NEWS AND VIEWS

Journal of Semiconductors
(2019) 40, 020402
doi: 10.1088/1674-4926/40/2/020402

Quantum-optical analogies of dimer structures

Jian Wang† and Shuang Zheng

Wuhan National Laboratory for Optoelectronics, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China

By using the concepts of canonical two-level systems, microwave-addressable photonic molecule enables on-demand photon storage and retrieval based on coupled lithium niobate microring resonators, which simultaneously achieve large electrical bandwidth, strong modulation efficiency, and long photon lifetime.

Citation: J Wang and S Zheng, Quantum-optical analogies of dimer structures[J]. *J. Semicond.*, 2019, 40(2), 020402. http://doi.org/10.1088/1674-4926/40/2/020402

In the past decades, engineered photonic waveguides and other structures have provided an extremely rich laboratory tool to visualize with optical waves the classic analogues of a wide variety of coherent quantum phenomena encountered in atomic, molecular or condensed-matter physics[1]. Owing to the powerful visualization methods and detection method of optics, photonic analogues of quantum systems have resulted in discoveries such as non-Hermitian quantum systems with parity-time symmetry, quantum collapses and revivals, Rabi oscillations and solid-state physics including Bloch oscillations, Anderson localization and others. These quantum-optical analogies also promote the development of related technologies including quantum ground-state cooling of nanomechanical systems, new classes of sensors, one-way lasers and orbital angular momentum microlaser.

With the development of semiconductor technologies in optical waves, the mature fabrication process including passive and active materials of various specially engineered optical waveguide structures or coupled optical waveguides has proven to provide a rich and varied approach for the classical analogues of a wide variety of quantum phenomena. Rectangular waveguide, as the fundamental structure on chip, has been widely used to investigate the on-chip quantum-optical analogies. By using curved photonic structures, quantum decay control and Zeno dynamics, electronic Bloch oscillations and Zener tunneling, Anderson localization and dynamic localization in crystalline potentials can all be observed on chip. As another building block device of photonic integrated circuits, microring resonators (MRRs) side coupled to signal waveguides provide compact, narrow band, and large free spectral range optical channel dropping filters. Additionally, MRRs have also been widely investigated with new concepts from non-Hermitian quantum systems and topological physics[2–7]. For example, single parity-time symmetric MRR with balanced gain/loss or complex index distribution can achieve single mode lasing and selection of either clockwise or counterclockwise mode at the exceptional point[2, 3]. Dimer structures composed of coupled MRRs have also been studied, which would be helpful for single mode lasing in coupled MRRs[4, 5]. Lasing topological edge states in active array of microring resonators have been realized, which benefit from the combination of non-Hermiticity and topology in active systems[6]. High-performance sensors have also been developed at higher-order exceptional points based on MRRs[7].

Moreover, a photonic analogue of a two-level system would enable the investigation of complex physical phenomena and unique functionalities, including on-demand photon storage and retrieval, coherent optical frequency shift and optical quantum information processing at room temperature. However, the dynamical controlling of such a two-level system is still challenging, and now coherent coupling between discrete photon energy modes has only been studied using all-optical methods[8, 9].

With the progress of various active/passive integrated platforms, high-speed modulation methods have been employed in photonic integrated chips and also provide another modulation dimension to control the parameters in quantum-optical analogies.

Electro-optic methods are ideally suited for the dynamic control of photonic two-level systems, owing to the fast response, programmability and large-scale integration.

In recent years, silicon photonics on the silicon-on-insulator (SOI) platform has emerged as the most promising technology due to the possibility of high-quality, low-cost and high-volume production of photonic integrated circuits (PICs) in complementary metal oxide semiconductor (CMOS) foundries. Based on free-carrier dispersion effect, high-speed silicon MRR modulators are key components serving as the information encoding engines from electrical to optical domain. Unfortunately, free-carrier dispersion is associated with free-carrier absorption loss which leads to shorter photon lifetimes than passive platforms. To realize coherent electro-optic control of a photonic two-level system, 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.

