (low loss) of the microresonators. The waveguide dimension of the microresonator is usually carefully designed concerning the dispersion and loss performance. However, one crucial aspect of microresonator performance—avoided crossing (AC) in resonance (also known as avoided mode crossing or avoided resonance crossing)—has not been fully addressed despite its significant impact on the Kerr frequency comb operation [16,17]. The AC is typically considered as a detrimental effect in generating stable frequency combs or bright solitons [17], especially when it is not anticipated in the designing stage of a single microresonator system. The AC in a single microresonator involves a modal coupling of two or more transverse modes in the waveguide of the resonator. As the transverse modes’ resonances do not share the same free spectral range (FSR), the resonances of the different modes are bound to overlap with (or come close to) each other at a periodic wavelength cycle. When the coupled transverse modes’ resonances approach each other in wavelength, resonance hybridization of the coupled modes occurs with the resonance profile exhibiting splitting features. As a result, the dispersion of the microresonator is locally and periodically perturbed, which may result in a distorted spectrum in frequency combs and unstable solitons [17,18].

There have been several prior experimental works addressing this issue; an intracavity tapering in a microring resonator [19,20] and an intracavity slit in a whispering gallery mode resonator [21] were employed to filter out the unwanted higher-order modes and the ordinarily polarized mode, respectively. However, there has been no attempt to suppress the AC induced by a fundamental polarization mode coupling (TE$_{00}$ − TM$_{00}$) in a microring resonator [18,22]. We highlight this untended problem since the polarization mode coupling in microresonators is extensively present—arising from various sources such as material-inherent birefringence [23], stress-induced birefringence [24], and structure profile (bending, slanted sidewall, asymmetric refractive index environment) [25,26] of the waveguide.

In this Letter, we present a method to efficiently suppress the AC (induced by TE$_{00}$ − TM$_{00}$ mode coupling) in a microresonator by reducing the cavity lifetime of the TM$_{00}$ mode. A simple directional coupler (DC)-based filter waveguide is concentrically coupled to the resonator, which selectively filters the TM$_{00}$ mode (unwanted mode) that is mode-coupled to the TE$_{00}$ mode (operational mode) in the resonator. We implement the proposed method in a microresonator based on the AlGaAs-on-insulator platform [12] and experimentally show significant suppression of the AC.

An AC-suppressed (ACS) microresonator consists of a microresonator supporting both fundamental TE and TM modes and a filter waveguide evanescently coupled to the resonator [Fig. 1(a)]. The waveguides are concentrically configured, forming a curved DC [27,28], where the TM$_{00}$ mode is in a phase-matched coupling condition with a large cross-coupling, and the TE$_{00}$ mode is in a phase-mismatched coupling condition with a negligible cross-coupling. Therefore, the filter waveguide significantly reduces the cavity lifetime of the TM$_{00}$ mode without affecting the TE$_{00}$ mode and thus suppresses the TE$_{00}$ − TM$_{00}$ mode-coupling-induced AC. Figure 1(b) shows a schematic of the ACS microresonator system consisting of a resonator, a bus waveguide, and a filter waveguide. Hereinafter, the waveguides have the same core material (AlGaAs) and a thickness of 320 nm, with cladding material being SiO$_2$ (top and bottom cladding having the same...
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coupling between the filter and resonator. With the optimum filter waveguide width ($W_F = 374$ nm), we use the FDE and finite-difference-time-domain simulation to propagate both TE$_{00}$ and TM$_{00}$ modes in the resonator–filter structure with a varying coupling angle $\theta$. The input and output ports were both on the resonator side; thus, the resulting modal transmission at the output represents coupling (loss) introduced by the filter waveguide. As shown in Fig. 1(e), the TM$_{00}$ mode (solid orange line) shows a substantial increase in coupling with the coupling angle due to the effective index matching of the resonator and filter waveguide. In contrast, the TE$_{00}$ mode (solid blue line) has an extremely low level of coupling ($\approx 0.1\%$, as shown in the inset) owing to the large effective index mismatch. Such polarization mode selective coupling above can be formulated in detail with coupled-mode theory [29], where the TE$_{00}$ modes are phase mismatched, and the TM$_{00}$ modes are phase matched. To minimize the footprint of the filter while maintaining sufficient TM$_{00}$ mode filtering, a coupling angle of 150° was chosen.

