

Cavity-based optical switching via phase modulation in warm rubidium vaporG. Booton¹, T. Wasawo¹, W. O. C. Davis², C. McGarry^{1,3}, K. R. Rusimova¹, A. O. C. Davis¹, J. Nunn⁴, and P. J. Mosley^{1,4}¹*Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom*²*School of Mathematical and Physical Sciences, Macquarie University, Sydney, New South Wales, Australia*³*School of Physics, University of Sydney, Sydney, New South Wales, Australia*⁴*ORCA Computing Ltd., 30 Eastbourne Terrace, London W2 6LA, United Kingdom*

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Optical switching remains a key outstanding challenge for scalable photonic quantum computing due to the trade-off between speed, bandwidth, and loss. Quantum photonics demands all three to enable high computational clock rates and resource-efficient scaling to large systems. We present a cavity-based optical switch that overcomes this limitation, demonstrating a rise time of 22 ns, an insertion loss of 2.4 dB, and an extinction ratio of 17.5, which bridges the gap between speed and efficiency in photonic switching. All-optical control is achieved via phase modulation of a signal field detuned from the near-degenerate two-photon absorption ladder in warm rubidium vapor. The ultimate performance of our switch will find applications in active multiplexing, loop-based quantum memory, and feed-forward for quantum error-correction protocols.

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Introduction. Photonic technologies are at the forefront of efforts to deliver quantum advantage [1–3]. However, the practical realization of scalable quantum technologies and quantum networks critically depends on photonic platforms that enable efficient, high-speed, and low-loss signal routing [4,5]. In particular, optical switches that can rapidly and controllably route photons from two input modes to two output modes with high efficiency are required. Without these, photonic architectures are limited to small scales. Current approaches attempt to mitigate these limitations through spatial or temporal multiplexing in fast, low-loss switch networks or by employing quantum memories for synchronization of independent probabilistic sources [6–9]. Atomic memory schemes are becoming increasingly more powerful; however, significant challenges remain in simultaneously achieving low noise, high efficiency, and long memory lifetimes [10–13]. An alternative approach based on a fast, low-loss optical switch within a loop-memory would enable greater storage efficiencies with low noise whilst avoiding the need for ultrahigh vacuum or cryogenic environments, offering a more scalable quantum network architecture [14–16]. An ultrafast, low-loss switch is desirable for many applications such as achieving high bit rates over long distances in quantum key distribution [17], high-bandwidth high-dimensional encoding which enables fast operations [18,19], and time-multiplexed [20] or frequency-multiplexed [21] single-photon sources. Beyond purely photonic networks, such switches could enable direct,

reconfigurable interconnects between trapping modules, allowing dynamic routing of photons rather than relying on the static topologies of current trapped-ion platforms [22].

Commercially available switching technologies are generally optimized for either low-loss or high-speed (short rise time) configurations. Achieving both of these criteria simultaneously, while maintaining high bandwidth, remains a substantial challenge that currently limits quantum network interconnects. For example, electro-optic modulators such as LiNbO₃ or BBO deliver GHz switching speeds but are often compromised with an insertion loss of greater than 3 dB. Alternatively, bulk Pockels cells offer low-loss operation; however, high drive voltages and short rise times necessitate considerable power dissipation leading to restricted repetition rates [23,24]. Microelectromechanical optical switches offer low-loss performance but typical response times are limited to the microsecond timescale [25,26]. Conversely, semiconductor-based all-optical switches demonstrate impressive switching speeds, but typically modulate loss to control transmission in a single channel rather than implementing low-loss routing. Absorption- or gain-based switching relies on modulating transparency through carrier absorption [27], and refractive index modulation on semiconductor architectures often endures large losses [28]. All-optical switching has been explored extensively through the use of electromagnetically induced transparency (EIT). Many schemes include the use of three- or four-level atomic systems which rely on induced absorption [29] or absorption gratings [30]. EIT has been exploited to switch with slow [31,32] or stopped light [33] down to the single-photon level or used to couple to Rydberg excitations to study quantum gates [34,35]. Whilst the EIT phenomena shows great potential for manipulation of light, being restricted to a resonant condition leads to large losses due to atomic absorption in

protocols with warm atomic vapors and restricts the speed due to the narrow EIT bandwidth. In cold or ultracold protocols, limitations due to optical density or motional dephasing arise, leading to low storage and retrieval efficiencies and therefore further limiting bandwidth. Instead of EIT, relief can be found through dispersive regimes within warm atomic vapors where large phase shifts have been optically induced with minimal loss by operating in the off-resonant regime [36].

