

Supplementary Material for: High-Q cryogenic surface acoustic wave resonators in the GHz range

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SUPPLEMENTARY MATERIAL

A. Device

Fig. S1 shows a reference device with reference design that uses a cavity length $d^* = 200.5 \lambda_0$, together with $N_{\text{IDT}} = 39$, $N_{\text{DBR}} = 500$, aperture $W = 45 \mu\text{m}$, and $\lambda_0 = 800 \text{ nm}$.

B. Setup

The frequency response of the SAW resonators was measured with a vector network analyzer (VNA) from Rohde & Schwarz at room temperature and approximately 4–5 K. The VNA is connected by SMA cables to a dipstick with low attenuation coaxial cables where PCB containing the devices is connected. The devices are wire bonded with aluminum wires. At room temperature, the VNA is calibrated to eliminate standing waves in the signal caused by the cables. After the sample is cooled down, the dipstick is slightly retracted before the measurement is made to avoid dissipation introduced by the liquid helium¹ since our system is not under vacuum. To minimize noise, the VNA is set to a power of -3 dBm and bandwidth of 1 kHz .

To ensure consistent convergence of the fit, the data were processed beforehand to eliminate artifacts due to the setup. The standing waves created by the cables cause smooth distortions within the frequency response of the resonator. This smooth background can be removed using an Asymmetric Least Squares (ALS) Baseline Correction, leaving the resonance dips of the res-

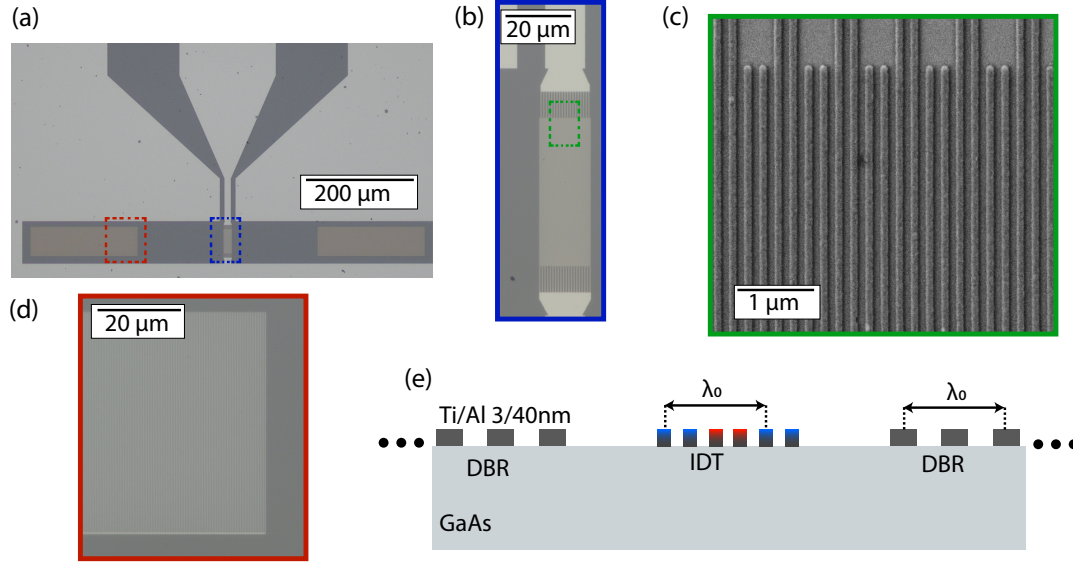


FIG. S1. Optical and SEM micrograph of a reference device (a) Full device surrounded by a ground plane fabricated at the same time as the IDT and DBRs with the same stack. The IDT is connected to a coplanar $50\ \Omega$ waveguide on one side, where a large bonding pad provides the sufficient space for wirebonding. The different color of the DBR and IDT is due to optical diffraction effects despite the two objects having the same metallization. (b-d) zoomed optical (b and d) and SEM (c) pictures of the device shown in panel (a), where the color of the frame corresponds to the dashed boxes. (e) Cross sectional diagram showing the stack of bulk substrate and the SAW resonator components. The IDT fingers are colored to represent the RF polarity. The diagram is not to scale. **Alt text:** (a) Optical overview of a fabricated SAW device connected to large contact pads. Colored boxes identify regions enlarged in later panels; the scale bar is 200 micrometers. (b) Optical close-up of the narrow resonator region between electrical leads. A green box marks the electrode area enlarged in panel (c); the scale bar is 20 micrometers. (c) Electron micrograph of the periodic metal electrode fingers, showing submicrometer spacing. The scale bar is 1 micrometer. (d) Optical close-up of one patterned end of the acoustic device and the adjacent etched boundary. The scale bar is 20 micrometers. (e) Cross-sectional schematic of the GaAs device. Titanium/aluminum electrodes form the central interdigitated transducer and two distributed Bragg reflectors, with electrode periods labeled by λ_0 .

