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Integrated Whispering-Gallery-Mode Resonator for Solid-State Coherent Quantum Photonics

Arianne Brooks, Xiao-Liu Chu,*, Zhe Liu, Rüdiger Schott, Arne Ludwig, Andreas D. Wieck, Leonardo Midolo, Peter Lodahl, and Nir Rotenberg

ABSTRACT: Tailored photonics cavities enhance light–matter interactions, ultimately enabling a fully coherent quantum interface. Here, we report an integrated microdisk cavity containing self-assembled quantum dots to coherently route photons between different access waveguides. We measure a Purcell factor of $F_{\text{exp}} = 6.9 \pm 0.9$ for a cavity quality factor of about 10,000, allowing us to observe clear signatures of coherent scattering of photons by the quantum dots. We show how this integrated system can coherently reroute photons between the drop and bus ports and how this routing is controlled by detuning the quantum dot and resonator or through the strength of the excitation beam, where a critical photon number less than one photon per lifetime is required. We discuss the strengths and limitations of this approach, focusing on how the coherent scattering and single-photon nonlinearity can be used to increase the efficiency of quantum devices such as routers or Bell-state analyzers.

KEYWORDS: quantum nanophotonics, quantum dots, resonators

INTRODUCTION

Photonic resonators enhance light–matter interactions and play a crucial role in quantum optics. Resonators such as photonic crystal cavities or whispering gallery mode (WGM) resonators have been fabricated on photonic chips, leading to pioneering demonstrations of strong light–matter coupling of single atoms and quantum dots (QDs) or an increase in the coherent interaction between photons and single organic molecules. WGM resonators also support chiral quantum interactions, where photons are emitted or scattered unidirectionally, enabling nonreciprocal single emitter photonic elements such as optical circulators, isolators, and atom–photon SWAP gates.

Here, we create an integrated photonic circuit consisting of a microdisk resonator with embedded self-assembled QDs, access waveguides, and grating couplers, as shown in Figure 1a. Enhancements provided by the resonator help mitigate decoherence effects, notably spectral diffusion, enabling observation of coherent scattering of photons from a QD and leading to coherent switching of photons between the bus and drop ports. This stands in contrast to earlier demonstrations using the nonlinear Kerr effect in microcavities, or where QDs embedded in a photonic crystal cavity modulate the transmission across a single channel. Moreover, exploiting the giant optical nonlinearity of quantum emitters allows our router to operate at the single-photon level with no background noise and at cryogenic temperatures, providing compatibility with state-of-the-art superconducting single-photon detectors. Cryogenic spectroscopy and time-resolved measurements in conjunction with quantum optical theory allow us to quantify the effect of the resonator on QD emission and to explore the dependence of photon routing on QD resonator detuning and excitation strength.

INTEGRATED MICRODISK RESONATORS

We fabricate GaAs disk-shaped cavities supporting WGMs that are optically addressed via evanescently coupled single-mode waveguides, as shown in Figure 1a. For our sample, we use a wafer with a QD density of $\approx 10 \, \mu\text{m}^{-2}$, supporting single emitter spectroscopy, and with no electrical contacts. Although electrical contacts have been shown to efficiently overcome QD broadening arising from electrostatic charge fluctuations, they increase absorption losses and fabrication complexity. An alternative strategy using Purcell enhancement to reduce the influence of noise processes is hence preferable. The high

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intrinsic quantum efficiency of QDs means that any nonradiative processes can be neglected (cf. Supporting Information). Consequently, we need only consider radiative decay, which occurs with rates \( \kappa_{\text{ev}} \) and \( \kappa_{\text{leak}} \) into the resonator modes and freespace, respectively, as depicted in Figure 1b.