We present an all-optical switch that fulfils the set of criteria for quantum applications capable of low-loss high-bandwidth high-speed operation simultaneously. Our switch reroutes a signal field through a cavity via a reflective or transmitted port by harnessing a cavity-enhanced off-resonant light-matter interaction in warm rubidium vapor, whilst minimizing absorption loss. Confining the fields to a doubly-resonant ring cavity enhances the interaction of the fields [37,38]. As an all-optical atomic system, our switch is inherently capable of operating at high speeds. The far off-resonant configuration of the fields enables us to switch via phase modulation induced upon a signal field as an interferometric switch through modulations of the atomic susceptibility. Our results establish the fundamental viability of this approach, with remaining challenges largely confined to engineering integration and optimization.

Rubidium-filled cavity as an all-optical switch. In our scheme, we have built a two-port ring cavity where two counterpropagating laser fields interact with atoms in an isotopically pure ^{87}Rb vapor cell. The conditional phase shift imparted on the signal field is induced by modulation of the complex susceptibility via a strong control field. We take advantage of the near-degenerate states in the three-level ladder configuration in ^{87}Rb , as illustrated in Fig. 1(a). The weak signal field addresses the $5S_{1/2}$ to $5P_{3/2}$ transition with a small detuning, Δ_s . A strong control field couples the $5P_{3/2}$ and $5D_{5/2}$ states with a small detuning, Δ_c .

An experimental schematic outlining the switching mechanism is shown in Fig. 1(b) with the control field off. The signal field transmits through the resonant ring cavity with little atomic absorption, hence the signal field is detected on the transmitted output port. The introduction of a control field coupling the higher energy states leads to dressed states and a two-photon resonance, therefore inducing a change in complex susceptibility, χ . This change in susceptibility induced upon the signal field alters the cavity resonance, and hence the input signal field is rerouted such that all the signal is detected on the reflected output, as shown in Fig. 1(c). From the complex refractive index $n = \sqrt{1 + \chi}$, we express the absorption coefficient $\alpha = -2\kappa\text{Im}(n)$, where κ is the wave vector, and the accumulated phase $\phi = \kappa L\text{Re}(n)$ over a distance L of the atomic vapor. The expression for dispersion gives rise to the phase shift $\Delta\phi$ imparted on the signal field, which is the phase difference in the cases of the control field being on and off. The accumulated phase shift as a function of both signal and control field frequency detunings $\Delta_{s,c}$ is shown in Fig. 1(d). We aim for a parameter space that has a high signal transmission through the vapor cell with some phase shift imparted on the signal field. A high cavity finesse is necessary to obtain a high extinction ratio in our switch. Additionally, the accumulated phase shift on the signal field is cavity enhanced by the finesse, further motivating the need

