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Electronically Programmable Photonic Molecule

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Physical systems with discrete energy levels are ubiquitous in nature and are fundamental building blocks of quantum technology. Realizing controllable artificial atom- and molecule-like systems for light would enable coherent and dynamic control of the frequency, amplitude and phase of photons [1–5]. In this work, we demonstrate a photonic molecule with two distinct energy-levels using coupled lithium niobate microring resonators and control it by external microwave excitation. We show light can be precisely controlled by programmed microwave signals using concepts of canonical two-level systems including Autler-Townes splitting, Stark shift, Rabi oscillation and Ramsey interference. Leveraging such coherent control, we show on-demand optical storage and retrieval by reconfiguring the photonic molecule into a bright-dark mode pair. These results of dynamic control of light in a programmable and scalable electro-optic platform open doors to applications in microwave signal processing [6], quantum photonic gates in the frequency domain [7] and exploring concepts in optical computing [8] and topological physics [3,9].

Photonic analogues of condensed matter systems have resulted in important discoveries like photonic crystals [5], parity-time symmetric systems [2] and topological photonic systems [3,9], and have led to breakthrough technologies including quantum ground state cooling of nanomechanical systems [10], new classes of sensors [11,12] and one-way lasers [4]. A photonic analogue of a two-level system could allow full-control over the energy and phase of photons using the concept of two-level systems control in atomic or molecular systems, where the state of the electron can be controlled and functionalized by external electromagnetic fields. Such a photonic system would enable the investigation of complex physical phenomena [2–4,7] and unique functionalities, including on-demand photon storage and retrieval, coherent optical frequency shift and optical quantum information processing at room temperature [7,13,14]. While realizing a photonic device with discrete energy levels is straightforward, for example using modes of an optical resonator, controlling such a system dynamically (i.e. inducing transitions between the levels) is challenging as it requires mixing of optical frequencies via strong nonlinear processes. As a result, coherent coupling between discrete photon energy modes have only been studied using all optical methods [14–17] and have limited design parameter space, configurability and scalability.

Electro-optic methods [6,18–23] are ideally suited for the dynamic control of photonic two-level systems since they have fast response, can be programmed and allow for large-scale integration. To realize a fully unitary photonic two-level system with coherent electro-optic control, the photon lifetime of each energy state needs to be much longer than the time required to drive the system from one state to the other. On the one hand, Large optical systems with optical amplifiers [24] can emulate a classical two-level system but the quantum coherence of the optical photons is destroyed in the process. On the other hand, conventional integrated photonic platforms have not been able to meet the requirements of long photon lifetime and fast modulation simultaneously. For example, fast phase modulators [7,25] can generate new optical frequencies but they do not support distinct and long-lived optical modes. Ultra-high *Q* on-chip resonators have traditionally been realized in passive materials, such as silicon dioxide (SiO_2) [26,27] and silicon nitride (Si_3N_4) [28,29], which can only be controlled electrically using slow thermal effect. Electrically active photonic platforms [18–22] based on silicon [18], III-V materials [15,20], plasmonic [19], graphene [22], and polymers [21] allow for fast electro-optic modulation at gigahertz frequencies, but suffer from dramatically reduced photon lifetimes compared to passive platforms. To circumvent this problem, out-of-plane picosecond optical pulses have been employed to generate ultrafast free-carriers in silicon that induces a broadband electro-optic tuning [16,30]. Purely electrical tuning is still highly desirable as narrow band microwave signals could offer dramatically better controllability, minimal added noise and scalability.

In this work, we overcome the existing performance trade-off paradigm and realize a programmable photonic two-level system that can be dynamically controlled using gigahertz microwave signals (Fig. 1a). Specifically, we create a microwave addressable photonic molecule using a pair of 80 μm radius integrated lithium niobate (LN) microring resonators patterned in close proximity to each other. The low optical loss [31] and efficient co-integration of optical waveguides and microwave electrodes [32,33] allow us to simultaneously achieve large electrical bandwidth (> 30 GHz), strong modulation efficiency (0.5 GHz/V) and long photon life time (~ 2 ns).

