Center for Quantum Networks
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Simulation-guided design of an integrated photonic cavity for frequency-multiplexed SPDC

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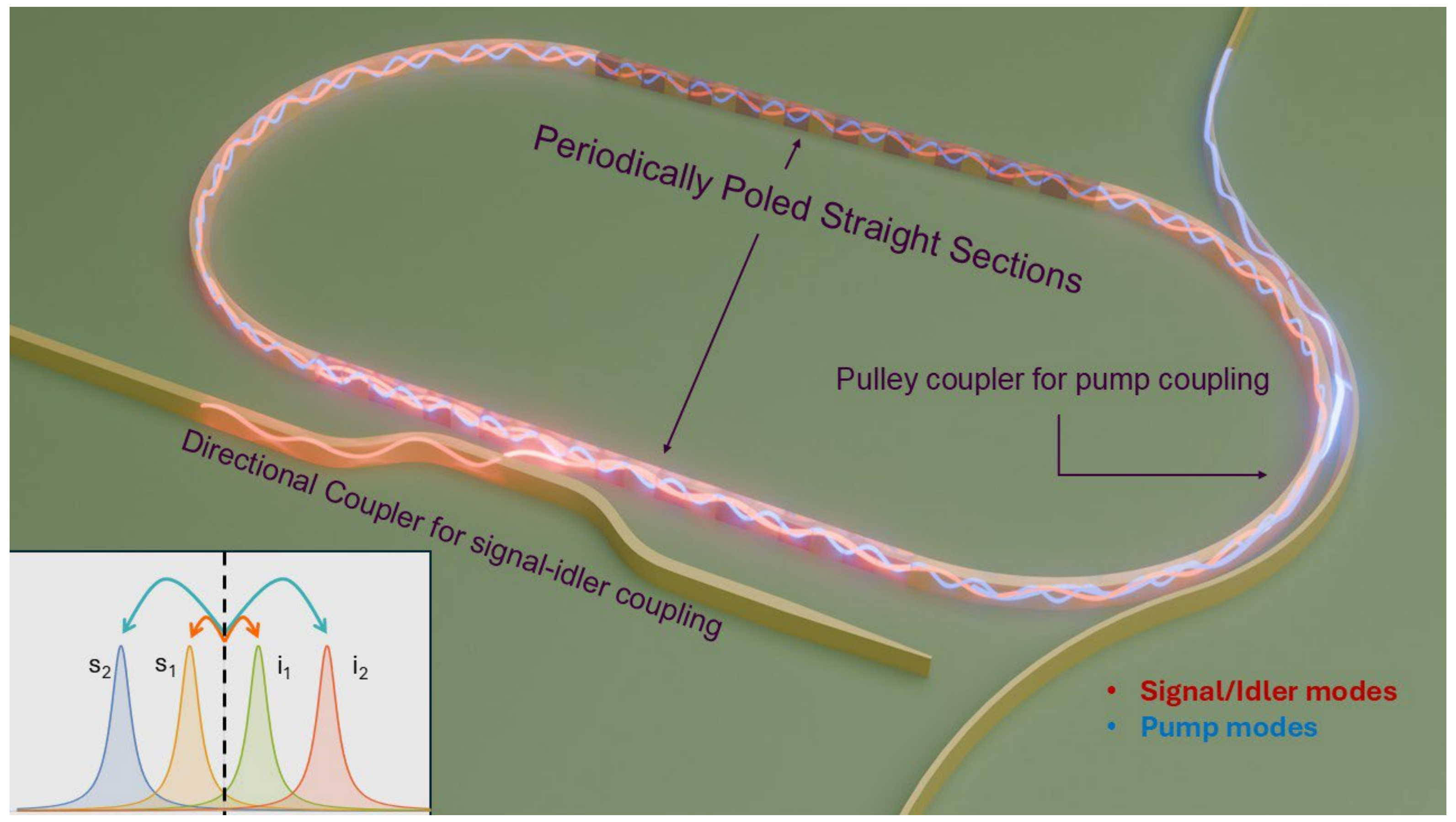

Figure 1. Proposed integrated photonic racetrack cavity layout for a frequency-multiplexed spontaneous parametric down-conversion photon pair source. An asymmetric pulley coupler couples the pump light in without reducing the cavity finesse at the signal/idler wavelengths.