The disk resonators are fabricated with a 3.5 \( \mu \text{m} \) radius, chosen to ensure an adequate support pillar (\( \approx 1.1 \mu\text{m} \)) remains after under-etching (dark region in Figure 1a,b). Finite element simulations (COMSOL Multiphysics) reveal negligible bending losses. In fact, for the first two radial modes, shown in Figure 1c, we find intrinsic quality factors (Q-factor) limited only by the computational accuracy (\( Q_{\text{theory}} \approx 10^{13} \)). This value is well above typical reported values of \( Q = 10^5 \) for QD-based GaAs resonators \(^{3-5}\) limited by surface roughness and gap-state-related surface absorption.\(^ {26} \) However, these effects can be decreased by employing surface passivation techniques, resulting in ultrahigh Q-factor resonators (\( Q \geq 10^6 \)).\(^ {29} \) In our case, a further reduction due to coupling between the resonator and the access waveguides is expected. From the field distributions, we calculate the effective mode volumes \(^{30} \) of the first and second radial modes \( V_{\text{eff}}^{(1)} \approx 18(\lambda/n)^3 \) and \( V_{\text{eff}}^{(2)} \approx 22(\lambda/n)^3 \) (cf. Supporting Information).

To characterize our resonator, we use an optimized grating coupler\(^ {31} \) to launch light from a tunable continuous-wave laser through the access waveguides and into the disk. The access waveguide is single mode at the 940 nm emission wavelength of the QDs and is tapered to a width of 220 \( \text{nm} \) in the vicinity of the resonator to improve coupling. Additionally, in a series of different structures, the gap between the disk and waveguides is varied between 40 and 160 \( \text{nm} \), in steps of 30 \( \text{nm} \), to determine the critical coupling geometry.

Working at cryogenic temperatures, we scan the excitation laser frequency over a 13 THz bandwidth and record the outcoupled intensity transmitted through the bus and drop ports, as shown in Figure 1a. Example spectra are shown in Figure 2a for a gap size of 100 \( \text{nm} \). In the bus port spectrum, which has been normalized to a highly dispersive background (all dips are shown; see Supporting Information for raw data), we observe sharp dips at the WGM frequencies where the disk couples light from one access waveguide to another. Since different resonator modes couple to the access waveguides with different efficiencies, the depths of the dips \( \Delta T \) vary. As expected, the dips in the bus port spectrum are well-correlated with peaks in the drop port spectrum, and the different resonance orders can be determined by the measured free spectral range. Furthermore, QDs in the cavity are excited nonresonantly using a Ti:sapphire laser at 810 nm (Tsunami) and the emission collected on a spectrometer. Note the strong emission enhancement when the QDs are on resonance with a cavity mode.

These measurements are repeated for all structures, fitting each cavity resonance with a Lorentzian function to determine its width \( \kappa \), allowing us to deduce the loaded Q-factor \( Q_{\text{exp}} = \omega_c / \kappa \), where \( \omega_c \) is the central resonance frequency. A histogram of \( Q_{\text{exp}} \) values is shown in Figure 2b, where a mean of 10600 ± 4700 is obtained and the largest average \( Q_{\text{exp}} \) is measured for first-order modes (\( Q^{(1)} = 13600 \pm 5400 \) vs \( Q^{(2)} = 9300 \pm 4900 \)).

To determine the optimal, critically coupled configuration, we consider the gap-width dependence of both \( Q \) and change in transmission \( \Delta T \) for the first-order mode (cf. Figure 2c; see Supporting Information for second-order mode). Qualitatively, as the gap size increases, leading to a weaker coupling between the resonator and access waveguides, \( \Delta T \) decreases with a corresponding increase in \( Q \). This trend agrees well with the theoretical prediction (solid curves) for the loaded ring resonator:\(^ {32} \)

\[
\Delta T = 1 - \left[ \frac{T_{\text{leak}}}{T_{\text{ev}} + (1 - T_{\text{ev}}) \left( \frac{1 - \kappa_{\text{g}}}{1 + \kappa_{\text{g}}} \right)^2} \right]
\]

(1)
Figure 2. (a) Exemplary bus (purple) and drop (green) port transmission intensity as a function of frequency, measured by scanning the laser and collecting light from respective port. Signatures of the optical resonances are clearly visible in both, and their separations agree well with the calculated free spectral range of the disk. For comparison, the emission spectrum for QDs excited nonresonantly and measured through the drop port is also presented (orange), showing strong emission enhancement when the QDs are on resonance. The first-order resonance that is coupled to a QD is marked with the red dashed box. (b) Histogram of first-order, second-order, and all mode Q-factors extracted from the bus port data for all structures results in a mean Q in excess of 10,000. (c) Dependence of \(Q\) (left axis) and average \(\Delta T\) on the structure gap width for the first-order mode. Error bars represent the statistical variance, whereas solid lines are theoretical fits from eq 2.