Now, reporting in Nature Photonics, *Mian Zhang* and colleagues at John A. Paulson School of Engineering and Applied Sciences, Harvard University experimentally demonstrate a 'photonic molecule' with two distinct energy levels using coupled lithium niobate MRRs and control it by external microwave excitation shown in Fig. 1. Owing to the Pockels effect ($\chi^{(2)}$) of lithium niobite, the frequency and phase of light in MRRs 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. Through such coherent control, on-de-

---

† Correspondence to: J Wang, jwang@hust.edu.cn

©2019 Chinese Institute of Electronics

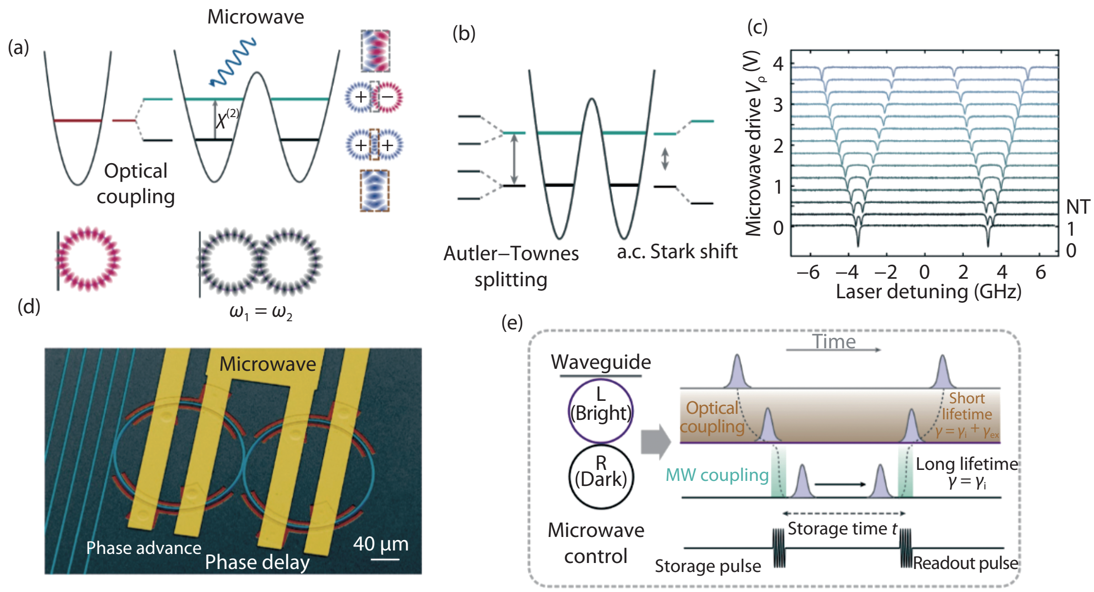

Fig. 1. (Color online) Microwave-dressed photonic module. (**a**) The photonic molecule is realized by a pair of identical coupled optical microring resonators (resonant frequency $\omega_1 = \omega_2$). The system has two distinct energy levels—a symmetric and an antisymmetric optical mode. (**b, c**) 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. (**d**) False-coloured scanning electron microscope image of the coupled microring resonators. (**e**) On-demand storage and retrieval of light using a photonic dark mode. Figure adapted from Ref. [10].

mand optical storage and retrieval can be observed by reconfiguring the photonic molecule into a bright–dark mode pair[10].

The size of the MRRs in the photonic molecule has been optimized, which is chosen to ensure optimum electro–optic overlap while still maintaining a tight bending radius. The high frequency microwave electrodes are also designed to achieve good electric performance. To enable strong overlap between microwave and optical fields without significantly increasing the optical loss, the gold microelectrodes are placed 2.5 μm away from the edge of the rings that form the photonic molecule. The low optical loss and efficient co-integration of optical waveguides and microwave electrodes contribute to simultaneously achieve impressive performance with large electrical bandwidth more than 30 GHz, strong modulation efficiency (0.5 GHz V^{-1}) and long photon lifetime (~2 ns). Specifically, *Mian Zhang* and co-workers create a microwave-addressable photonic molecule using a pair of integrated lithium niobate microring resonators, 80 μm in radius, patterned close to each other. The photonic molecule supports a pair of well-defined optical energy levels, corresponding to two different modes, symmetric (S) and antisymmetric (AS) optical mode. 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 S mode and a higher-frequency AS mode. The two new eigenmodes represent the two energy levels of the photonic molecule shown in Fig. 1(a). In such a dimer system, the electro–optic effect plays the equivalent role to an electric dipole moment in 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 (d.c.) electric field, the mode splitting of the dimer can be controlled. This added frequency detuning reduces the optical coupling between the two MRRs and results in the characteristic avoided crossing curve in coupled resonator systems. This control is analogous to the d.c. Stark effect used in atomic systems. Actually, such a familiar dimer structure has been studied based on SOI platform, which has been applied to realize various tunable filters. However, the modulation speed and quality factor cannot be achieved at the same time. Therefore, lithium niobate integrated devices provide a remarkable platform for investigating light-matter interaction and quantum-analogies.