The ZALM protocol requires a frequency-multiplexed, frequency-entangled source of photons that are suitable for frequency-heralding. An integrated cavity source would be able to produce photon pairs with the desired joint spectral amplitude (JSA) patterns. By periodically poling the straight section of a racetrack resonator and using wavelength-selective couplers, we can design a resonator that is compatible with both z-cut and x-cut uniaxial crystal wafers, meaning the same designs can be easily updated for various material platforms based on the current state of the art fabrication technology.

Integrated devices are easier to mass-produce than free-space optical devices which makes them suitable for building quantum networks at scale. However, the industry-standard photonic simulation tools cannot predict quantum state outputs natively. To fill the hole in the available tools, have built a simulation pipeline which predicts the JSA and the pair generation rate (PGR) of an integrated cavity from classical finite-difference electromagnetics simulations.

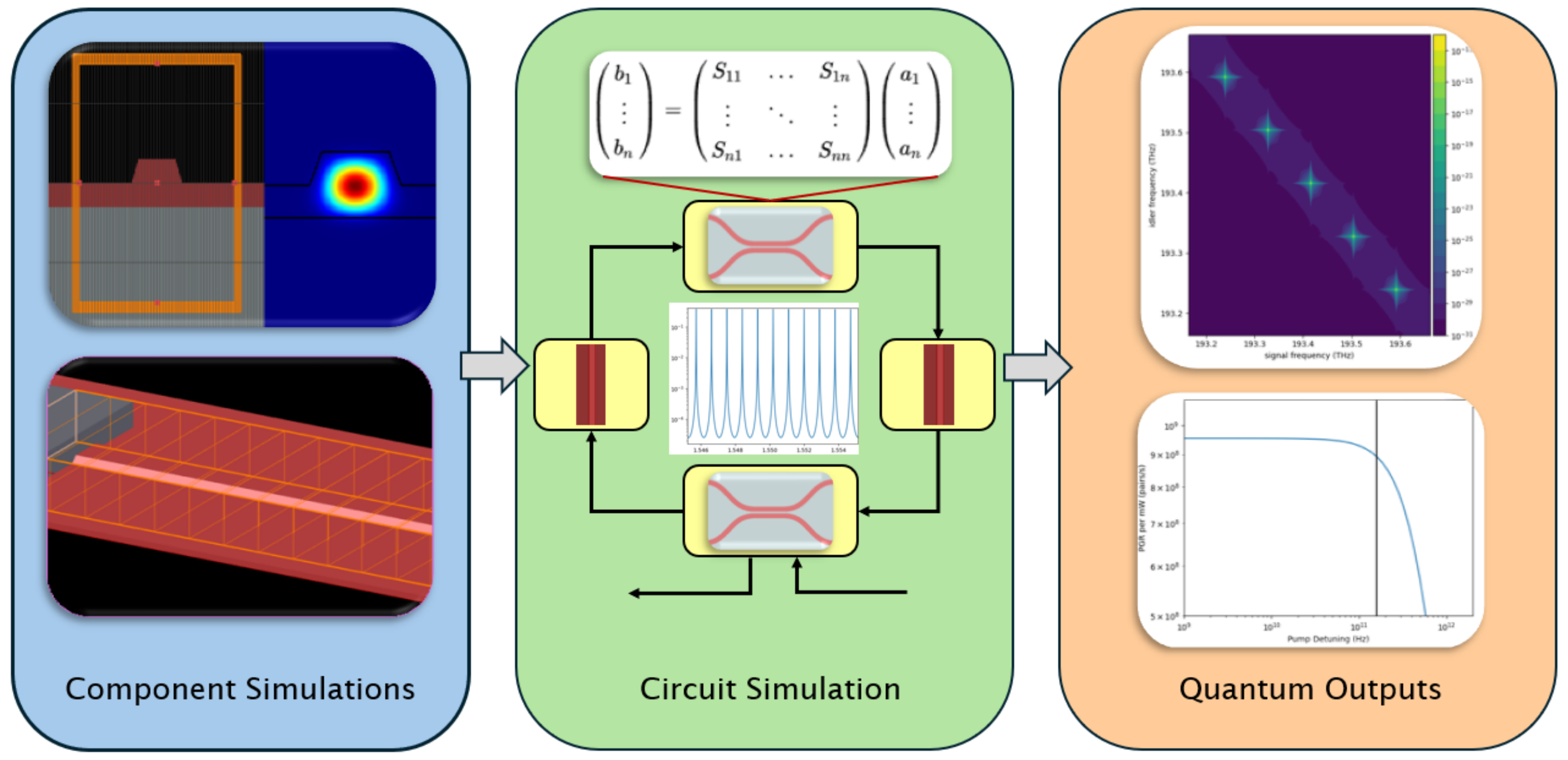

Figure 2. Overview of source simulation pipeline. Scattering parameters are extracted from finite difference simulations (Lumerical FDTD, EME, FDE) which are then used in a photonic circuit simulator to calculate the classical frequency response of the cavity. Finally, a theoretical model of the cavity SPDC is used to numerically calculate the produced photon pairs' JSA and PGR.

