Ultra-high-Q UV microring resonators based on a single-crystalline AlN platform: supplementary material

Xianwen Liu\textsuperscript{1,2}, Alexander W. Bruch\textsuperscript{1}, Zheng Gong\textsuperscript{1}, Juanjuan Lu\textsuperscript{1}, Joshua B. Surya\textsuperscript{1}, Liang Zhang\textsuperscript{2}, Junxi Wang\textsuperscript{2}, Jianchang Yan\textsuperscript{2}, and Hong X. Tang\textsuperscript{1,*}

\textsuperscript{1}Department of Electrical Engineering, Yale University, New Haven, CT 06511, USA
\textsuperscript{2}R & D Center for Semiconductor Lighting, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
*Corresponding author:hong.tang@yale.edu

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This document provides supplementary information to “Ultra-high-Q UV microring resonators based on a single-crystalline AlN platform,” https://doi.org/10.1364/OPTICA.5.001279, including the relevant dispersion simulation, transmission background in the ultraviolet region, and the influence of sidewall and Rayleigh scattering losses.

1. DISPERSION SIMULATION

The aluminum nitride (AlN) film used in this study is a $c$-oriented (0001) uniaxial crystal. As a result, we account for the birefringence effect in the dispersion simulation, where transverse electric (TE) and transverse magnetic (TM) modes in the AlN waveguide experience their respective refractive indices of extraordinary and ordinary lights, as plotted in Fig. S1(a). Based on this material index, we characterize the dispersion profiles of the AlN microring using a finite element method (FEM) solver. Figure S1(b) depicts the simulated effective index ($n_{\text{eff}}$) of fundamental and first-order TM and TE modes (i.e., $TM_{00}$, $TM_{10}$, $TE_{00}$, and $TE_{10}$). Note that $TM_{00}$ mode exhibits a larger $n_{\text{eff}}$ value than that of $TE_{00}$ mode resulting from the birefringence effect. The free spectral range (FSR) is derived in Fig. S1(c) where the values around 390 nm (indicated by dashed lines) are consistent with our experimental results and help us assign the mode families in Fig. 2 of the main text.

Figure S1(d) shows a strong normal group-velocity dispersion (GVD) of the AlN microrings used in this study, which is anticipated at short wavelengths due to the dominant material dispersion and will suppress efficient four-wave mixing. Nonetheless, nonlinear photonic applications in the UV region are accessible by exploiting the intrinsic $\chi^{(2)}$ susceptibility of AlN. As plotted in Fig. S2, the microring with a height of 0.5 $\mu$m allows a larger phase-matching width between $TM_{00}$ visible and second-order ($TM_{20}$) UV modes when the ring width is varied. In contrast, the phase-matched $TM_{20}$ mode is cut off when employing a thin AlN film with the thickness below 0.3 $\mu$m.

**Fig. S1.** Dispersion simulation of the AlN microring used in this study (radius: 30 $\mu$m, cross section: 0.8 × 0.5 $\mu$m$^2$). (a) Refractive indices of bulk AlN for extraordinary and ordinary lights, respectively. (b–d) Simulated $n_{\text{eff}}$, FSR, and GVD for TM and TE mode families, respectively. In (c), the simulated FSR values at 390 nm are indicated by the dashed lines. In (d), avoided mode crossings are responsible for the discontinuous spikes and dips in the GVD curves of $TE_{10}$ and $TM_{10}$ modes.
2. BACKGROUND FLUCTUATION IN TRANSMISSION SPECTRUM

Figure S3 shows an exemplary UV transmittance recorded at an optimal coupling of the output UV beam into the following fiber port at the wavelength of 390 nm. It is evident that the background variation of the transmittance in Fig. 2 of the main text is greatly suppressed when a piecewise alignment approach is exploited.

3. SIDEWALL SCATTERING LOSS

According to Eq. (1) of the main text, the sidewall scattering loss in optical waveguides is in proportion to the modal intensity at the core-cladding interface \( E_2^2 \int E^2 ds \). Figure S4 shows the simulation by FEM that \( E_2^2 \int E^2 ds \) increases significantly at a small ring width below 0.6 \( \mu \)m, while it tends to be a constant value at a large ring width above 1.0 \( \mu \)m. The TE\(_{00}\) mode is also found to exhibit a larger \( E_2^2 \int E^2 ds \) than that of TM\(_{00}\) mode. The theoretical prediction is consistent with experimental results in Fig. 3 of the main text.

