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Multi-mode ultra-strong coupling (I): spectroscopic experiments using a vacuum-gap transmon circuit architecture SAL J. BOSMAN, MARIO F. GELY, Kavli Institute of NanoScience, Delft University of Technology,, VIBHOR SINGH, Indian Institute of Science, Bangalore, ALESSANDRO BRUNO, Qutech Advanced Research Center, Delft University of Technology,, DANIEL BOTHNER, GARY A. STEELE, Kavli Institute of NanoScience, Delft University of Technology, — In circuit QED, multi-mode extensions of the quantum Rabi model suffer from divergence problems. Here, we spectroscopically study multi-mode ultra-strong coupling using a transmon circuit architecture, which provides no clear guidelines on how many modes play a role in the dynamics of the system. As our transmon qubit, we employ a suspended island above the voltage anti-node of a $\lambda/4$ coplanar microwave resonator, thereby realising a circuit where 88% of the qubit capacitance is formed by a vacuum-gap capacitor with the center conductor of the resonator. We measure vacuum Rabi splitting over multiple modes up to 2 GHz, reaching coupling ratios of $g/\omega = 0.18$, well within the ultra-strong coupling regime. We observe a qubit-mediated mode coupling, measurable up to the fifth mode at 38 GHz. Using a novel analytical quantum circuit model of this architecture, which includes all modes without introducing divergencies, we are able to fit the full spectrum and extract a vacuum fluctuations induced Bloch-Siegert shift of up to 62 MHz. This circuit architecture expands the versatility of the transmon technology platform and opens many possibilities in multi-mode physics in the ultra-strong coupling regime.

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