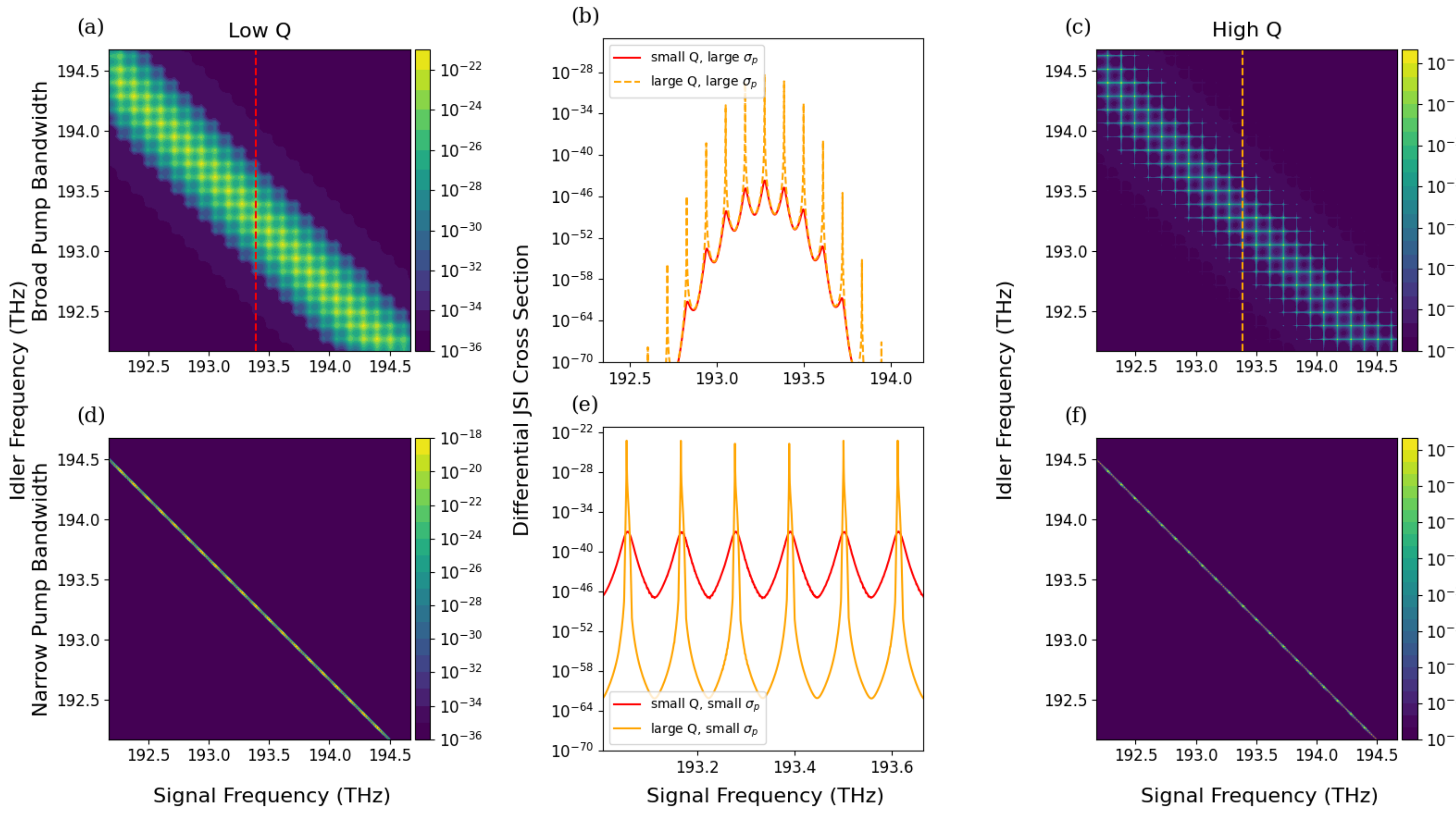

Figure 3. JSA predictions for cavity sources with varying Q and pump bandwidths. To produce the desired island-JSA pattern, a high Q cavity is desired, and the pump bandwidth should be narrow enough to eliminate side-islands. Plots (b),(e) show slices of the JSA from each plot, plot (b) a marginal distribution where the signal frequency is constant, and plot (e) the distribution along the diagonal which follows the $\omega_s + \omega_i = \omega_p$ line.

Using our pipeline and theoretical models, [1] we varied the simulated cavity characteristics, calculated the JSA for each case, and observed the following:

1. If we use a pump bandwidth that is larger than the free spectral range (FSR) of the cavity, we get off-diagonal islands which makes the photon pair unsuitable for frequency heralding.
2. Low Qs increase the overlap between the various islands, creating coupling between the distinct frequency-modes which introduces the possibility of heralding in the wrong frequency mode.

Therefore, a high-Q (>10^5) and a narrow pump bandwidth are desired.