In the given configuration, we emphasize that the coupling of the TM$_{00}$ mode is beyond 70%, while that of the TE$_{00}$ mode is kept low ($\approx 0.1\%$). Since the AC in resonance typically occurs in a broad wavelength range, we also analyze the wavelength dependency over a 100-nm window [Fig. 1(f)]. The coupling of the TM$_{00}$ mode deviates as we move away from the design wavelength of 1550 nm due to the different waveguide confinement and effective index mismatch. Although the TM$_{00}$ mode filtering (coupling) efficiency is sufficient for the suppression of AC within the presented wavelength range (higher than 40% coupling in this configuration), a more sophisticated filter waveguide design [30] may allow wavelength-insensitive performance.

To experimentally validate our method, we fabricate an AlGaAsOI-based reference device [see Fig. 2(a)] and an ACS resonator device [see Fig. 2(b)]. The AlGaAsOI wafer is prepared by wafer-bonding and substrate removal processes [31]. The microresonators are patterned by optimized electron-beam lithography [32], dry-etched with chloride-based chemistry, and cladded with SiO$_2$ using plasma-enhanced chemical vapor deposition. Both devices have identical point-coupled racetrack microresonators with a nominal cross-sectional dimension of $320 \times 470$ nm$^2$, cavity length of 808 $\mu$m, and curved section radius of 17.2 $\mu$m, and resonator-bus point coupling gap of 225 nm. The filter waveguide in the ACS device is configured with a width of 374 nm, coupling angle of 150°, and resonator–filter coupling gap of 500 nm. The filter waveguide is terminated with tapering to 120 nm and a 3-μm-radius bend in both ends [as shown in Fig. 2(b)] to prevent backreflection that may adversely affect the suppression of AC. With the reference and ACS devices fabricated on the same chip, a characterization setup [33] was used to acquire the dispersion performance of the resonators.

Transmission spectra of the reference device [Fig. 2(c)] show a large extinction ratio for both TE$_{00}$ and TM$_{00}$ mode resonances where the TE$_{00}$ mode is slightly under-coupled, and the TM$_{00}$ mode is over-coupled. When the TE$_{00}$ and TM$_{00}$ modes’ resonances overlap with each other (indicated with black arrow), we find a locally lowered extinction ratio for both modes, and the corresponding zoom-in (right box) shows a noticeable hybridized (splitting) feature arising from the AC. In comparison, the transmission spectra of the ACS device [Fig. 2(d)] show a significantly lower extinction ratio for TM$_{00}$ mode, as it is
severely under-coupled with a large round-trip loss of the mode. In contrast, the ACS device is free of the TE$_{00}$–TM$_{00}$ resonance hybridization and the abrupt lowering of the extinction ratio. FSRs of the TE$_{00}$ and TM$_{00}$ modes were acquired for the reference device, while only the TE$_{00}$ mode FSR was available for the ACS device, as the TM$_{00}$ mode resonances (extinction ratio lower than $-1$ dB) were too shallow to be resolved. The FSR of the reference device [Fig. 2(c)] has noticeable periodic outliers in the shared wavelength location (dotted gray line) for the TE$_{00}$ (solid blue circle) and TM$_{00}$ (solid orange circle) mode resonances, which infers that the TE$_{00}$ – TM$_{00}$ mode coupling is the source of the AC. The TE$_{00}$ mode FSR of the ACS device [Fig. 2(f)] shows data points following a smooth line that fits well with that of the reference device, where the average FSRs of both devices are 94.7 GHz. As the resonator lengths are identical, the average group index is the same for both devices.