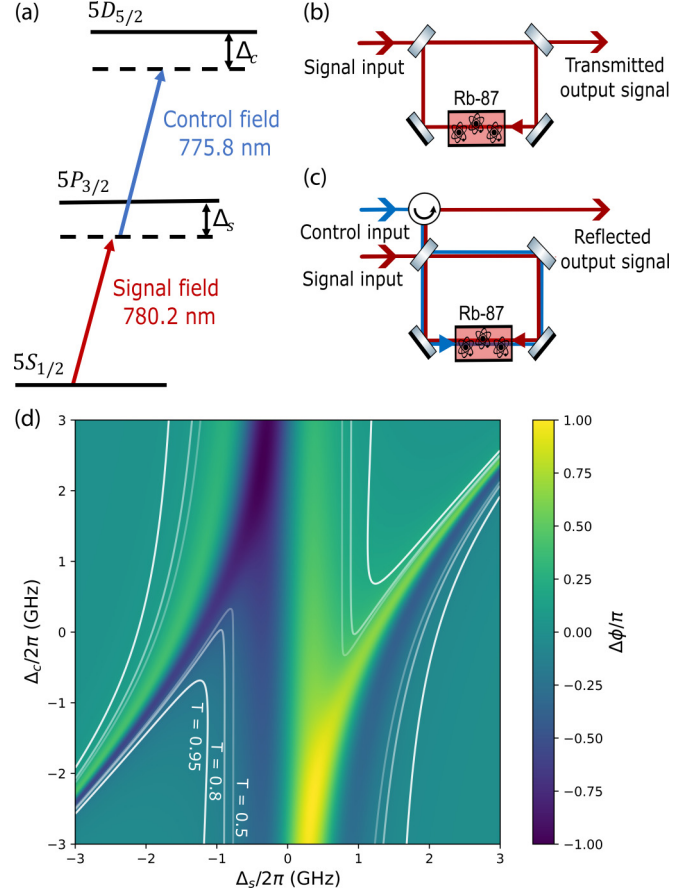


FIG. 1. (a) The relevant three-level ladder configuration used in ^{87}Rb . (b) Switch operation with the control field off. The signal is transmitted through the ring cavity. (c) Switch operation with the control field on. A control field excites the two-photon transition and induces a shift in the cavity resonance, hence the incoming signal field is routed to the reflective port. (d) Two-dimensional theoretical parameter search showing the imparted phase shift $\Delta\phi$ as a function of both the signal and the control field frequency detunings, $\Delta_{s,c}$. The overlaid (white) contours refer to transmission areas greater than 50%, 80%, and 95%, respectively. The transmission data account only for atomic absorption and exclude any cavity effects.

for a high-finesse cavity. However, there is a trade-off between finesse and switching speed of our ring cavity. The maximum operational speed is governed by the cavity ring-down time, which is estimated down to approximately 20 ns, which could be improved by miniaturization of the cavity.

Experimental setup. The experimental switching setup is shown in Fig. 2. The signal field was generated by a 780-nm external cavity diode laser (ECDL, MOGLabs CEL), which was blue detuned from the $5S_{1/2}(F' = 2)$ feature. The control field was generated by a 776-nm ECDL (MOGLabs CEL), intensity modulated by an electro-optic modulator (Exail NIR-MPX800), and then amplified (MOGLabs MOAL) to produce a square control pulse of approximately 25-mW peak power and down to 42-ns pulse duration. Each laser was frequency stabilized using a scanning transfer cavity [39], where the laser fields were superimposed with a frequency stabilized reference laser into a Fabry-Pérot cavity. Resonances occur as the scanning transfer cavity length is swept as a