Figure 3. (a) Low-power, frequency-dependent intensity as a function of cavity–laser detuning recorded both from the drop port (green) and bus port (purple), taken at 7 K when the QD and cavity are nearly on resonance. Fits to theory (orange curves, eq 4) enable extracting parameters such as the QD and cavity line widths, here 2.8 and 36.6 GHz, respectively. (b) Lifetime measurement for the QD on resonance with the cavity (blue) and in a bulk sample (red) with corresponding fits. (c) Power-dependent change in transmission of the QD of (a), showing a clear decrease in extinction for higher incident photon fluxes. Also shown is the theoretical transmission (see main text) for the QD–cavity system accounting only for dephasing (black) and also for spectral diffusion (orange). For the latter, a critical photon number of 0.9 photons per lifetime is found (orange dashed line). For comparison, the predicted saturation curve for a QD in a waveguide (i.e., with no Purcell enhancement) is shown (purple).
\[
\frac{1}{Q_{\text{exp}}} = \frac{1}{Q_{\text{int}}} (1 + \kappa_g)
\]

(2)

where \( \kappa_g = \kappa_{Gd} e^{-\xi L} \) characterizes the coupling rate between the cavity and access waveguides, \( \xi \) is the characteristic length, \( g \) is the gap size, \( T_{cc} \) is the transmission at critical coupling, and \( Q_{\text{int}} \) is the intrinsic Q-factor of the resonator (i.e., in the absence of the access waveguides). We find, through data fitting, \( Q_{\text{int}} = (2.3 \pm 0.1) \times 10^4 \) and a critical coupling gap size of \( \sim 67 \pm 10 \) nm, well within the reach of modern nanofabrication techniques.

### RESONANT SCATTERING FROM A QUANTUM DOT

We now study how the resonators alter light–matter interactions with embedded QDs. Figure 3a shows the drop (left axis, green) and bus (right axis, purple) intensities as a function of cavity–laser detuning for a sample with a 100 nm gap at 7 K and at 5 \( \mu \)W excitation power. A clear signature of the coherent interaction between photons and the QD is evident (highlighted by dashed lines in Figure 3a), resulting in a rerouting of the photons between the bus and drop ports, at a QD–cavity detuning of \( \delta = 0.02 \)\( f \). In the bus port, we observe a clear extinction of the transmission indicative of interference between the photons scattered by the QD and the incoming probe field.\(^{22,33}\) Similarly, we observe a peak in the bus port intensity at the same location, as additional photons are scattered into this channel by the QD.

To accurately model the frequency response presented in Figure 3a, we first require knowledge of the emitter decay rate, given by the sum of \( \gamma_{\text{leak}} \) and \( \gamma_{\text{cav}} \). We therefore measure the QD lifetime in both bulk GaAs and when coupled to the microdisk, as presented in Figure 3b. Bulk (red data) measurements are well-fitted by a single-exponential decay with an average value of \( \gamma_{\text{bulk}} = 0.63 \pm 0.07 \) ns\(^{-1} \), corresponding to the natural line width of \( \gamma_{\text{bulk}}/2\pi = 0.1 \pm 0.01 \) GHz. In contrast, a double-exponential is needed to fit the cavity-enhanced lifetime measurement (blue data), which we attribute to the different coupling of the two orthogonally polarized QD transition dipoles to the cavity. One dipole is well-coupled to the cavity and hence has a fast decay rate \( \gamma_{\text{fast}} = \gamma_{\text{cav}} + \gamma_{\text{leak}} = 4.97 \pm 0.08 \) ns\(^{-1} \) (0.79 \pm 0.01 GHz line width), while the other is weakly coupled with a decay rate \( \gamma_{\text{slow}} = 0.83 \pm 0.01 \) ns\(^{-1} \) (0.31 \pm 0.002 GHz line width). By comparing the decay rate of the well-coupled transition \( \gamma_{\text{fast}} \) to that of bulk \( \gamma_{\text{bulk}} \), we find a lifetime enhancement of 7.9 due to the cavity. While embedding the QD in the microdisk likely suppresses emission into free-space, relative to an emitter in the bulk, in what follows, we assume that \( \gamma_{\text{leak}} \approx \gamma_{\text{bulk}} \) as is done in the literature.\(^{34}\) We therefore extract lower bounds on the Purcell factor and the coupling efficiency of our system. Finally, we take the pure dephasing rate for the QD embedded in the microdisks and at temperatures ranging from 6 to 12 K to be \( \gamma_{\text{dp}}/2\pi = 0.01 \) GHz, as previously reported.\(^{35}\)

