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Electronically programmable photonic molecule

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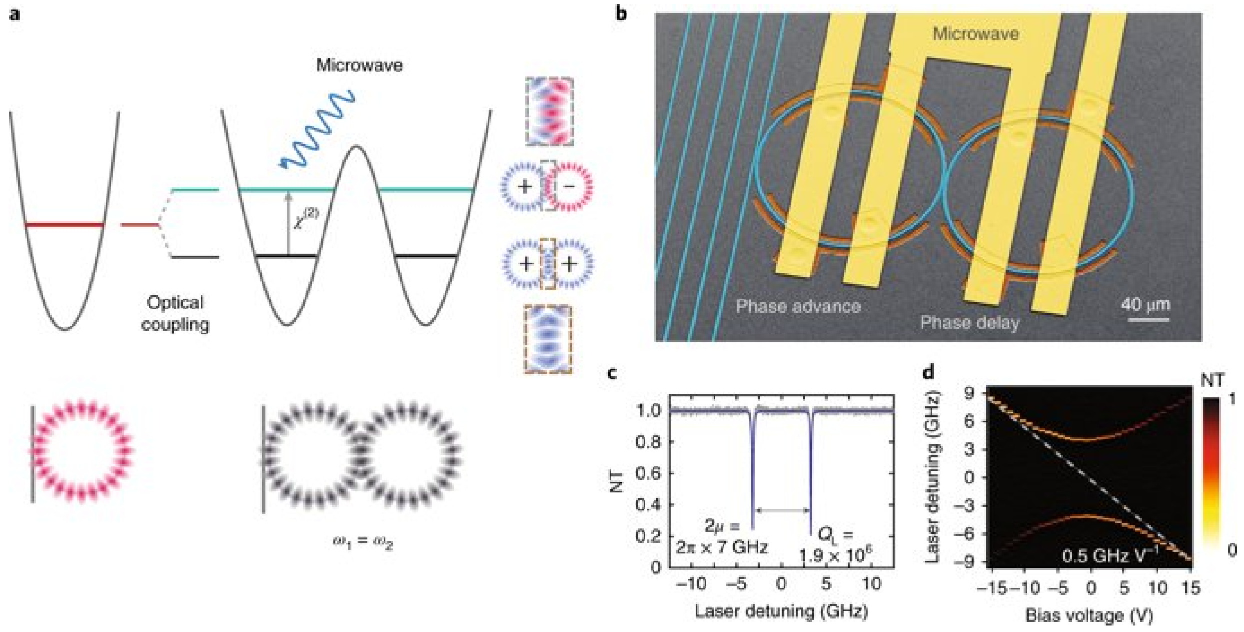
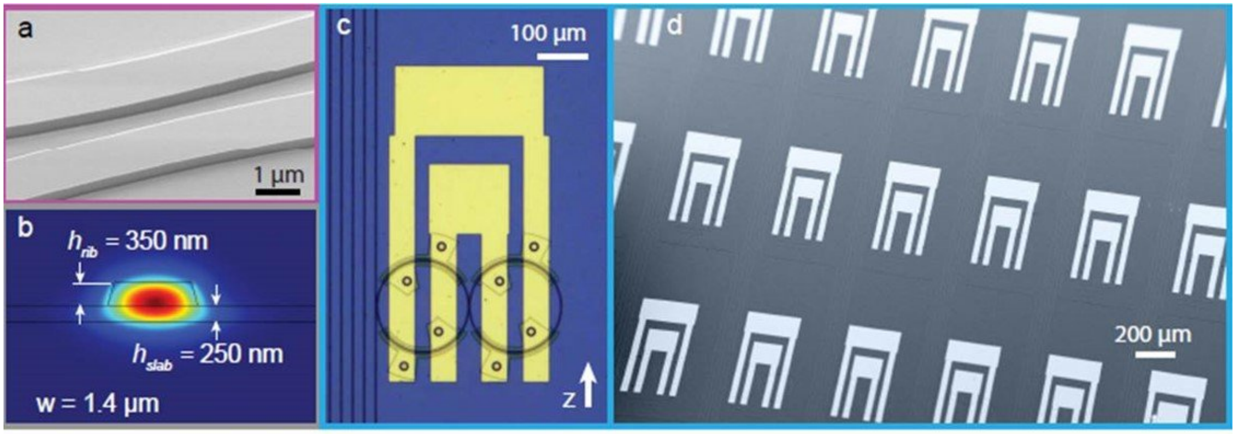