Integrated dispersion ($D_{int}$) and second-order dispersion ($D_2$) were obtained from the series of the TE$_{00}$ mode resonance frequency [Figs. 3(a) and 3(b)]. The integrated dispersion is defined by $D_{int} = \omega_j - \omega_0 - D_1 \mu = 1/2 D_2 \mu^2 + \cdots$, where $\mu$ is the relative mode number, $\omega_j$ is the frequency of the $j$th resonance, $\omega_0$ is the center resonance frequency, and $D_1/2\pi$ is the FSR near the center resonance frequency. Subsequently, the $D_2$ was derived from the Taylor series fitting of the $D_{int}$. The analyzed $D_2$ for the reference and ACS devices are $2\pi \times 3.10$ MHz and $2\pi \times 3.02$ MHz, respectively. The small difference in the $D_2$ confirms that the filter structure’s impact on the TE$_{00}$ mode dispersion parameter is negligible. To quantify the AC perturbation in the integrated dispersion profile, we derive a frequency deviation $\Delta f$ [Figs. 3(c) and 3(d)] by subtracting the fitted $D_{int}$ (solid red line) from the $D_{int}$ data points (solid blue circle). The maximum frequency deviations ($\Delta f_{\text{max}}$) are 1.45 GHz and 280 MHz for the reference and ACS devices, respectively, and the root-mean-squared deviations ($\Delta f_{\text{RMSD}}$) are 285 MHz and 94 MHz, respectively. The result indicates a significant lowering of the frequency deviation (dispersion defects) in the ACS device. Up to 159 TE$_{00}$ mode resonances were evaluated for the intrinsic quality factor ($Q_{\text{int}}$), as shown in Figs. 3(e) and 3(f). The reference device histogram of the $Q_{\text{int}}$ (right box) clearly shows a skewed distribution attributed to the outliers (hybridized resonances with low $Q_{\text{int}}$), whereas the ACS device has a symmetric distribution. The mean (median) values of the TE$_{00}$ mode $Q_{\text{int}}$ were $1.19 \times 10^5 (1.22 \times 10^5)$ for the reference device and $1.16 \times 10^5 (1.16 \times 10^5)$ for the ACS device. The filter shows negligible impact on the $Q_{\text{int}}$ for the TE$_{00}$ mode because the filter-induced round-trip loss is low [0.1%, see Fig. 1(f)], and such a round-trip loss corresponds to a $Q$ of $1.3 \times 10^7$. The results suggest the ACS device supports low-loss operation for the TE$_{00}$ mode and high-loss filtering of the TM$_{00}$ mode, thus suppressing the AC in resonance.

In an optical system that requires the highest possible TE$_{00}$ mode quality factor of the ACS microresonator, a lower TE$_{00}$ mode coupling loss can be achieved by several means: (1) providing a larger difference in the TE$_{00}$ mode effective index between the resonator and the filter by introducing a larger resonator–filter coupling gap (larger radius of curvature difference between the resonator and the filter by introducing a larger resonator–filter coupling gap), and (2) selectively reducing the resonator TE$_{00}$ field overlap to the filter TE$_{00}$ mode by having a wider cross-sectional width of the resonator in the filter coupled section. We add a caveat that the optimization for the low-loss TE$_{00}$ mode may entail compromised TM$_{00}$ mode filtering efficiency. Thus, a balance between the low-loss TE$_{00}$ mode operation and sufficient TM$_{00}$ mode filtering should be adjusted depending on the microresonator system. The ACS microresonator may be beneficial beyond the frequency comb application, where it can also be applied for spectrally stabilizing squeezing/anti-squeezing factors in quantum microcombs [34] and suppressing mode competition in integrated lasers [35].

In conclusion, we demonstrated a method to effectively suppress the AC induced by polarization mode coupling in an AlGaAsO1 microresonator. Our scheme employs a filter waveguide evanescently coupled to a resonator designed to selectively couple (filter) out the TM$_{00}$ mode while keeping the TE$_{00}$ mode.

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**Fig. 2.** Optical microscope images of the (a) reference and (b) ACS device. Transmission spectra of the (c) reference and (d) ACS device. Left box shows eight mode resonances, with the fifth resonance from the left being an overlapping resonance (denoted with an arrow) of the TE$_{00}$ and TM$_{00}$ modes; right box shows a zoom-in at the wavelength around the fifth resonance. FSRs of the (e) reference and (f) ACS device.

**Fig. 3.** Integrated dispersion ($D_{int}$) of the (a) reference and (b) ACS device. Frequency deviation ($\Delta f$) of the (c) reference and (d) ACS device. Intrinsic quality factor ($Q_{\text{int}}$) of the (e) reference and (f) ACS device. Solid gray line represents the mean $Q_{\text{int}}$, and the right boxes show the histogram of the analyzed $Q_{\text{int}}$. Letter
in the resonator. We anticipate a particular advantage of the method when applied to large-scale production and novel material platform microresonator systems guaranteeing robustness against the undesired AC in resonance.

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**Data Availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

**REFERENCES**