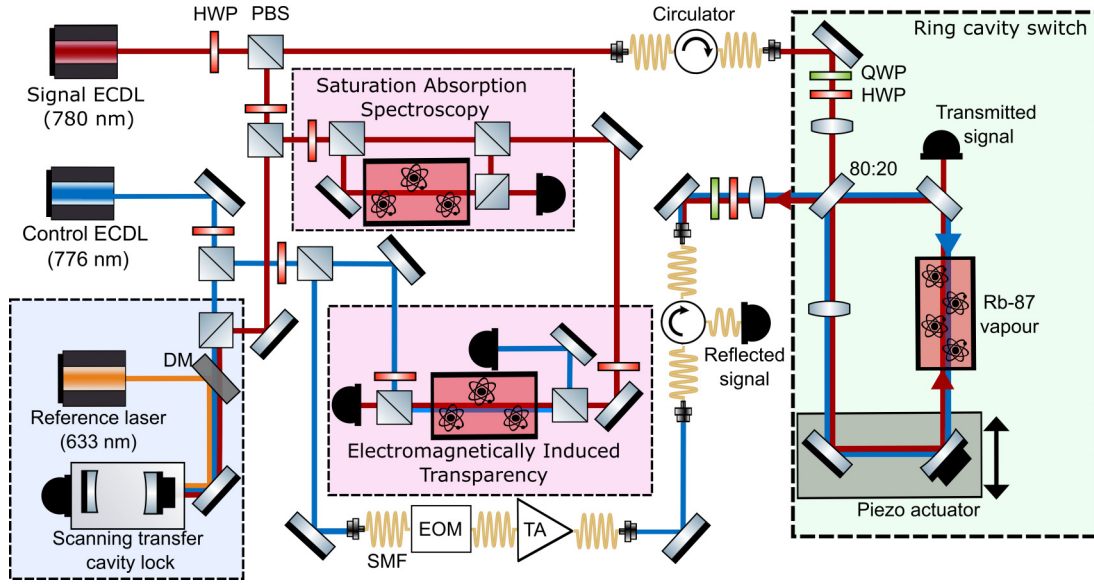


FIG. 2. The signal and control fields propagate through saturation absorption spectroscopy and electromagnetic-induced transparency experiments as an initial frequency reference. A scanning transfer cavity lock is used to lock the laser frequencies to take experimental data. The signal and control fields then exit the single mode fiber and counter propagate around a doubly resonant ring cavity. Detectors are placed on the reflected and transmitted ports. HWP, half-wave plate; QWP, quarter-wave plate; PBS, polarizing beam splitter; EOM, electro-optic modulation; TA, tapered optical amplifier; SMF, single-mode fiber.

function of input lasing frequency, and the signal and control field resonances occur within one free spectral range of the reference laser. The relative positions of the signal and control field resonances were measured and then an error signal was generated from a RedPitaya locking system.

The optical ring cavity consists of two beam splitters that have a 80:20 reflectivity:transmission ratio and two dielectric mirrors, one of which is fixed and the other is mounted onto a piezoelectric transducer for fine cavity length adjustment. The cavity finesse was measured as 18 and a bandwidth was estimated from the finesse to be approximately 40 MHz. The cavity ring-up time τ can be calculated from the experimentally measured finesse by $\tau = \frac{F \cdot L}{c}$ to be 20 ns. This limits the maximum operational frequency of a cavity-based switch of our given finesse and size. The atomic medium is isotropically enriched rubidium-87 vapor and is placed inside the ring cavity. The vapor is contained within a 5-cm glass cell with antireflection coatings, heated to approximately 60 °C to increase the optical depth whilst minimizing atomic absorption. A lens inside the cavity focuses the signal and control to the center of the atomic vapor cell. The signal and control light are coupled into the fundamental transverse cavity mode, such that sharp resonances are seen on an oscilloscope. When the control field is applied, the signal field undergoes a π -phase shift and is switched from the transmitted port to the reflected port. The reflected signal travels back on the control arm of the experiment and is detected after a circulator, and the transmitted light exits the cavity on the second port and is detected in free space. To ensure good overlap between the laser fields and the cavity resonance, two mirrors are placed on a translation stage for small adjustments to the cavity length.

Figure 3 shows the performance from our cavity-integrated switch with full π -phase shifts at three different modulation rates. The voltage from the photodiode monitoring the signal

transmission (reflection) is shown by the solid red (dotted blue) line. The shaded regions indicate the control field is on. The transmitted signal power with the control field on, T_{on} , is proportional to the average value of the red trace in the shaded region, and similarly for T_{off} in the unshaded regions with the control field off. The switching contrast C of the transmitted

