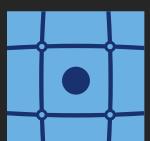




Российский
Квантовый
Центр



Quantum networks based on circular superfluid currents of exciton-polaritons



Alexey Kavokin

Westlake University, Hangzhou,
China

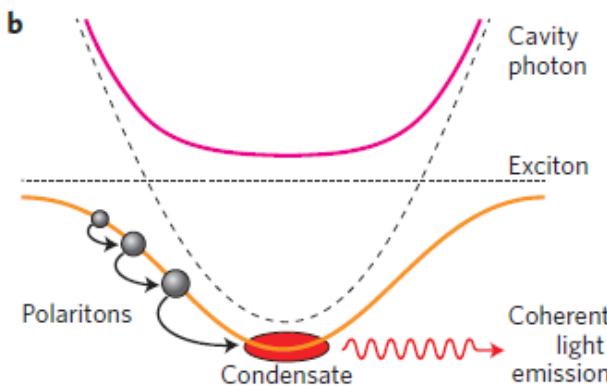
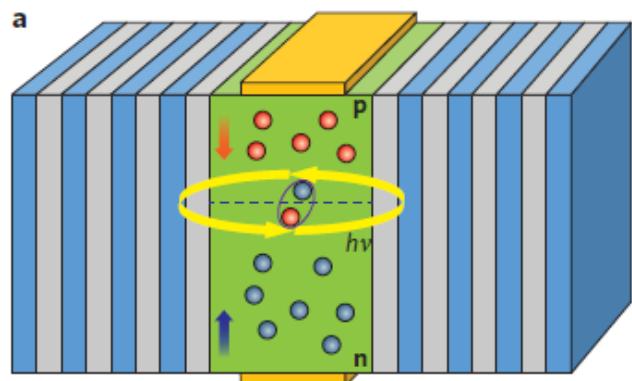
University of Southampton, UK

Russian Quantum Center,
Russia

Our ambition: polariton
qubits will outperform
Google qubits



Polariton lasers: out of equilibrium BEC emits a coherent light



Photon mode dispersion

$$\frac{\omega}{c} n = \sqrt{\left(\frac{2\pi}{L}\right)^2 + k_{\parallel}^2}$$

Ultralight effective mass $\propto (10^{-5} - 10^{-4}) m_0$

Exciton-polaritons form Bose-Einstein condensates that spontaneously emit coherent light

The concept:

A. Imamoglu, et al, Phys. Lett. A 214, 193 (1996).

Prediction of the room temperature BEC and polariton lasing:

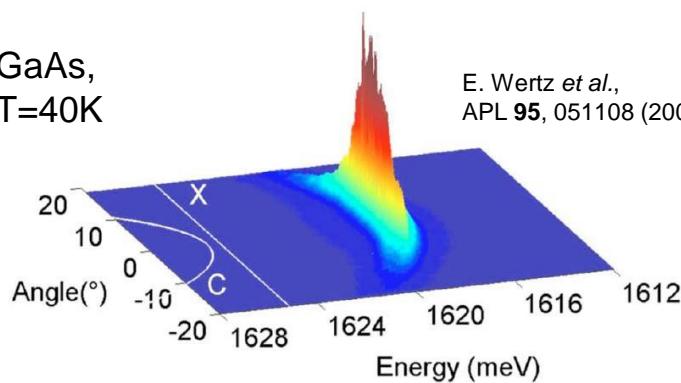
"Semiconductor microcavities: towards polariton lasers", Kavokin A, Malpuech G, Gil B, *J. Nitride Semicond. Res.* **8**, 3, 3 (2003)

$$T_c = \left(\frac{n}{\zeta(3/2)} \right)^{2/3} \frac{2\pi\hbar^2}{mk_B} \approx 3.3125 \frac{\hbar^2 n^{2/3}}{mk_B}$$