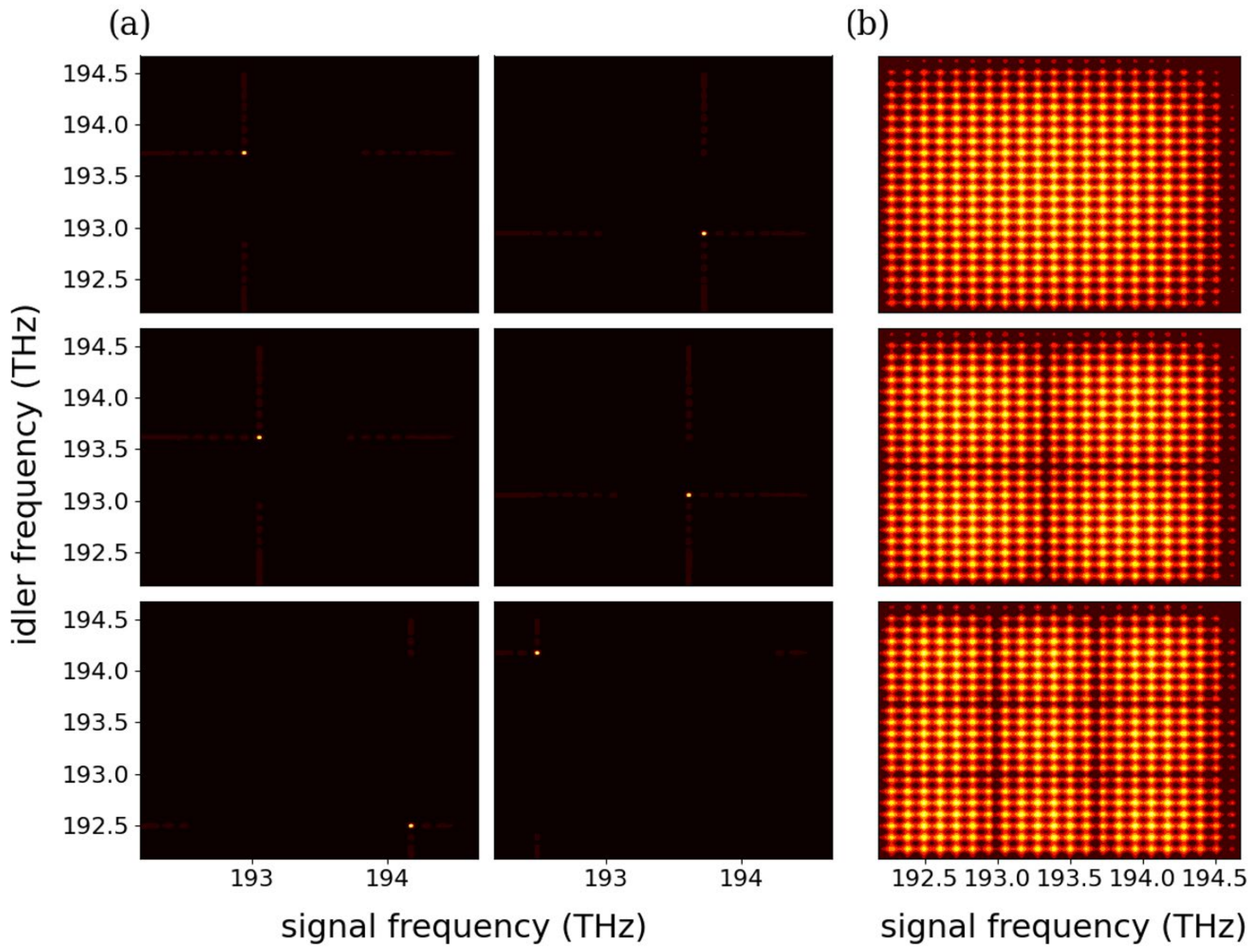

Figure 4. Schmidt modes of a cavity source's JSA with a narrow pump bandwidth (a), and broad pump bandwidth (b). Due to the overlapping grid-like structure in the broad pump case, the frequency-state of the two photons is not suitable for frequency-heralding.