Microwave-controlled photonic molecule. a) The photonic molecule is realized by a pair of identical coupled optical microring resonators (resonant frequency ω1=ω2). The system has two distinct energy levels—a symmetric and an antisymmetric optical mode (indicated here by blue/blue shading for the symmetric and red/blue for the antisymmetric mode) that are spatially out of phase by π. The microwave field can interact coherently with the two-level system through the strong Pockels effect (χ(2)) of lithium niobate. b) False-colored scanning electron microscope image of the coupled microring resonators. c) Measured transmission spectrum of the photonic two-level system. The two optical modes are separated by 2μ= 2π× 7 GHz with linewidths of γ= 2π× 96 MHz corresponding to a loaded optical quality factor of 1.9 × 106. d) The resulting transmission spectra from an applied d.c. field show an anticrossing curve due to the finite optical coupling between the two rings, which is analogous to the d.c. Stark effect in a canonical two-level system. NT, normalized transmission. Credit: Nature Photonics, doi: https://doi.org/10.1038/s41566-018-0317-y

Physical systems with discrete energy levels are ubiquitous in nature and form fundamental building blocks of quantum technology. Artificial atom-like and molecule-like systems were previously demonstrated to regulate light for coherent and dynamic control of the frequency, amplitude and the phase of photons. In a recent study, Mian Zhang and colleagues engineered a photonic molecule with two distinct energy levels, using coupled lithium niobate micro-ring resonators that could be controlled via external microwave excitation. The frequency and phase of light could be precisely operated by programmed microwave signals using canonical two-level systems to include Autler-Townes splitting, Stark shift, Rabi oscillation and Ramsey interference phenomena in the study. Through such coherent control, the scientists showed on-demand optical storage and retrieval by reconfiguring the photonic molecule into a bright-dark mode pair. The dynamic control of light in a programmable and scalable electro-optic system will open doors for applications in microwave-signal processing, quantum photonic gates in the frequency domain and to explore concepts in optical computing as well as in topological physics.

The results are now published on *Nature Photonics*, where Zhang et al. overcame the existing performance trade-off, to realize a programmable photonic two-level system that can be controlled dynamically via gigahertz microwave signals. To accomplish this, the scientists created a microwave addressable photonic molecule using a pair of integrated lithium niobate micro-ring resonators patterned close to each other (radius 80 μm). The combined effects of low optical loss, efficient cointegration of optical waveguides and microwave electrodes allowed the simultaneous realization of a large electrical bandwidth (> 30 GHz), strong modulation efficiency and long photon lifetime (~2 ns).

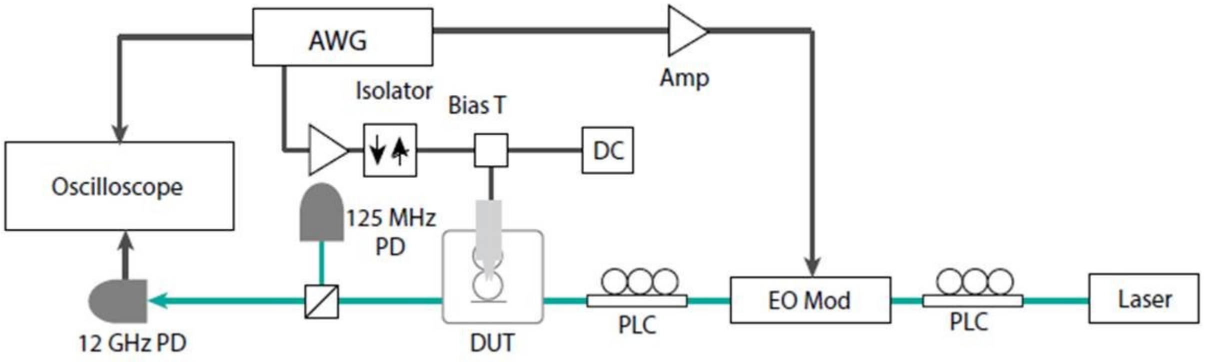
A photonic analogue of a two-level system can typically facilitate the investigation of complex physical phenomena in materials, electronics and optics. Such systems convey important functions, including unique on-demand photon storage and retrieval, coherent optical frequency shift and optical quantum information processing at room temperature. For dynamic control of photonic two-level systems, electro-optic methods are ideally suited due to their fast response, programmability and possibility for large-scale integration.



Device and experimental setup detail. a) Scanning electron microscope (SEM) image of the gap between the coupled microring resonators. b) Cross-section of the optical mode profile in the ring resonator. c) Microring image of the full device showing the double ring and microwave electrodes. d) SEM image of the array of double ring devices fabricated on a single chip. Credit: Nature Photonics, doi: https://doi.org/10.1038/s41566-018-0317-y

For electro-optic control of a two-level system, the photon lifetime of each energy state must be longer than the time required for the system to be driven from one state to the other. Conventional integrated photonic platforms have not met the requirements of a simultaneously long photon life-time and fast modulation so far. Electrically active photonic platforms (based on silicon, graphene and other polymers), allow fast electro-optic modulation at gigahertz frequencies but suffer from shorter photon lifetimes. However, pure electrical tuning is still highly desirable, as narrowband microwave signals offer much better control with minimal noise and scalability.