Polariton lasers have been realised in many semiconductor systems

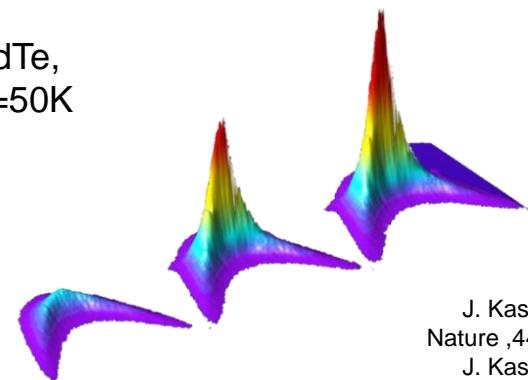
GaAs,
T=40K

E. Wertz *et al.*,
APL **95**, 051108 (2009)

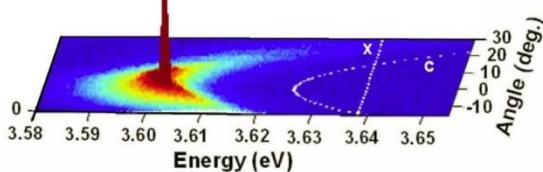


CdTe,
T=50K

J. Kasprzak *et al.*,
Nature **443**, 409 (2006)
J. Kasprzak *et al.*,
PRL **101**, 146404 (2008)

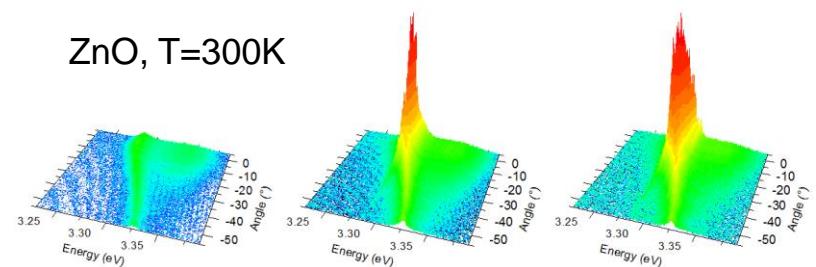


GaN, T=300K



G. Christmann *et al.*,
APL **93**, 051102 (2008)

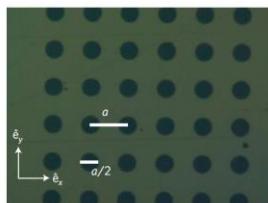
ZnO, T=300K



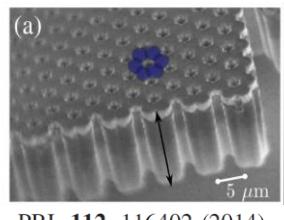
Thierry Guillet, J. Zuniga-Perez, APL 2012

Polariton Lattices

Lithographic lattices:



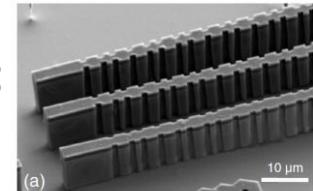
Yamamoto
Nature Physics 2011



PRL 112, 116402 (2014)

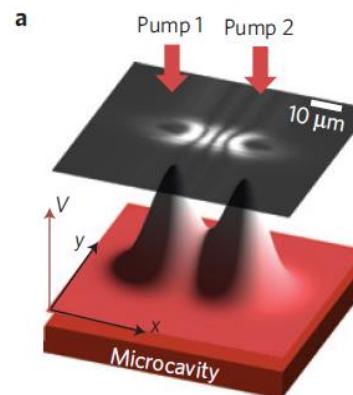
Bloch

Bloch

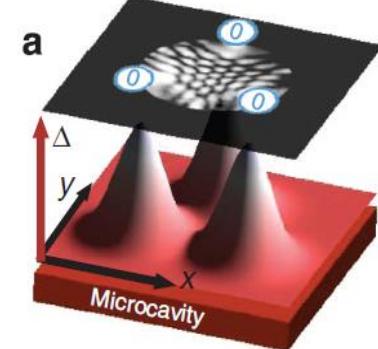


PRL 112, 146404 (2014)

Optical lattices:

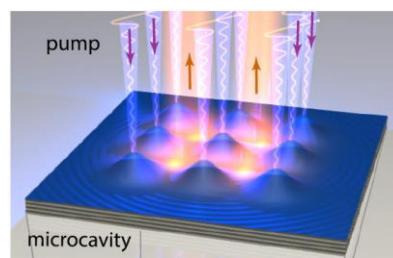


Baumberg
Nature Physics 2012



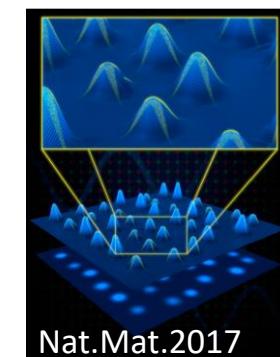
Baumberg
Nature Comms 2012

Optical lattices
of trapped condensates



PRL 119, 067401 (2017)

Baumberg

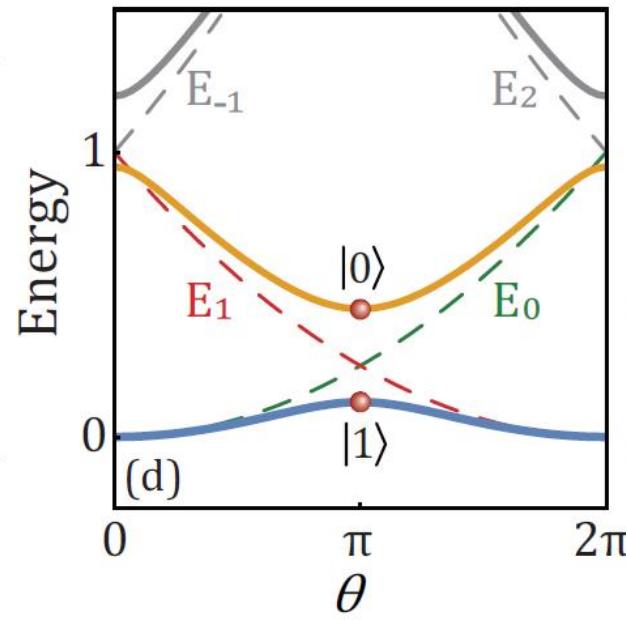
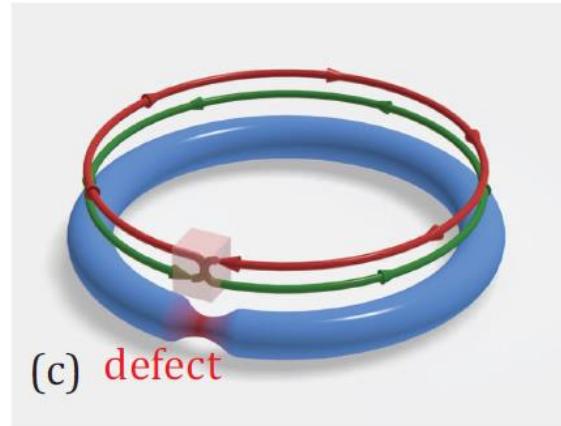
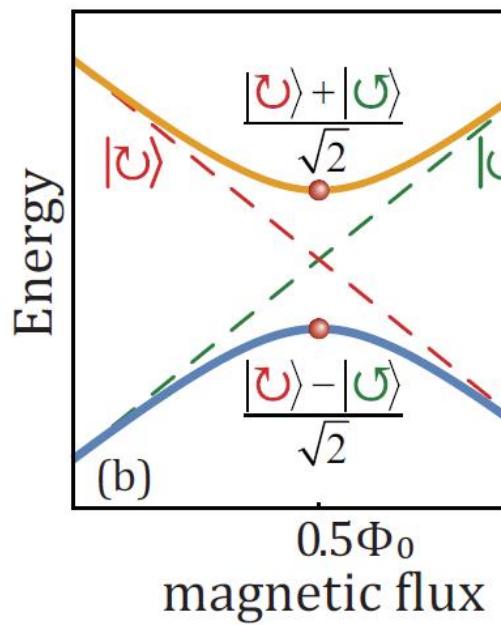
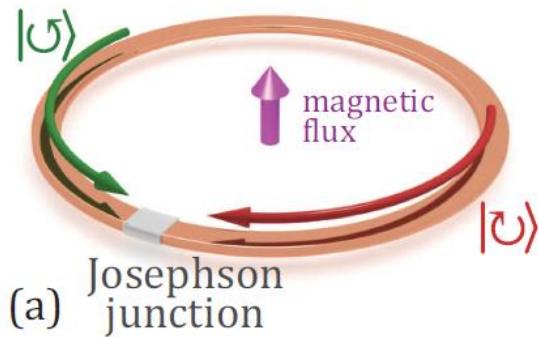