The photonic molecule supports a pair of well-defined optical energy levels, which are evident from the optical transmission measured using a tuneable telecom wavelength laser (Fig 1c; also, see Supplementary for full spectrum). The two optical energy levels are formed by the evanescent coupling of light from one resonator to another through a 500-nm gap. When the optical coupling strength μ exceeds the optical loss rate γ of each cavity, the coupling leads to a normal mode splitting resulting in a frequency doublet consisting of a lower frequency symmetric (S) and a higher frequency antisymmetric (AS) optical mode (Fig. 1a and c). The S (AS) mode spatially spans both optical cavities, with the light in the two cavities being in- (out-of-) phase. The two new eigenmodes, separated in frequency by $2\mu = 2\pi \times 7$ GHz, are the two energy levels of the photonic molecule. In our case, the two optical modes have cavity linewidths of $\gamma = 2\pi \times 96$ MHz, corresponding to a loaded (intrinsic) quality factors of $Q_L = 1.9 \times 10^6$ ($Q_i = 2.5 \times 10^6$), thus forming a well-resolved two-level system (Fig. 1c).

We induce photonic transitions in the two-level system using high-frequency electro-optic phase modulation of the two modes. The phase modulation is realized through the Pockels effect ($\chi^{(2)}$) of LN, where the optical refractive index can be changed by an applied electric field, with a response time on the femtosecond scale. To enable strong overlap between microwave and optical fields without significantly increasing the optical loss, we place gold microelectrodes 2.5 μm away from the edge of the rings that form the photonic molecule (Fig. 1b). Importantly, the microwave circuit layout is designed to induce a phase delay on one ring and a phase advance on the other ring therefore introducing coupling between the spatially orthogonal S and AS modes (Fig. 1a and Supplementary).

We explore the analogy between an atomic two-level system and the photonic two-level system, and leverage it to demonstrate the control of the photonic molecule. In our system, the electro-optic effect plays the equivalent role as that of an electric dipole moment in the case of an atomic two-level system, while in both systems external electromagnetic fields are used to couple and address their energy levels. In the presence of an external direct-current (DC) electric field, the resonance frequencies of each ring are pulled in the opposite direction. This added frequency detuning reduces the optical coupling between the two resonators and results in the characteristic avoided crossing curve in coupled resonator systems (Fig. 1d). The resonator frequency detuning is accomplished by applying a DC bias voltage in the range of ± 15 V to the microwave electrodes. This control is analogues to the DC Stark effect used in atomic systems. The extracted tuning/modulation efficiency $g = 2\pi \times 0.5$ GHz/V is an order of magnitude larger than previously demonstrated in bulk electro-optic resonator systems[34,35], and is due to the highly efficient overlap between microwave and optical fields enabled by our system (see Methods).

Next, we use a continuous wave (CW) coherent microwave field to control our photonic two-level system. This situation is similar to an atomic two-level system under a strong coherent excitation, with an important difference that in our case the number of photons that could populate each of the two levels is not limited to one, resembling that of an atomic ensemble. When the microwave frequency matches the energy difference of the two levels, an effective coupling between the two initially decoupled S and AS modes is introduced, leading to a second order mode splitting in the couple ring resonators. The exact the splitting frequency (Ω) can be precisely controlled up to several gigahertz by controlling the amplitude of the microwave signals. This microwave-induced photonic mode splitting is a dissipative coupling between the optical modes in analogues to the Autler-Townes splitting (Rabi splitting) in electronic systems (Fig. 2a ,b) resonantly excited with CW light. When the microwave frequency is far detuned from the transition frequency, the microwave induced photonic-coupling becomes weaker and an effective dispersive effect in the level splitting dominates, similar to the AC Stark shift in atomic systems (Fig. 2c). Importantly, this effect can be used to control the effective coupling strength between the energy levels of the photonic molecule, which are otherwise determined by geometric factors.