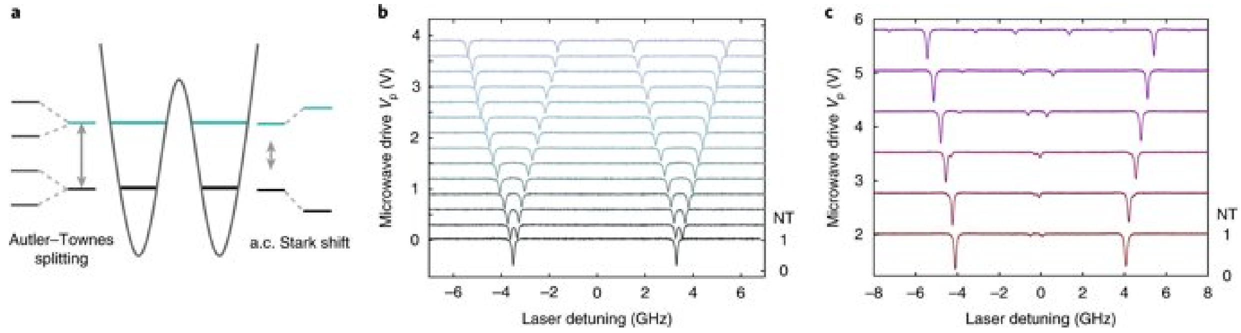
In their work, Zhang et al. showed that optical transmission of the photonic molecule measured using a telecom-wavelength laser, supported a pair of well-defined optical energy levels. The evanescent coupling of light from one resonator to another was enabled through a 500 nm gap between the micro-ring resonators to form the two well-resolved optical energy levels. The scientists explored the analogy between an atomic and photonic two-level system to demonstrate control of the photonic molecule.



Extended experimental setup. The device is optically pumped by a tunable telecom laser centered around 1630 nm. The light is sent through an external electro-optic modulator and polarization controllers (PLC) before coupling into the chip with a lensed fiber. The output optical signal, also coupled with a lensed fiber is sent to a 12 GHz photodetector. The converted electrical signal is directed to an oscilloscope. The microwave control signals are generated by an arbitrary wave generator (AWG) and amplified before being sent into the device. A bias T is used to allow DC control on the microresonators. An electrical isolator is used to capture the electrical reflection from the microresonators. The oscilloscope, device drive signals and modulator drive signals are all synchronized. Credit: Nature Photonics, doi: https://doi.org/10.1038/s41566-018-0317-y

In the experiments, light from the tunable telecom wavelength laser was launched into the lithium niobate waveguides and collected from them via a pair of lensed optical fibres. The scientists used an arbitrary waveform generator to operate microwave control signals before sending them to electrical amplifiers. The efficient overlap between microwaves and optical fields observed in the system enabled higher tuning/modulation efficiency than those previously observed with bulk electro-optic systems. Such coherent microwave-to-optical conversion can link electronic quantum processes and memories via low-loss optical telecommunication, for applications in future quantum information networks.