onator intact. The off-resonant background is then normalized to 0 dB relative attenuation. This procedure removes only a slowly varying background and does not affect the extracted quality factor, which is determined by the resonance linewidth and phase response. The finite length of

the coaxial cables leads to a delay of the signal between the input and output of the VNA. This causes a slope in the phase of the signal. While there are more elaborate procedures to properly account for this delay², removing a linear offset of the resonator phase improves the convergence of the resonator fit. The quality factors used for further analysis are the result of the average of the central resonances in the comb, where the internal quality factor is the most consistent.

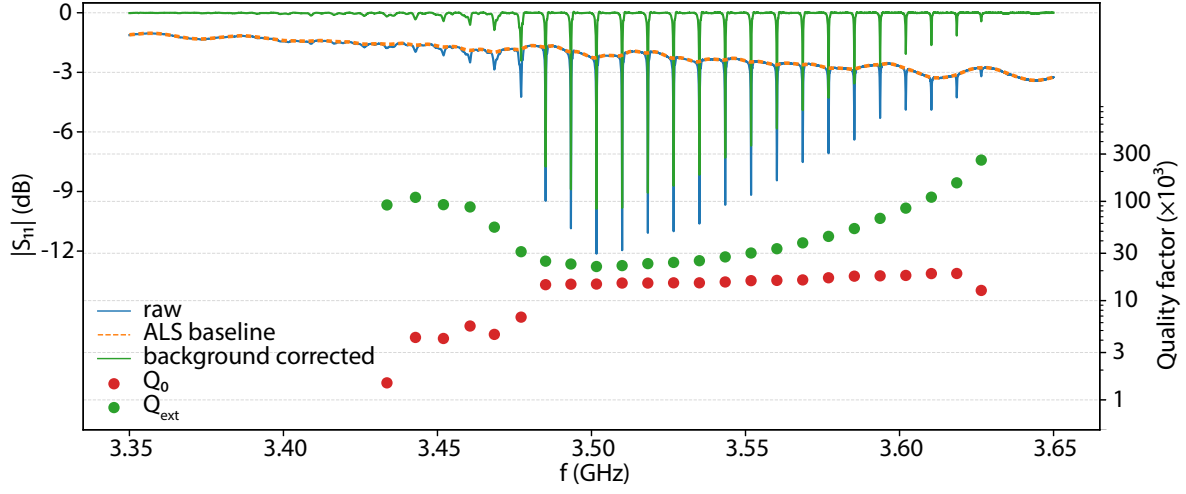


FIG. S2. Background removal operation of the trace in Fig. 1(a) in the main text. External and internal quality factors are indicated. **Alt text:** The quality factors and the spectrum are shown in the same plot. Spectrum data: Raw reflection magnitude, the asymmetric-least-squares baseline, and the background-corrected trace are plotted from 3.35 to 3.65 GHz. Baseline removal preserves the narrow resonant dips. Quality-factor data: Internal Q_0 and external Q_{ext} values are overlaid on a logarithmic right axis. Q_0 is comparatively uniform for central modes, while Q_{ext} increases strongly toward the edges of the measured band.

C. Power dependence

Surface and interface defects, including two-level systems (TLS), can contribute to acoustic loss and may produce a characteristic drive-power dependence at sufficiently low temperature and excitation power^{3–5}. In our devices, the resonance frequencies correspond to $hf/k_B \simeq 170$ –230 mK, which is well below the measurement temperature of approximately 5 K. Therefore, resonant TLS saturation is not expected to be the dominant temperature-dependent loss mechanism in this regime. Consistent with this expectation, the drive-power sweeps show no measurable

change in resonance frequency or quality factor within the standard error over the accessible power range as seen in Fig. S3. Increasing the drive power mainly improves the signal-to-noise ratio, indicating that nonlinear or TLS-like power-dependent losses are not the main limitation in these measurements.