We demonstrate that the photonic molecule can be used for unitary transformation of light in the frequency domain by controlling the dispersive and dissipative coupling between the two optical modes. In the context of two-level systems, such control on the amplitude and phase is described by Rabi oscillation and Ramsey interference (See supplementary). The dynamics of the photonic two-level system can be directly visualized through the time evolution of the output photons. We apply a microwave field at the mode splitting frequency to drive dissipative optical coupling (i.e. Rabi oscillations) between the two levels of our photonic molecule (Fig. 3), similar to the Autler-Townes splitting measurements (Fig. 2b). The observed Rabi oscillation corresponds to a rotation along the real axis of the energy Bloch sphere (Figure 3c, inset) and indicates that light tunnels back and forth between the two optical modes at two different optical frequencies. In other words, using the language of nonlinear optics, applied microwave signal drives a sequence of resonance enhanced sum- and difference-frequency generation (SFG and DFG) processes that result in energy of photons being changed several times (more than 10 in Figure 3c) before it is eventually dissipated due to the cavity photon loss (cavity life time ~ 1.6 ns). To study the Rabi oscillation, we initialize the system by coupling a CW laser into the S mode and measure the real-time optical transmission as the microwave drive is turned on (see Methods and Supplementary). We achieve a large range of Rabi frequencies at low applied voltages (Fig. 3a), which is in excellent agreement with theoretical predictions (Fig. 3b and Supplementary). In particular, for a peak drive voltage of $V_p = 1.1$ V, we observe coherent Rabi oscillation with a frequency of 1.1 GHz, ~ 16% of the initial mode splitting. Even stronger driving regimes, where the Rabi frequencies are close or even exceeding the level splitting, could be accessible in our system, enabling the exploration of extreme conditions where the rotating-wave approximation completely breaks down [36].

To show the control over the relative phase of the two photonic levels in our system (i.e. rotation along the imaginary axis), we measure photonic Ramsey interference by driving optical transition with detuned microwave pulses at 7.8 GHz that induces a dispersive element in the optical coupling. After initializing the system in the S mode, we apply a microwave π/2 pulse to transform the optical field into a superposition of the two states. As the microwave is turned off for a time period of τ, the superposition state precesses along the equator of the Bloch sphere at a rate determined by the microwave detuning δ. After sending another microwave π/2 pulse, the photons are rotated to different energy states, determined by the delay τ, and measured using a photodetector. The result is the so-called Ramsey interference shown in Fig. 3d. As the optical lifetime of the two-level system (~ 1.6 ns) is much shorter than the coherence time of the laser (~ μs), the phase coherence time of the two energy levels obtained in this measurement is dominated by cavity dissipation in good agreement with that obtained from the Rabi oscillation.

We leverage the ability to perform unitary transformations in the frequency domain to achieve on-demand photon storage and retrieval - a critical task for optical signal processing. While a static resonator can be used to slow down the propagation of a photon, such slow-down is fundamentally limited by the frequency bandwidth of the resonator, i.e. the delay-bandwidth product, and cannot be controlled on-demand. In contrast, the use of a dynamically-modulated resonator system can overcome the delay-bandwidth product constraint, enabling new functionalities such as optical buffering [37]. To enable controllable write and read of light into a resonator from an external waveguide, the optical coupling strength needs to be altered faster than the photon lifetime in the cavity. To achieve this, we apply a large DC bias voltage (15 V) to reconfigure the double-ring system into a pair of bright and dark modes. In this limit, one of the modes is mainly localized in the 1st ring (purple in Fig. 4a), and thus is still accessible to the input optical waveguide and is optically bright, while the other mode is mainly localized in the 2nd ring (grey in Fig. 4a) and thus is decoupled from the input optical waveguide by geometry and becomes optically dark (See Supplementary for details). Notably, optical access to the dark optical mode can be granted by applying a microwave signal with the frequency matched to the difference between the two optical modes (Fig. 4a). The microwave modulation results in an effective coupling between the bright and the dark mode, which we directly observe from the avoided crossing in the spectrum of the bright optical mode (Fig. 4b). In our experiment, the waveguide coupling is designed to be critically-coupled to a single resonator maximizing the transmission extinction ratio. We excite the critically-coupled bright mode from the optical waveguide, and then apply a microwave π pulse to switch light from the bright to the dark mode (Fig. 4c). Once the microwave signal is turned off, the photons are trapped in the dark mode and become decoupled from the waveguide leaving cavity intrinsic dissipation as the only photon loss mechanism. After a desired storage time, we apply another microwave π pulse to deterministically retrieve the photons from the dark mode back into the bright mode and then into the optical waveguide (Fig. 4c). Tracking the intensity of the retrieved light, we extract a dark mode lifetime of 2 ns, which is about two times of the lifetime of the critically-coupled bright mode as expected (Fig. 4d). Using an over-coupled bright optical modes, while further improving the quality factor of the integrated lithium niobate resonators towards its material limit ($> 10^9$), could result in a tunable storage time of hundreds of nanoseconds (See Supplementary).