Nat. Mat. 2017

Optical lattices
of expanding condensates

Our proposal: Polariton qubits built on circular currents

A
superconducting
circuit

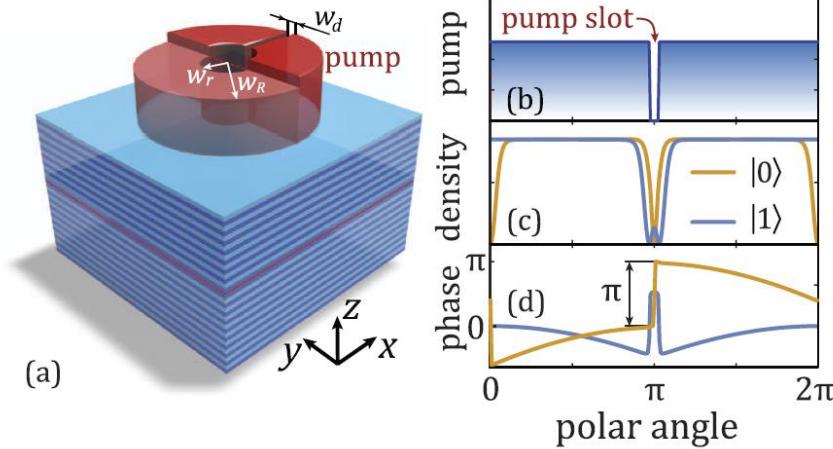


A superfluid polariton ring



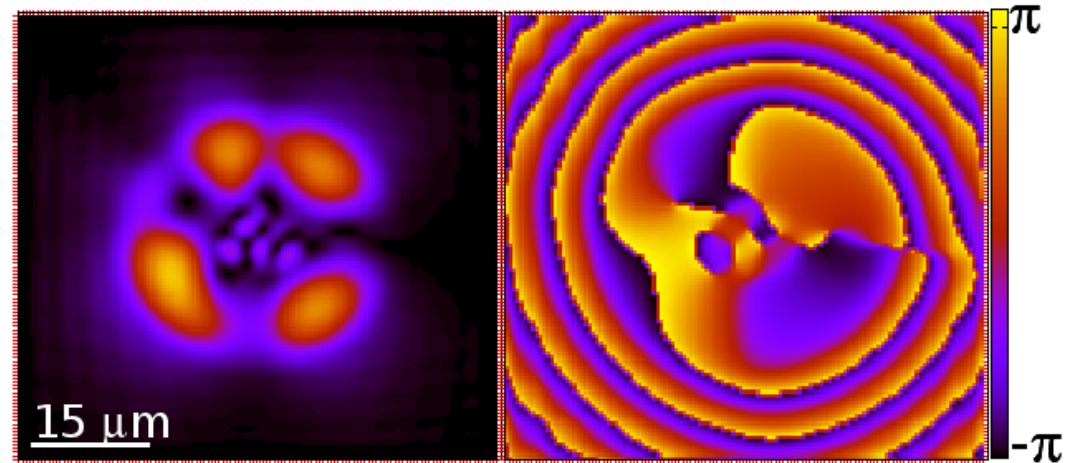
And polariton qubits can be built on circular currents!