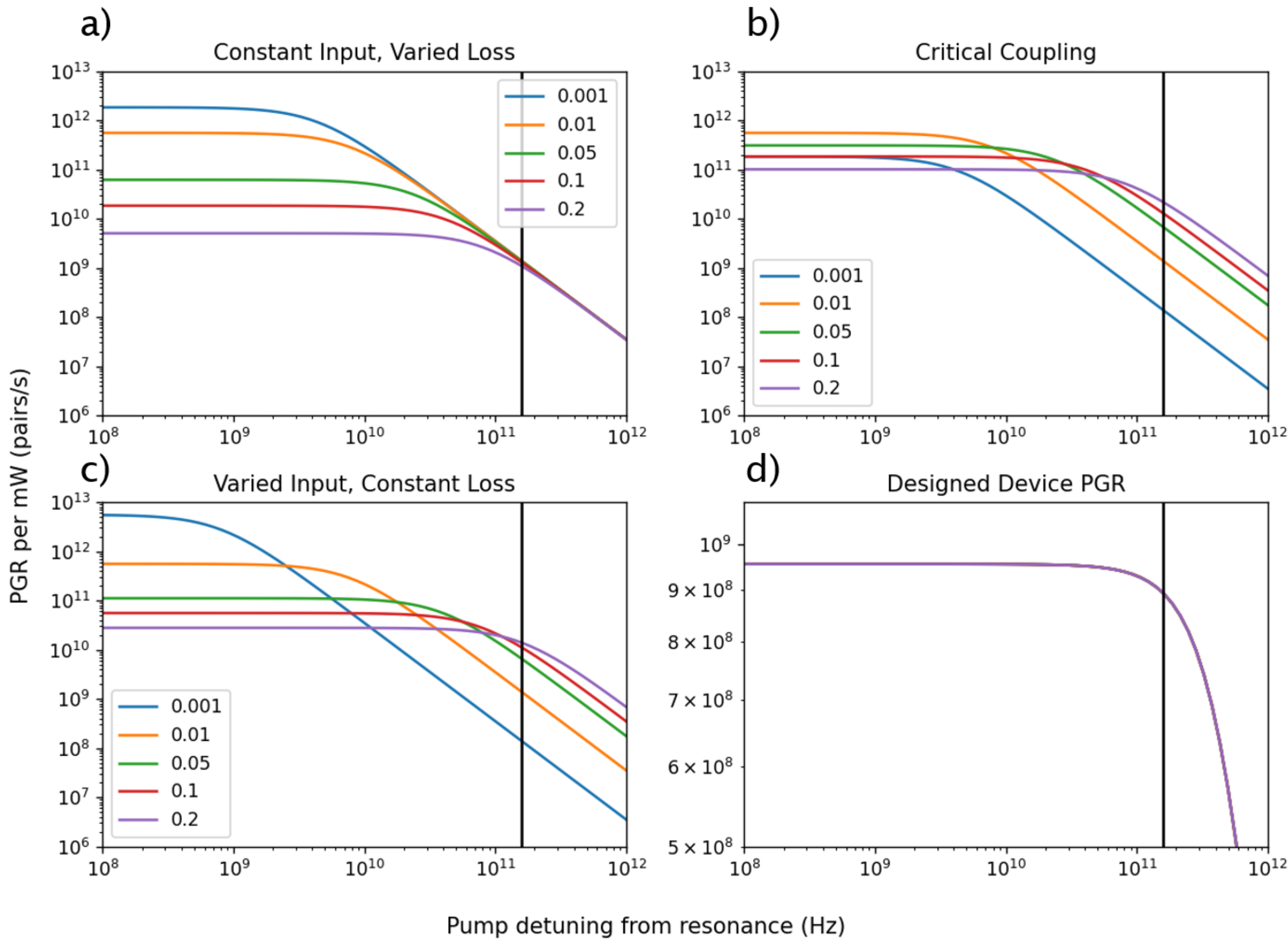

Figure 5. Cavity Source PGR vs. pump detuning for pump resonance properties. Plots (a), (b), (c) are simulations of resonators with semi-ideal couplers to show the effect of increased pump loss/input-output coupling in various cases, and plot (d) is our resonator source's calculated PGR. The legend indicates single-pass coupling constants for the varied parameter. When the subtitle of a plot indicates a constant value, it is set to a 0.01 single-pass coupling constant. The black vertical line indicates maximum detuning, i.e. when the pump is exactly halfway between the two nearest resonances.

We designed our resonator to produce resonant signal and idler photons (double resonance), but it is difficult in practice to make a resonator that is resonant at the pump wavelength as well as at several We calculated the PGR for several ideal couplers and introduced an "imaginary" coupling channel which simulates the effect of extra losses in the cavity. Figure 5 shows the following general trends:

1. Higher pump losses decrease the PGR on-resonance, but have little effect off-resonance.
2. Lower pump coupling increases PGR on-resonance but decreases it off-resonance.
3. High pump coupling decreases PGR on-resonance, but increases it off-resonance.

Unfortunately, triple resonance is difficult to achieve in practice due to fabrication variance for wavelengths that are far apart (775nm and 1550 nm) while also restricting the pump to be in a specific location for multi-island degenerate down-conversion. Therefore, for our initial designs we assumed a completely off-resonant pump which means we don't need to know how close our pump is to resonance. By optimizing for high PGR at maximum detuning, we calculated a PGR of 0.9 GHz/mW per resonant island, for a total of 39.8 GHz/mw PGR efficiency across 44 double-resonant modes.

Acknowledgements

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