D. Extraction of finger reflectivity, SAW velocity, and mode spacing

The mode spacing provides a direct estimate of the single-finger reflectivity of the DBRs and of the SAW velocity. We model the resonator as an acoustic Fabry–Pérot cavity with an effective length larger than the lithographic cavity size, because the standing wave penetrates into the DBRs. The mode spacing is therefore

$$\Delta f = \frac{v}{2L_c}, \quad L_c = d^* + 2L_p, \quad (1)$$

where d^* is the physical separation between the IDT and one DBR and L_p is the penetration length into one reflector. For a weak periodic reflector, the acoustic amplitude decays inside the grating over a characteristic length

$$L_p \simeq \frac{\lambda_0}{4|r_s|}, \quad (2)$$

where r_s is the single-finger amplitude reflectivity. The factor $1/|r_s|$ reflects the number of weakly reflecting periods required to build up the mirror response, while the numerical factor follows from the Bragg condition and the phase relation between successive reflections in the grating.

Using $f_0 = v/\lambda_0$, Eqs. (1) and (2) give

$$\Delta f = \frac{f_0}{2d^*/\lambda_0 + 1/|r_s|}, \quad \frac{f_0}{\Delta f} = \frac{2d^*}{\lambda_0} + \frac{1}{|r_s|}. \quad (3)$$

Thus, a linear fit of $f_0/\Delta f$ as a function of d^*/λ_0 yields the single-finger reflectivity from the intercept. The SAW velocity is extracted independently from a linear fit of $1/\Delta f$ as a function of the physical cavity size d^* , for which the slope is $2/v$. The corresponding fits are shown in Fig. S4.

For the devices studied here, we obtain

$$|r_s| = (3.4 \pm 0.1)\%, \quad v = (2867 \pm 8) \text{ ms}^{-1}, \quad L_p \simeq 5.9 \text{ } \mu\text{m} \simeq 7.4 \lambda_0. \quad (4)$$

The extracted value of r_s also determines the DBR mirror strength. In the weak-reflection limit, the total amplitude reflectivity of a DBR with N_{DBR} fingers is approximately

$$|\Gamma| \simeq \tanh(N_{\text{DBR}}|r_s|). \quad (5)$$

For $N_{\text{DBR}} = 500$, this gives $N_{\text{DBR}}|r_s| \gg 1$, corresponding to near-unity reflectivity at the center of the stop band. The corresponding DBR stop-band width can be estimated as

$$\Delta f_{\text{DBR}} \simeq \frac{2f_0|r_s|}{\pi}. \quad (6)$$

This bandwidth sets the frequency range over which the acoustic mirrors provide efficient confinement. Modes far from the stop-band center experience reduced mirror reflectivity and therefore weaker confinement.

In a one-port resonator, the IDT acts both as the emitter and detector of SAWs. Because the IDT has a finite number of electrodes, its transduction efficiency is frequency dependent and follows an envelope set by its spatial Fourier transform. To leading order, the accessible bandwidth scales inversely with the number of IDT electrodes^{4,6},

$$\Delta f_{\text{IDT}} \approx 1.8 \frac{f_0}{N_{\text{IDT}}}. \quad (7)$$

The measured spectrum is therefore shaped by two frequency-dependent filters: the DBR stop band determines the range of frequencies over which modes are confined, while the IDT bandwidth determines how efficiently those modes are excited and detected. This explains why modes away from the design frequency appear with reduced amplitude in Fig. 1(a) of the main text.