4. RAYLEIGH SCATTERING LOSS

(a) Measured TM\(_{00}\) resonance of a visible AlN microring (radius: 60 \( \mu \)m, cross section: 1.4 \( \times \) 0.5 \( \mu \)m\(^2\), gap: 0.3 \( \mu \)m) with the simulated modal profile shown in the inset. (b) Measured TM\(_{00}\) resonance of a NIR AlN microring (radius: 100 \( \mu \)m, cross section: 3.0 \( \times \) 1.6 \( \mu \)m\(^2\), gap: 0.4 \( \mu \)m, gap: 0.6 \( \mu \)m) via a swept telecom laser. Inset shows the simulated modal profile. (c) A logarithmic plot of \( \alpha_{\text{ring}} \) versus the wavelength for our single-crystalline AlN microrings, including the values at 390 and 455 nm for the 0.8-\( \mu \)m-wide AlN microring in the main text. The linear fit (green) of the experimental data (red) indicates an approximate \( \alpha_{\text{ring}} \propto \lambda^{-3} \) in our AlN chips. The light blue fit (dashed line) with a reduced fitting error is plotted by assuming an even lower \( \alpha_{\text{ring}} \) of 0.5 dB/cm and 0.05 dB/cm in visible and NIR regions, respectively.
We further explore the influence of Rayleigh scattering loss ($\alpha_{\text{Rayleigh}}$) by including the recorded $Q$-factors at visible and near-infrared (NIR) wavelengths using the AlN microrings fabricated from the same recipe. Figure S5(a) plots the $Q$-factors around 771 nm from a 0.5-µm-thick AlN microring that is characterized by the Ti:sapphire laser in Fig. 1(e) of the main text. The extracted $Q_{\text{int}}$ is $4.8 \times 10^5$ at under-coupled condition, corresponding to a propagation loss ($\alpha_{\text{ring}}$) of 1.6 dB/cm. We believe that a higher visible $Q_{\text{int}}$ can be anticipated provided that a thicker AlN film (e.g., 1 µm) is employed to reduce the scattering loss from the bottom and top interfaces.

Figure S5(b) depicts the $Q$-factors around 1550 nm from an AlN microring designed at NIR wavelengths. The recorded $Q_{\text{int}}$ is up to $2.0 \times 10^6$ at under-coupled condition, corresponding to a low $\alpha_{\text{ring}}$ of 0.2 dB/cm. Since Rayleigh scattering loss is related to the wavelength as $\alpha_{\text{Rayleigh}} \propto \lambda^{-4}$, we summarize the recorded $\alpha_{\text{ring}}$ at the wavelengths from 390 to 1550 nm in Fig. S5(c). Based on the expression: $\log(\alpha_{\text{ring}}) = A - m \cdot \log(\lambda)$ (A and m are relevant coefficients), a linear fit (green curve) is carried out in Fig. S5(c) with an approximate $\alpha_{\text{ring}} \propto \lambda^{-3}$, which is slightly deviated from the Rayleigh scattering-induced loss ($\propto \lambda^{-4}$). The discrepancy can be interpreted by excluding the interface scattering loss ($\alpha_{\text{interface}}$) of the AlN microrings at visible and NIR wavelengths so as to permit an even lower $\alpha_{\text{ring}} = \alpha_{\text{Rayleigh}} + \alpha_{\text{interface}} + \alpha_{\text{absorption}}$, where the material absorption loss ($\alpha_{\text{absorption}}$) is negligible due to the large bandgap (~6.2 eV) of the AlN film. For instance, when assuming a lower $\alpha_{\text{ring}}$ of 0.5 dB/cm and 0.05 dB/cm for the visible and NIR AlN microrings (light blue plots in Fig. S5(c)), we obtain a $\alpha_{\text{ring}} \propto \lambda^{-3.6}$ based on the same $\alpha_{\text{ring}}$ at 390 and 455 nm. This result together with the reduced fitting error ($\pm 0.17$) suggests that $\alpha_{\text{ring}}$ at 390 and 455 nm is close to the Rayleigh scattering-dominated loss, and $\alpha_{\text{interface}}$ in the AlN microring at 390 and 455 nm is mitigated using a relatively large cross section of $0.8 \times 0.5$ µm².