Having determined \( \gamma_{\text{cav}}, \gamma_{\text{leak}}, \) and \( \gamma_{\text{dp}} \), we repeat the spectral measurements such as those presented in Figure 3a, increasing the excitation laser power. For the drop port (green data), for example, the transmitted intensity is \( t_{\text{drop}} = \eta |t_{\text{drop}}|^2 \), where \( \eta \) accounts for the incident photon flux and the cavity-mediated coupling efficiency between the bus and drop port waveguides. The transmission coefficient, including coherent scattering from the QD, is given by\(^{20,36}\)

\[
t_{\text{drop}} = t_0 \left[ 1 + \frac{f}{1 + \frac{2\Delta\omega}{\gamma_{\text{cav}} + 2\gamma_{\text{dp}}}} \right] \left[ 1 + \frac{2\Delta\omega + \delta}{(\kappa/2)} \right]
\]

(3)

where \( \Delta\omega = \omega_{\text{max}} - \omega_{\text{QD}} \) is the laser detuning to the QD resonance, \( f = \gamma_{\text{cav}}/(\gamma_{\text{leak}} + 2\gamma_{\text{dp}}) \), \( t_0 = 1/[1 + i(\Delta\omega + \delta)/(\kappa/2)] \), and \( \kappa \) is the saturation parameter accounting for the incident power (see Supporting Information for the relationship of \( S \) to input power and photon number per lifetime and the corresponding \( b_{\text{max}} \)). Spectral diffusion in the system results in “wandering” of the QD resonance, which can be modeled by a convolution of the transmission with a Gaussian with line width \( \sigma_{\text{ad}} \).\(^{37}\)

\[
T_{\text{drop,conv}} = |t_{\text{drop}}|^2 \sigma_{\text{ad}}(\omega) \exp \left( -\frac{1}{2} \left( \frac{\Delta\omega - \delta}{\sigma_{\text{ad}}} \right)^2 \right)
\]

(4)

where

\[
\sigma_{\text{ad}}(\omega) = 1 / \sqrt{2\pi \sigma_{\text{ad}}} \exp \left( -\frac{1}{2} \left( \frac{\Delta\omega - \delta}{\sigma_{\text{ad}}} \right)^2 \right)
\]

(5)

As can be seen in Figure 3a, the frequency response is well-reproduced by the theory.

In practice, bus and drop port frequency-resolved data at different excitation powers are simultaneously fit with \( \delta, \omega_{\text{QD}}, \kappa, S \), and \( \sigma_{\text{ad}} \) as free parameters, noting that \( \sigma_{\text{ad}} \) is temperature-dependent (see Figure 6 in the Supporting Information). For the 5 \( \mu \)W data presented in Figure 3a, we find \( S = 1.5 \pm 0.2 \) (corresponding to a 1.4 \pm 0.2 photons per lifetime), a QD–cavity detuning of \( \delta = 0.02 \)\( f \), where \( \kappa/2\pi = 36.6 \pm 2 \) GHz and spectral diffusion of \( \sigma_{\text{ad}}/2\pi = 0.6 \pm 0.1 \) GHz. We also find a coherent extinction of photons in the drop port \( (\Delta I_{\text{drop}}/\Delta I_{\text{bus}}) \) of \( 24 \pm 3 \% \), as those photons are rerouted back into the bus port \( (\Delta I_{\text{bus}}) \) by the QD. The measured ratio of \( \sigma_{\text{ad}}/\gamma_{\text{cav}} \approx 0.87 \) is 4 times better than what has been achieved in slow-light photonic crystals with QDs that are not electrically contacted,\(^{36}\) where a peak extinction of 8% was observed.