E. Quality factor fit

SAW resonators are commonly modeled using the Butterworth von Dyke equivalent circuit⁷ to describe their frequency response. Close to the resonance frequency, the resonator can be described by a simpler series RLC circuit, which allows the reflection coefficient to be written as a function of the internal and external quality factor. Using $\delta f = (f - f_0)/f_0$ with f_0 being the resonance frequency, the fitting function to extract the internal Q_0 and external Q_{ext} quality factors

from the resonance is given by Eq. 8.

$$S_{11}(f) = A \cdot \frac{\frac{Q_{ext}-Q_0}{Q_{ext}} + i2Q_0\delta f}{\frac{Q_{ext}+Q_0}{Q_{ext}} + i2Q_0\delta f} \cdot e^{i\phi} \quad (8)$$

Here, ϕ accounts for an arbitrary sweep starting phase and A for a global scaling factor. The values of interest are the resonance frequency f_0 and Q_0 , Q_{ext} . By choosing a complex-valued Q_{ext} , we can account for asymmetric resonance shapes. The fitting was performed using an adapted version of the complex resonator model⁸. Rather than fitting only the magnitude of the data, this model fits the circular shape of the resonance in the complex plane.

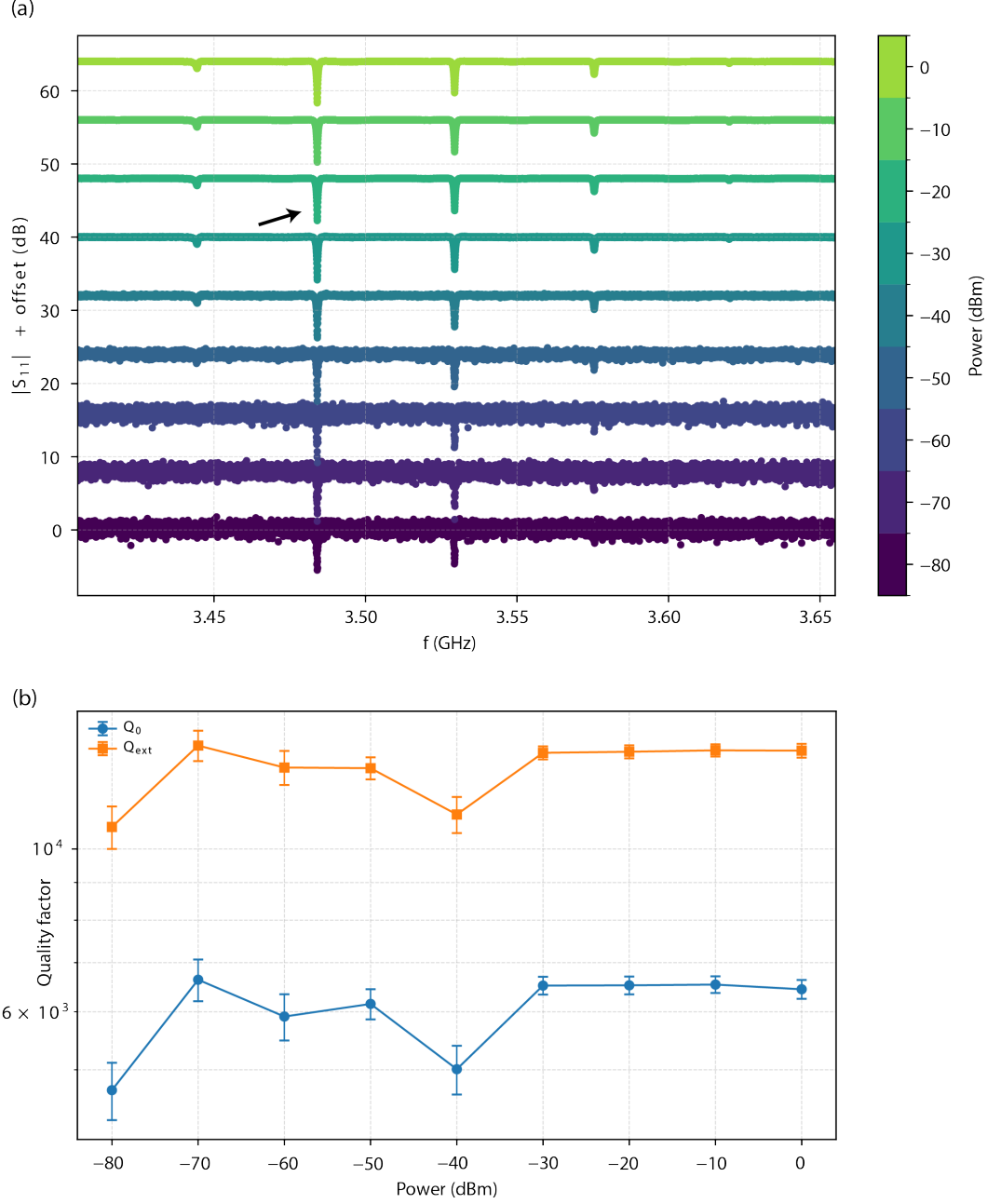


FIG. S3. Power dependence of a selected resonance. (a) Cascade plot of baseline-corrected S_{11} traces, vertically offset for clarity, with increasing VNA power. (b) Extracted Q_0 and Q_{ext} as a function of drive power for the dip indicated by the arrow in panel (a) and error bars from the fit. **Alt text:** (a) Vertically offset reflection spectra for input powers from -80 to 0 dBm, colored from dark purple