Such a photonic two-level system is also controlled by continuous-wave coherent microwave field, which is similar to an atomic two-level system under a strong coherent excitation. When the microwave frequency equals to 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 coupled MRRs shown in Fig. 1(b). By tuning the amplitude of the microwave signals, the exact splitting frequency (Ω) can be precisely controlled up to several gigahertz shown Fig. 1(c). When the microwave frequency is detuned far from the energy difference, the microwave-induced photonic mode coupling becomes weaker, and an effective dispersive effect can be observed, similar to the a.c. Stark shift in atomic systems. The photonic molecule can also be used for unitary transformation of light in the frequency domain by controlling the dispersive and dissipative coupling between the two optical modes. By controlling over the amplitude and phase, Rabi oscillation and Ramsey interference can be measured, which agree well with the theoretically predicted results.

Moreover, such a photonic module is applied to achieve on-demand photon storage and retrieval—a critical task for optical signal processing in Fig. 1(e). It is well known that MRRs can slow down the group velocity of light propagation, but such slow-down is fundamentally limited by the delay–bandwidth product and thus cannot be controlled on demand. The use of a dynamically modulated resonator system can overcome the constraint imposed by the delay–bandwidth limit, which means that the optical coupling strength needs to be altered faster than the photon lifetime in the cavity. First, a large d.c. bias voltage is applied to reconfigure the double-ring system into a pair of bright and dark modes. Then, the coupling of the dark optical mode can be controlled by applying a microwave signal with the frequency matched to the difference between the two optical modes. In the experiment, *Mian Zhang* and co-workers achieve a tunable delay of ~15 ns with a quality factor similar to previous reported values ($Q \sim 10^7$), which is more than an order of magnitude better than storing the light in the bright mode. In the future, if the quality factor of the MRRs can be further improved, hundreds of delay time could be realized.

Very recently, integrated lithium niobate electro–optic modulators based on CMOS technology or SOI platform have been demonstrated[11]. Such important progress potentially provides a new generation of compact, high performance optical modulators for telecommunications and data-interconnects. Here, dimer structure based on lithium niobite platform also provides a powerful platform to investigate quantum-optical analogies. This work is an important step towards bringing high-speed dynamic control into quantum photonics, such as two-level and multi-level quantum photonic systems. Especially, the coherent and dynamic control of a two-level photonic molecule with microwave fields and desired photon storage and retrieval operations opens a door to a new form of robust control over photons.

References

[1] Longhi S. Quantum-optical analogies using photonic structures. Laser Photonics Rev, 2009, 3(3), 243

[2] Feng L, Wong Z J, Ma R M, et al. Single-mode laser by parity-time symmetry breaking. Science, 2014, 346(6212), 972

[3] Miao P, Zhang Z, Sun J, et al. Orbital angular momentum microlaser. Science, 2016, 353(6298), 464

[4] Hodaei H, Miri M A, Heinrich M, et al. Parity-time–symmetric microring lasers. Science, 2014, 346(6212), 975

[5] Hodaei H, Miri M A, Hassan A U, et al. Single mode lasing in transversely multi-moded PT-symmetric microring resonators. Laser Photonics Rev, 2016, 10(3), 494

[6] Parto M, Wittek S, Hodaei H, et al. Edge-mode lasing in 1D topological active arrays. Phys Rev Lett, 2018, 120(11), 113901

[7] Hodaei H, Hassan A U, Wittek S, et al. Enhanced sensitivity at higher-order exceptional points. Nature, 2017, 548(7666), 187

[8] Guo X, Zou C L, Jung H, et al. On-chip strong coupling and efficient frequency conversion between telecom and visible optical modes. Phys Rev Lett, 2016, 117(12), 123902

[9] Sato Y, Tanaka Y, Upham J, et al. Strong coupling between distant photonic nanocavities and its dynamic control. Nat Photonics, 2012, 6(1), 56

[10] Zhang M, Wang C, Hu Y, et al. Electronically programmable photonic molecule. Nat Photonics, 2019, 13(1), 36

[11] Wang C, Zhang M, Chen X, et al. Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages. Nature, 2018, 562(7725), 101