Our demonstration of the coherent and dynamic control of a two-level photonic molecule with microwave fields and on-demand photon storage and retrieval paves a path to a new paradigm of control over photons. These results represent the initial step towards integrated electro-optic coherent manipulation of photonic states and energies, and could have immediate applications in signal processing and quantum photonics. With microwave control and the possible integration of on-chip photonic components including filters, routers and modulators, a new generation of photonic-electronic systems with advanced functionalities can be put in practice. Considering the vast design parameter space of couple resonators, dynamically controlled two- and multi-level photonic systems have the potential to enable a new class of photonic technologies including topological photonics [9], advanced photonic computation concepts [8,38] and on-chip frequency-based optical quantum systems [7,13].

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Methods

Devices are fabricated on single crystalline thin-film lithium niobate (LN) device layer bonded onto a silicon (Si) handle wafers with a 2 μm thick thermally grown silicon dioxide layer on top. Standard electron-beam (e-beam) lithography is used to realize optical waveguide and microresonator patterns in hydrogen silsequioxane (HSQ) e-beam resist. The patterns is then transferred into the LN layer using argon plasma etching in a standard inductively couple plasma reactive ion etching (ICP-RIE) tool. The etched depth is 350 nm leaving a 250 nm LN slab behind. The slab allows for efficient electrical field penetration into the waveguide core region. The first layer of the gold interconnects is patterned using e-beam lithography and the metals are deposited with e-beam evaporation methods and lift-off processes. Next, a 1.6 μm silicon dioxide layer is deposited on top using plasma enhanced physical vapour deposition (PECVD) method. Finally, metal vias and the top metal layer are realized using a standard photolithography followed by e-beam evaporation and lift-off processes [39].

The light from a tuneable telecom wavelength laser (SANTEC TS510) is launched into, and collected from, the LN waveguides using a pair of lensed optical fibres. The microwave control signals are generated from an arbitrary waveform generator (AWG, TEKTRONIX 70001A), before they are sent to electrical amplifiers. Electrical circulator or isolators are used to prevent multiple electrical reflections. For the Rabi oscillation measurements, the electric field amplitude (c_1) in the S mode is measured by interfering the light out-coupled from the double-ring system with the pump light in the optical waveguide. The interference produces a homodyne signal for c_1 that is sent to a 12 GHz photodiode (Newport 1544A), and due to the optical frequency difference, the rapid interference signal between the pump light and c_2 can be filtered out electrically using a low-pass filter. For the Ramsey measurements, the optical power is sampled after the 2nd $\pi/2$ pulse using the fast photodiode. For the photon storage measurements, the pump light is synchronously turned off with the first π pulse allowing for direct power readout of the retrieved light and prevent pump further leaking into the bright mode. The modulation on the pump signal is achieved by an external electro-optic modulator synchronized with the microwave control signals. The microwave energy consumption (E_R) for a single Rabi flop can be estimated as $E_R = \frac{1}{2} CV^2 \sim 10$ fJ for the condition in Figure 3c. The power consumption for continuous Rabi excitation (Fig. 2a) is $P_R = E_R\,\Omega \sim 60$ μW, where Ω is the Rabi frequency. In the experiment, since the microwave is generated and terminated with standard 50-Ω impedance elements, the total electrical power consumption is 24 mW where the majority of the power is dissipated in the load.

Methods Reference

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Data Availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Supplementary Information

Supplementary information accompanies this paper.