to yellow-green. Resonance positions and line shapes remain nearly unchanged while the noise decreases as power increases; an arrow marks a representative resonance. (b) Internal and external quality factors versus power. Both fluctuate at the lowest powers with large error bars but are approximately constant, indicating no systematic power dependence in the accessible range.

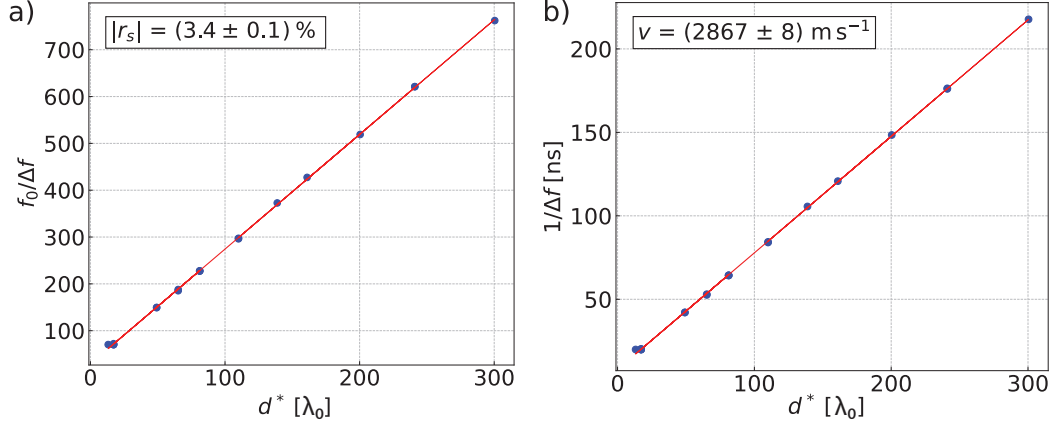


FIG. S4. Extraction of the single-finger reflectivity and SAW velocity from the cavity mode spacing. (a) Inverse normalized mode spacing $f_0/\Delta f$ as a function of cavity size d^*/λ_0 . The linear fit follows Eq. (3), and the intercept yields the single-finger reflectivity $|r_s|$. (b) Inverse mode spacing $1/\Delta f$ as a function of the physical cavity size d^* . The slope of the linear fit gives the SAW velocity v . Error bars are smaller than the symbol size and are omitted for clarity. **Alt text:** (a) Normalized inverse mode spacing $f_0/\Delta f$ versus cavity size d^*/λ_0 . Blue data follow a red linear fit; the intercept gives a single-finger reflectivity $|r_s| = 3.4$ plus or minus 0.1 percent. (b) Inverse mode spacing $1/\Delta f$ versus physical cavity size d^* . Blue data follow a red linear fit whose slope gives a surface acoustic wave velocity $v = 2867$ plus or minus 8 m/s.

F. Measured devices

TABLE S1: Main dip fit results. The angle with respect to the cleaving direction θ , resonant frequency, quality factors of the most prominent resonance, the phase jump $\Delta\phi$, and median internal quality factor $\tilde{Q}_0/10^3$ for each device are indicated.