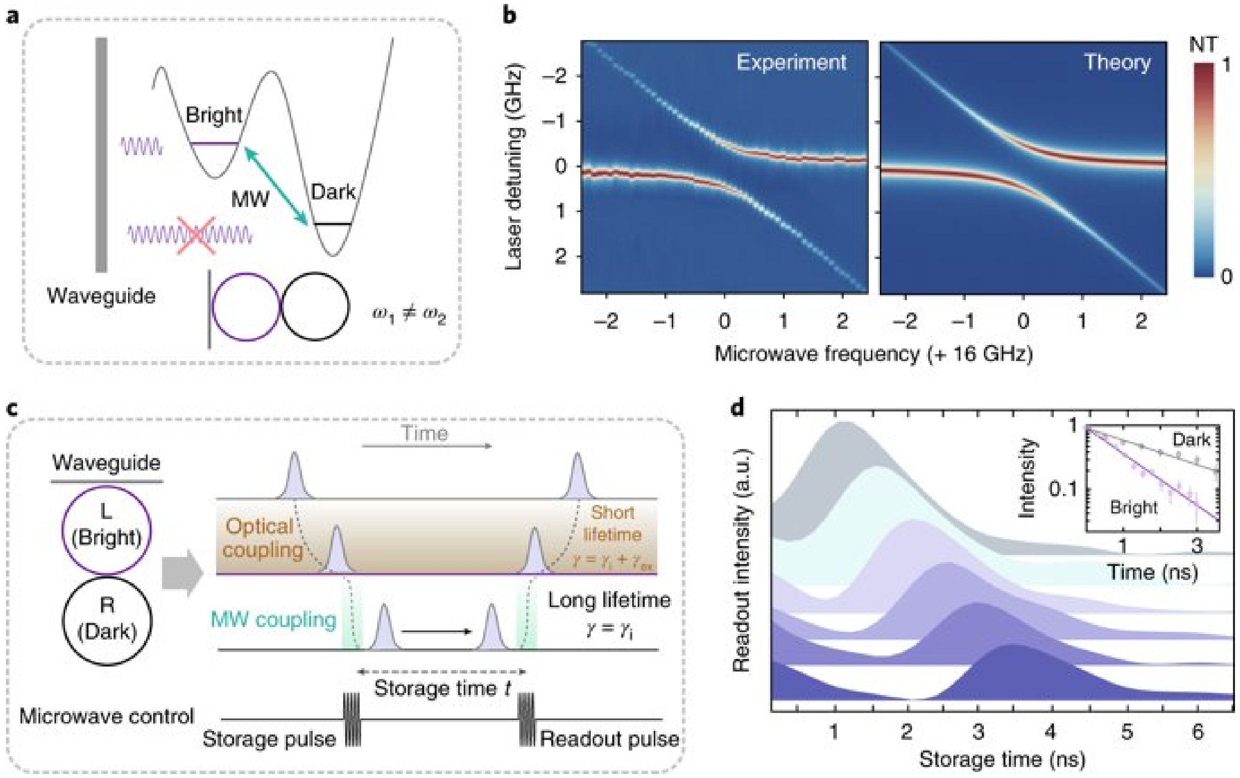
Zhang et al. next used a continuous-wave coherent microwave field to control a photonic two-level system. In this system, the number of photons that could populate each of the two levels was not limited to one. The splitting frequency of the system was precisely controlled up to several gigahertz by controlling the amplitude of the microwave signals. The effect was used to control the effective coupling strength between the energy levels of the photonic molecule. Coherent spectral dynamics in the photonic molecule were investigated for a variety of microwave strengths applied to the photonic two-level system. The scientists also described the controlled amplitude and phase of the system using Rabi oscillation and Ramsey interference, while using Bloch spheres/geometric representations of the photonic two-level energy system to represent the phenomena.



Microwave dressed photonic waveguides. a) When the applied microwave frequency is tuned to match the mode separation, dissipative coupling leads the two photonic levels to split into four levels. This effect is analogous to Autler–Townes 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 analogous to a.c. Stark shifts. b) Measured Autler–Townes splitting in the photonic molecule, where the splitting can be accurately controlled by the amplitude of the applied microwave signal. c) Measured photonic a.c. Stark shifts for a microwave signal at 4.5 GHz. Credit: Nature Photonics, doi: https://doi.org/10.1038/s41566-018-0317-y

The work allowed controlled writing and reading of light into a resonator, from an external waveguide to achieve on-demand photon storage and retrieval, a critical task for optical signal processing. To facilitate this experimentally, Zhang et al. applied a large DC bias voltage (15 V) to reconfigure the double-ring system into a pair of bright and dark modes. In the setup, the mode localized in the first ring provided access to the optical waveguides and became optically bright

(bright mode). The other mode was localized in the second ring that was geometrically decoupled from the input optical waveguide to become optically dark. Accordingly, the scientists demonstrated coherent and dynamic control of a two-level photonic molecule with microwave fields and on-demand photon storage/retrieval through meticulous experiments in the study. The work opens a path to a new form of control on photons. The results are an initial step with potentially immediate applications in signal processing and quantum photonics.



On-demand storage and retrieval of light using a photonic dark mode. a) The photonic molecule is programmed to result 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 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 second microwave π pulse retrieves the light from the dark to the bright mode. γ, γi and γex are the lifetimes 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, shown by the traces from top to bottom with a 0.5 ns delay increment. Inset: the extracted intensity of the retrieved light shows nearly twice the lifetime of the critically coupled bright mode. The error bars show the uncertainty in the optical intensity readout. MW, microwave; NT, normalized transmission; a.u., arbitrary units. Credit: Nature Photonics, doi: https://doi.org/10.1038/s41566-018-0317-y

The design parameters of the coupled resonators provide space to investigate the dynamic control of two-level and multi-level photonic systems, leading to a new class of photonic technologies. The scientists envision that these findings will lead to advances in topological photonics, advanced photonic computation concepts and on-chip frequency-based optical quantum systems in the near future.

More information: Mian Zhang et al. Electronically programmable photonic molecule, *Nature Photonics* (2018). DOI: 10.1038/s41566-018-0317-y

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