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Author contributions

M.Z., C.W., S.F. and M.L. conceived the experiment. M.Z., C.W. and A.S. fabricated the devices. M.Z. and Y.H. performed numerical simulations. M.Z., C.W. and T.R. carried out the experiments. M.Z. wrote the manuscript with contribution from all authors. M. L. supervised the project.

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Competing financial interest

M.Z., C.W. and M.L. are involved in developing lithium niobate technologies at HyperLight Corporation.

Figure 1. Microwave-controlled photonic molecule. **a**, The photonic molecule is realized by a pair of identical coupled optical microring resonators ($\omega_1 = \omega_2$), which has two distinct energy levels-a symmetric (S) and an antisymmetric (AS) optical mode that are spatially π out of phase. Microwave field can interact coherently with the two-level system through the strong Pockels effect ($\chi^{(2)}$) of lithium niobate. **b**, False-coloured scanning electron microscope (SEM) image of the coupled microring resonators. **c**, Measured transmission spectrum of the photonic two-level system. The two optical modes are separated by $2\mu = 2\pi \times 7$ GHz with linewidths of $\gamma = 2\pi \times 96$ MHz corresponding to a loaded optical quality factor of 1.9×10^6. **d**, The resulting transmission spectra from an applied DC field show an anti-crossing curve due to the finite optical coupling between the two rings, which is analogues to the DC Stark effect in a canonical two-level system. NT: normalized transmission.

Figure 2. Microwave dressed photonic states. a, When the applied microwave frequency is tuned to the match the mode separation, dissipative coupling leads the two photonic levels to split into four levels. This effect is analogues to the Autler-Townes (AT) splitting. When the microwave is detuned far from the photonic mode splitting, the photonic energy levels experience a dispersive effect, leading to a shift in the photonic levels. This effect is in analogues to AC Stark shifts. **b**, Measured AT splitting in the photonic molecule where the splitting can be accurately controlled by the amplitude of the applied microwave. **c,** Measured photonic AC Stark shifts for a microwave signal at 4.5 GHz. NT: normalized transmission.

Figure 3. Coherent spectral dynamics in the photonic molecule. a-b, Measured (a) and theoretically predicted (b) coherent oscillation between the two optical modes (Rabi oscillation) for various microwave strengths applied to the photonic two-level system. As the microwave field is turned on at $t = 0$, light oscillates between the two energy levels c_0 and c_1 leading to the observed signals. **c**, 1.1 GHz Rabi oscillation observed for microwave $V_p = 1.1$ V. This corresponds to rotation along the real-axis of the Bloch sphere. Inset shows the corresponding optical intensity in mode c_1. **d**, Oscillatory signals measured on a photodetector when δ-detuned microwave π/2 pulses are applied (photonic analogy of Ramsey interference). The first π/2 pulse prepares the light in a superposition of the two optical modes with a precession frequency determined by δ. The second π/2 pulse with a delay τ have oscillating projections on to c_1 resulting in the measured interference fringes. The solid curve shows calculated signal (see Supplementary).

Figure 4. On-demand storage and retrieval of light using a photonic dark mode a, The photonic molecule is programmed so that $\omega_1 \neq \omega_2$, resulting in localized bright and dark modes. As a result, the bright mode can be accessed from the optical waveguide, while the dark mode cannot (forbidden by geometry). **b,** A microwave field applied to the system can induce an effective coupling between the bright and dark modes, indicated by the avoided crossing in the optical transmission spectrum. **c**, Light can be deterministically stored and retrieved using the bright-dark mode pair and microwave control. A microwave π pulse can be applied to transfer light from the bright to the dark mode. As the microwave is turned off, light is restricted from any external waveguide coupling. After a certain desired storage time, a 2nd microwave π pulse retrieves the light from the dark to the bright mode. γ, γ_{i} and γ_{ex} are the lifetime of the bright optical mode, intrinsic damping and waveguide coupling rate respectively. **d**, The retrieved light from the dark mode measured at different time delays. Inset: the extracted intensity of the retrieved light shows nearly twice the lifetime of the critically coupled bright mode. NT: normalized transmission.