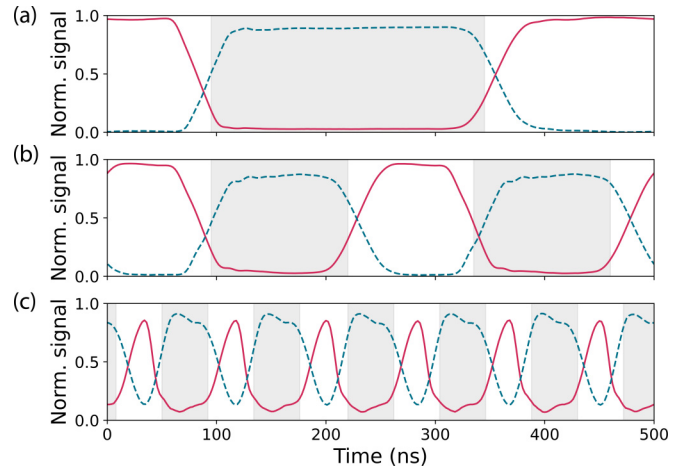


FIG. 3. Switching results highlighting three different control modulation rates. The solid red trace shows the transmitted data, the dashed blue shows the reflection data, and the shaded regions indicate the control field is on. The signal and control field detuning was -0.65 GHz. (a) A 2-MHz control field modulation, with a switching contrast of 89% and an extinction ratio of 17.5. (b) A 4-MHz control field modulation, with a switching contrast of 89% and an extinction ratio of 17.4. (c) A 12-MHz control field modulation with a switching contrast of 82% and an extinction ratio of 9.9.

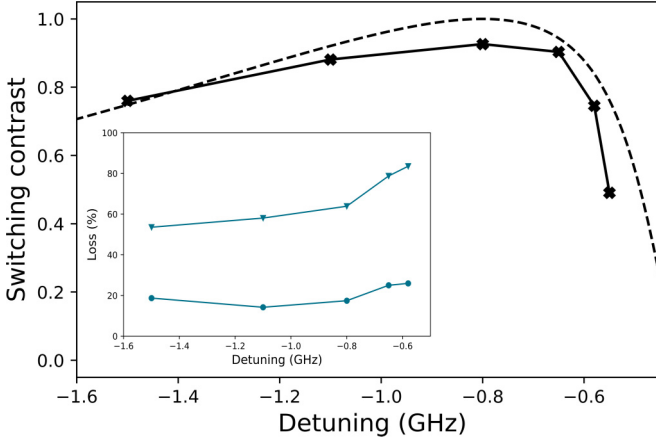


FIG. 4. Systematic characterization of the switching contrast. The signal and control frequency detunings are stepped through simultaneously such that $\Delta_c = \Delta_s$. The experimental data (solid black) are shown alongside simulation data (dashed black) of the switching contrast. The inset shows measurements of the insertion (circle) and intracavity (triangle) losses.

signal power is defined as

$$C = \frac{T_{\text{on}} - T_{\text{off}}}{T_{\text{on}} + T_{\text{off}}}. \quad (1)$$

A switching contrast of 89% is achieved with a extinction ratio, defined as $T_{\text{off}}/T_{\text{on}}$, of 17.5 in Fig. 3(a). The limit of the switch speed is experimentally demonstrated in Fig. 3(c), with an open eye diagram at a switching time of 42 ns with a switching contrast of 82% and a rise time of 22 ns. The data support the predicted cavity ring-up time and therefore the fundamental limit of our experiment. The switch performance in terms of contrast and loss as a function of the simultaneous signal and control field detunings is shown in Fig. 4, where the switching contrast is plotted with experimental data alongside an analytic model. The model considers the transmission of the signal field through an optical cavity with an additional phase accumulated on the signal from the rubidium vapor. The transmission function is derived from the coupled ring-cavity dynamics which relates the incoming signal field directly to the transmitted output $T(\phi)$, with a phase ϕ :

$$T(\phi) = \frac{t_1^2 t_2^2 \eta}{1 + r_1^2 r_2^2 \eta - 2r_1 r_2 \eta \cos(\phi)}, \quad (2)$$

where r_1 and r_2 are the beam-splitter reflectivities, and t_1 and t_2 are the transmissions of the beam splitters, and η is the cavity loss. The phase in Eq. (2) is then updated with the refractive index modulation induced from the atomic susceptibility such that