Photon routing can be controlled either through the QD–cavity detuning or by varying the intensity of the incident photon stream. We first demonstrate the latter, presenting the fraction of photons rerouted from the drop to bus ports as a function of the incident photon flux per lifetime in Figure 3c. Here, the extinction measurements (symbols) are compared with three theoretical predictions (using eq 3 above and the fitted parameters): the QD resonator with broadening due to pure dephasing and spectral diffusion (orange curve), with pure dephasing only (as for an electrically contacted sample, black curve), or a QD in a waveguide (i.e., no emission enhancement, purple curve). Measurement results are well-reproduced when both pure dephasing and spectral diffusion are considered, and for this detuning \( (\delta = 0.02 \)\( f \)), a critical number of photons per lifetime of \( n_t = 0.94 \pm 0.2 \) and maximum extinction of \( \Delta I_{\text{drop, max}} = -53 \pm 4 \% \) in the limit of low power \( (S = 0) \) were found. For comparison, the maximum extinction realizable for a QD without Purcell enhancement is \( -15 \pm 4 \% \). For an electrically contacted QD system, where \( \sigma_{\text{ad}} = 0 \), the critical photon number is expected to decrease to \( n_t = 0.3 \pm 0.02 \), with a maximum \( \Delta I_{\text{drop, max}} = -98 \pm 2 \% \) achievable (black curve) (see Supporting Information). These results benchmark the conditions for coherent routing of photons between the bus and drop ports at the single-photon level.
Routing can also be controlled by changing the QD–cavity detuning, which we do by varying the sample temperature,39 hence tuning the QD through the cavity resonance from −0.3κ to 0.09κ (Figure S4 in Supporting Information). As the QD is scanned through the resonance, γ_{fast} increases, as shown in Figure 4a (purple) and peaks at γ_{fast} = 5.11 ± 0.08 ns⁻¹ at 8 K (δ = −0.04κ), corresponding to an 8-fold emission enhancement. In contrast, the weakly coupled transition decay rate (orange) remains constant and near the bulk decay rate (shaded region).

Figure 4c demonstrates how our system can be used as a coherent photon router, showing the fraction of photons scattered out of the drop port (left axis, green symbols) and into the bus port (right axis, purple symbols) for photons on resonance with the cavity (ω_{cav}) as a function of the QD–cavity detuning. Here, we observe that a QD detuning of 0.39κ (requiring a temperature change of only 6 K) is sufficient to prevent routing, corresponding to a shift of 5.1 QD line widths. For an electrically contacted resonator, the fraction of photons scattered into the bus port increases to 56 ± 3% (dashed curve), where the intensity of the incoming photon stream adds an additional control parameter allowing this value to be increased to 97 ± 2% (dotted curve). Instead of temperature tuning the QD, it is possible to achieve similar control electronically with a contacted sample40 or even all-optically.13

### DISCUSSION

Enhancing quantum light–matter interactions simultaneously increases the coupling of photons to desired modes and the coherence of the emission. We quantify this enhancement using the Purcell factor $F = \frac{\gamma_{cav}}{\gamma_{bulk}}$. Experimentally, we find $F_{Exp} = 6.9 ± 0.9$ (cf. Figure 4a). For our resonator $V_{eff} \approx 18(\lambda/n)^2$ and $Q_{exp} = 8900 ± 100$, such that the predicted value

$$F_{Ideal} = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3\frac{Q_{exp}}{V_{eff}} = 38 ± 1$$

which is larger than $F_{Exp}$ due to spatial mismatch of the QD relative to the field maximum of the optical mode, which affects the coupling with coherent photons. Deterministic positioning42,43 can address this issue.

Increasing $F$ not only increases the emission rate but also decreases the relative effect of decoherence mechanisms such as pure dephasing or spectral diffusion. For our QD, the latter is the dominant source of decoherence such that $\sigma_{dd}/F_{Bulk} = 6 (F = 1)$. In Figure 5a, we display how this ratio decreases as $F$ increases, noting that moderate $F \geq 6$ suffices to reach a near-unity ratio. A further 2 orders of magnitude reduction in decoherence is obtainable in the absence of spectral diffusion, motivating the use of electrically contacted resonators. In Figure 5b, we further present the dependence of the maximum change in drop port intensity (i.e., rerouting efficiency, left axis) on the Purcell factor in the cases where the emitter suffers from both pure dephasing and spectral diffusion (solid curve) or just the former (dotted curve). Even for the noncontacted systems, we expect a rerouting efficiency >80% for moderate enhancements of $F \approx 20$, while for an electrically contacted sample near-perfect routing is predicted at $F \approx 10$. We predict similar dependencies for the critical photon number (Figure 5b, right axis), where for an on-resonance emitter we observe that moderate Purcell
CONCLUSIONS