Device	λ_0 (nm)	d^*/λ_0	θ (°)	f_0 (GHz)	$Q_0/10^3$	$ Q_{\text{ext}} /10^3$	$f_0 Q_0/10^{13}$	$\Delta\phi$ (rad)	$\tilde{Q}_0/10^3$
$V1_{P2}$	800	0.5	0	3.53	3.88	7.67	1.37	1.08	3.74
$V4_{P5}$	800	0.5	0	3.54	5.16	9.52	1.83	1.2	5.01
NE_C	800	25.5	0	3.48	8.5	51.82	2.96	0.37	8.19
SW_C	800	25.5	0	3.53	10.03	35.63	3.54	0.71	9.58
NW_G	800	25.5	0	3.51	9.76	32.06	3.42	0.75	9.40
SE_J	800	50.5	0	3.49	11.49	49.86	4.01	0.49	11.13
SW_B	800	50.5	0	3.5	13.31	30.34	4.66	0.93	12.82
NE_B	800	50.5	0	3.5	16.07	35.59	5.63	0.99	15.56
SE_E	800	150.5	0	3.52	17.51	423.03	6.17	0.09	17.13
SE_I	800	200.5	0	3.49	19.69	286.82	6.87	0.14	18.99
SE_C	800	200.5	0	3.52	19.33	337.41	6.8	0.13	18.18
NW_C	800	200.5	0	3.5	19.93	438.95	6.98	0.09	19.53
NW_I	800	200.5	0	3.47	20.68	356.2	7.18	0.12	19.82
NW_P	800	300.5	0	3.47	23.47	249.38	8.13	0.19	23.05
SE_P	800	300.5	0	3.5	21.4	232.43	7.48	0.19	20.91
NE_i	800	25.5	5	3.47	4.69	166.97	1.63	0.07	4.60
SW_I	800	25.5	5	3.52	3.38	111.36	1.19	0.07	3.27
NE_J	800	200.5	5	3.48	4.34	224.12	1.51	0.04	4.17
NE_K	800	25.5	10	3.48	3.92	57.45	1.37	0.16	3.80
SW_K	800	25.5	10	3.49	3.39	43.45	1.18	0.18	3.26
NE_l	800	200.5	10	3.47	7.34	303.94	2.55	0.05	7.17
SW_L	800	200.5	10	3.45	5.87	145.7	2.03	0.1	5.66

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TABLE S1: Main dip fit results continued.

Device	λ_0 (nm)	d^*/λ_0	θ (°)	f_0 (GHz)	$Q_0/10^3$	$ Q_{\text{ext}} /10^3$	$f_0 Q_0/10^{13}$	$\Delta\phi$ (rad)	$\tilde{Q}_0/10^3$
SE_S	800	25.5	20	3.41	2.47	88.68	0.84	0.06	2.42
NW_S	800	25.5	20	3.42	1.9	34.38	0.65	0.12	1.81
NW_R	800	200.5	20	3.4	2.49	151.37	0.85	0.04	2.39
$TF1_O$	800	200.5	30	3.38	10.01	449.92	3.39	0.05	9.74
$TF1_P$	800	200.5	30	3.4	5.33	393.59	1.81	0.03	5.22
$TF2_O$	800	200.5	30	3.38	9.16	255.79	3.1	0.08	8.92
$TF2_P$	800	200.5	30	3.39	7.07	319.07	2.39	0.04	6.83
NW_M	575	200.5	0	4.64	12.16	249.55	5.64	0.11	11.74
SW_F	575	200.5	0	4.71	13.78	177.57	6.48	0.16	13.32
SW_D	600	200.5	0	4.51	16.02	317.45	7.23	0.1	15.28
SE_V	680	200.5	0	4.06	15.9	221.03	6.45	0.15	15.55
SE_D	750	200.5	0	3.69	17.61	674.37	6.49	0.05	16.87
SE_B	820	200.5	0	3.41	19.73	218.4	6.74	0.19	18.99
SE_K	1200	200.5	0	2.37	27.65	454.76	6.57	0.12	27.12
SE_L	1200	200.5	0	2.38	28.2	325.38	6.7	0.18	26.98
NW_K	1200	200.5	0	2.37	25.51	388.42	6.06	0.13	24.41
FBC_Q	575	21.5	0	4.68	2.87	48.71	1.34	0.14	2.76
FBC_K	600	21.5	0	4.6	3.98	36.58	1.83	0.23	3.83
FBC_M	680	21.5	0	4.13	4.71	40.7	1.95	0.36	4.46
FBC_C	750	21.5	0	3.76	4.89	27.29	1.84	0.43	4.80
FBC_H	820	21.5	0	3.45	5.98	58.42	2.06	0.21	5.72
FBC_P	920	21.5	0	3.1	6.57	27.6	2.04	0.51	6.37
FBC_L	1200	21.5	0	2.39	7.04	56.75	1.68	0.25	6.77