$$\phi = \frac{2\pi}{\lambda_s} [(\text{Re}(n) - 1)L_v + L_c], \quad (3)$$

where L_v and L_c are the length of the atomic vapor cell and the cavity length, respectively. The loss factor η including the rubidium absorption becomes

$$\eta = \eta_{\text{rt}} - \frac{4\pi \text{Im}(n)}{\lambda_s}, \quad (4)$$

where η_{rt} is the approximate cavity round-trip loss with no atoms. The modeled switching contrast of the transmission is plotted when stepped through the signal and control frequency detunings, under the condition where $\Delta_c = \Delta_s$ throughout to ensure the two-photon absorption remains strong. Two free parameters, temperature and intracavity power, were determined by a least-squares optimization between the experimental and simulated data. The best fit corresponded to a vapor cell temperature of 59 °C and an intracavity control power of 500 mW. These values are close to the experimental values where the temperature of the vapor cell was measured externally to be approximately 60 °C and the intracavity power was approximated by the input control power $P = 25$ mW with cavity enhancement $P \cdot \mathcal{F}$.

The insertion loss and the intracavity loss are plotted in the inset of Fig. 4. The intracavity loss is attributed to atomic absorption and additional loss arising from scattering on internal optics, imperfect antireflection coatings on the vapor cell, and rubidium condensation on the cell windows within the cavity. We define this as $1 - (T_{\text{on}} + R_{\text{on}})$, where R_{on} is defined in a similar way to T_{on} . At optimum operation, the intracavity loss is measured to be 17%. The insertion loss is defined as the ratio of the power of the transmitted signal to the input signal. This insertion loss is larger than the intracavity loss due to imperfect mode matching of the cavity with the input signal mode.

At frequencies close to atomic resonance, a poor switching contrast is seen due to increased atomic absorption, leading to high insertion loss; however, low intracavity loss is observed due to observation of EIT. The contrast improves with further detuning due to less atomic absorption, and the signal transmission increases. The switching contrast begins to tail off at far-detuned frequencies due to more control power being needed to provide sufficient phase shift, whilst the loss of the system remains relatively low.

Discussions and conclusions. In conclusion, we have presented an all-optical switch that has the ability to operate at high speeds, with a rise time of 22 ns. The rise time is limited by the cavity ring-down time, theoretically estimated as 20 ns and is validated by the experimental limit shown in this Letter. The insertion loss of the device is 3.7 dB at optimum operation, which can be reduced to 2.4 dB at far-detuned laser frequencies, which is accompanied by a slight reduction in the switching contrast. The insertion loss is also further reduced to 1.6 dB with a reduction in the mirror reflectivity, but this results in a smaller extinction ratio of our switch. The ratio between the experimentally measured cavity finesse and the maximum theoretical finesse is 90%, meaning that intracavity loss is minimal. Intracavity loss is measured at approximately 17%, predominately due to atomic absorption. Higher cavity finesse can be achieved by miniaturization of the cavity and reduction of the cavity mode volume. The current experimental configuration shows potential for miniaturization to simultaneously reduce the insertion loss and probe competitive switching speeds, as the current limit on the speeds is due to the cavity rise and fall times. Strong interactions have already been demonstrated between atomic vapors and microresonators [40], and developments in miniaturized cavities and microfabricated vapor cells [41–43] show a path forward to offer significant advantages in

comparison with commercially available quantum technologies. Microstructured optical fiber is an alternative route to achieve this, where fiber interconnects form an enclosed cell for filling with rubidium vapor [44]. An all-fiber integration of our switch would provide seamless integration into existing fiber networks, and enhanced light-matter interaction would also allow for greater switching contrasts to be shown due to the reduction of necessary control power [45]. The all-optical switching in rubidium vapor presented here demonstrates a marked improvement over existing optical switching technology and therefore is a significant step forward towards scalable quantum technologies.

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Data availability. The data that support the findings of this article are openly available [46], embargo periods may apply.

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