In summary, we present an integrated WGM resonator system for on-chip quantum photonics based on single self-assembled QDs. For such a system, which can be easily integrated with other photonic components, Q-factors in excess of 20,000 are observed, enhancing emission into the desired optical modes to simultaneously achieve a high coupling efficiency $\beta > 0.85$ and compensate for the majority of the decoherence mechanisms. Using this platform, we demonstrate coherent rerouting of photons between the drop and bus ports, observing a peak efficiency of $43 \pm 4\%$ at a flux of 0.6 photons per lifetime that decreases to $15 \pm 2\%$ at 2.8 photons per lifetime. We show control over this routing using both temperature tuning and via the excitation intensity, with the latter requiring a critical photon number of only 0.94 photons per lifetime.

Although our coherent router already operates below the single-photon level, it can be further improved using advanced nanofabrication protocols, allowing deterministic placement and electrical gating of the emitters. Optimally placed QD, in our (gateless) system, for example, is predicted to decrease $n_s$ to 0.3 photons per lifetime and increase the maximal routing efficiency to $93 \pm 4\%$ at low photon fluxes. Adding gates would suppress spectral diffusion, resulting in $n_s = 0.3$ photons per lifetime, and a theoretical peak routing efficiency of $98 \pm 2\%$. Altogether, our platform enables coherent light--matter scattering and efficient quantum optical nonlinearities at the single-photon level, two key functionalities of solid-state quantum technologies.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.1c02818. Theoretical models and fabrication details (PDF)

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Supporting Information

Figure 5. Effect of the Purcell enhancement on system parameters. (a) As $F$ increases, so too does the emitter–resonator coupling efficiency $\beta$ (left axis, solid). Conversely, an increase in the emission rate $\gamma_{\text{em}} = F_\text{bulk}$ decreases the relative effect of the spectral diffusion $\sigma_{\text{sd}}$ (right axis, solid) and dephasing $\gamma_{\text{dp}}$ (right axis, dashed) to the system decoherence. (b) Maximum drop port extinction (left) and critical photon number $n_s$ (right) achievable as a function of $F$, both with (solid) and without (dotted) spectral diffusion.

Factors are sufficient to overcome spectral diffusion for single-photon nonlinearities.

Hitherto we have discussed how a QD–microdisk resonator system can function as a coherent router; however, it can also be used for control or processing of quantum optical states. As an example, our system can act as a Bell-state analyzer, a key element of a quantum optical network, either in a standard cavity–QED configuration or as a passive, nonlinear scatterer. For cavity–QED, the Purcell factor can be re-expressed in terms of the QD–cavity coupling strength, $g = \sqrt{F_{\text{exp}}/\kappa_{\text{bulk}}}/2$. The resulting $g/2\pi = 2.5 \pm 0.3$ GHz can be used to write the cooperativity of the system $C = 4g^2/\kappa_{\text{bulk}} = 6.9 \pm 0.9$. Given the success rate of a cavity–QED-based analyzer of $1-1/C$, we expect our modest $F_{\text{exp}} = 6.9$ device to succeed $86 \pm 11\%$ of the time.

On the other hand, the success of a Bell-state analyzer based on passive, coherent scattering from the QD depends on the emitter–waveguide coupling efficiency $\beta$. By expressing the (lower-bound) $\beta$-factor as

$$\beta = \frac{\gamma_{\text{em}}}{\gamma_{\text{em}} + \gamma_{\text{deph}}} = \frac{F}{F + 1}$$

we find an experimental $\beta_{\text{exp}} \approx 0.87 \pm 0.01$, which increases to $\beta_{\text{ideal}} \approx 0.97$ for an optimally positioned QD. For this scheme, the success rate scales as $(2\beta - 1)/\beta$, showing that near-perfect operation should be possible with our system.
The authors declare no competing financial interest.

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