Alt text: Device-level fit results list wavelength, normalized cavity length, rotation angle, resonance frequency, internal and external quality factors, frequency-quality-factor product, phase jump, and median internal quality factor. The highest values, approximately 25000-28000, occur for long cavities at zero rotation and 1200-nanometer wavelength. The table is on two pages.

TABLE S2. Main dip fit results for devices with $\theta = 0$ with respect to the cleaving direction. The phase jump $\Delta\phi$, whether the device lies on an etched substrate, and the number of mesa steps and median quality factor $\tilde{Q}_0/10^3$ for each device are indicated.

Device	λ_0 (nm)	d^*/λ_0	f_0 (GHz)	$Q_0/10^3$	$ Q_{\text{ext}} /10^3$	$f_0 Q_0/10^{13}$	$\Delta\phi$ (rad)	$\tilde{Q}_0/10^3$	Etched	Mesa
<i>FT1_C</i>	800	200.5	3.54	24.18	63.13	8.55	0.83	22.32	No	0
<i>FT1_A</i>	800	200.5	3.52	17.3	91.35	6.09	0.39	15.88	No	0
<i>FT1_B</i>	800	200.5	3.53	13.57	99.03	4.8	0.29	12.66	No	0
<i>FT2_A</i>	800	200.5	3.51	19.51	104.76	6.85	0.38	18.56	No	0
<i>FT1_D</i>	800	200.5	3.51	19.12	82.58	6.72	0.47	17.60	Yes	0
<i>FT1_M</i>	800	200.5	3.52	16.22	93.6	5.71	0.35	15.41	Yes	0
<i>FT1_G</i>	800	200.5	3.51	27.77	50.84	9.76	1.2	25.70	Yes	0
<i>FT1_J</i>	800	200.5	3.52	21.91	63.64	7.72	0.75	20.49	Yes	0
<i>FT2_D</i>	800	200.5	3.51	12.29	111.33	4.31	0.22	11.56	Yes	0
<i>FT2_G</i>	800	200.5	3.52	26.6	62.37	9.36	0.92	25.24	Yes	0
<i>FT2_J</i>	800	200.5	3.51	17.82	105.03	6.26	0.35	16.52	Yes	0
<i>FT1_E</i>	800	200.5	3.53	5.43	46.42	1.91	0.23	5.12	Yes	1
<i>FT1_K</i>	800	200.5	3.52	5.47	94.82	1.93	0.11	5.00	Yes	1
<i>FT2_K</i>	800	200.5	3.52	4.74	47.91	1.67	0.21	4.40	Yes	1
<i>FT2_E</i>	800	200.5	3.51	4.77	141.53	1.68	0.07	4.47	Yes	1
<i>FT2_I</i>	800	200.5	3.52	7.03	49.4	2.47	0.31	6.54	Yes	1
<i>FT1_F</i>	800	200.5	3.52	3.2	126.35	1.13	0.05	2.95	Yes	2
<i>FT1_L</i>	800	200.5	3.51	2.89	144.54	1.02	0.04	2.72	Yes	2
<i>FT2_L</i>	800	200.5	3.52	2.57	89.72	0.91	0.25	2.43	Yes	2
<i>FT2_F</i>	800	200.5	3.52	3.52	56.43	1.24	0.13	3.39	Yes	2
<i>FT2_H</i>	800	200.5	3.51	2.36	62.24	0.83	0.08	2.24	Yes	2

Alt text: Device-level fit results for zero-rotation devices compare non-etched resonators, uniformly etched resonators, and devices containing one or two mesa steps. Uniform etching leaves quality factors broadly comparable to non-etched controls, whereas one mesa reduces median Q_0 to roughly 4000-6500 and two mesas to roughly 2000-3400.

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