Split-ring polariton condensates

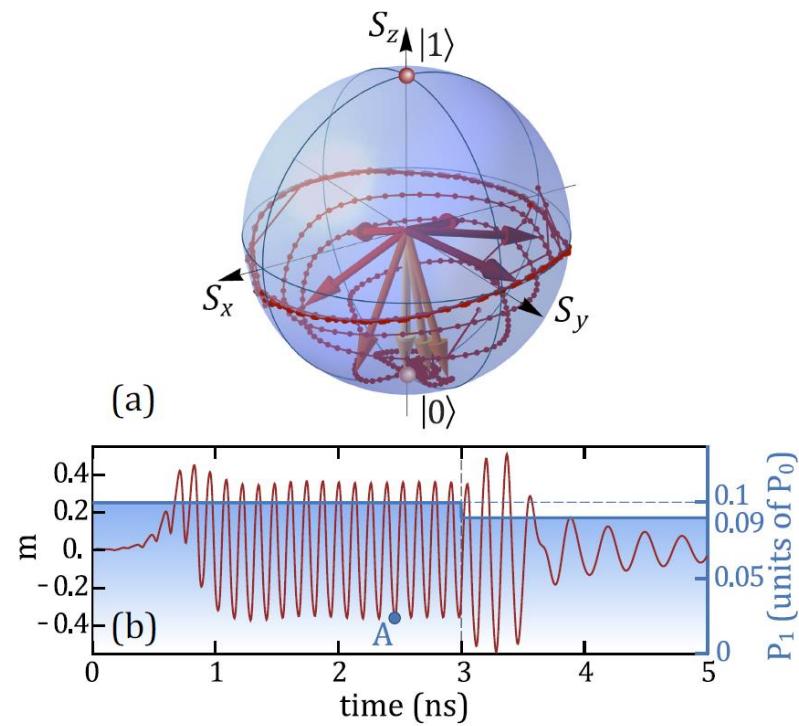
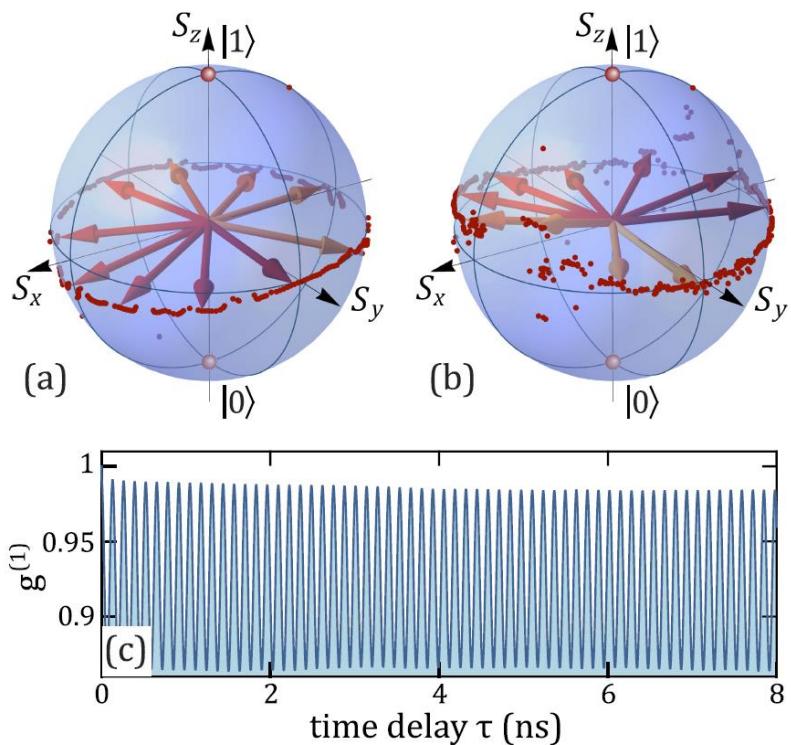


The non-resonant optical excitation by horse-shoe laser beams

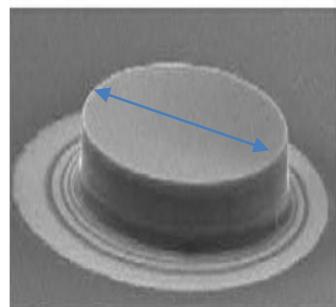
Persistent oscillations between clockwise and anticlockwise current states



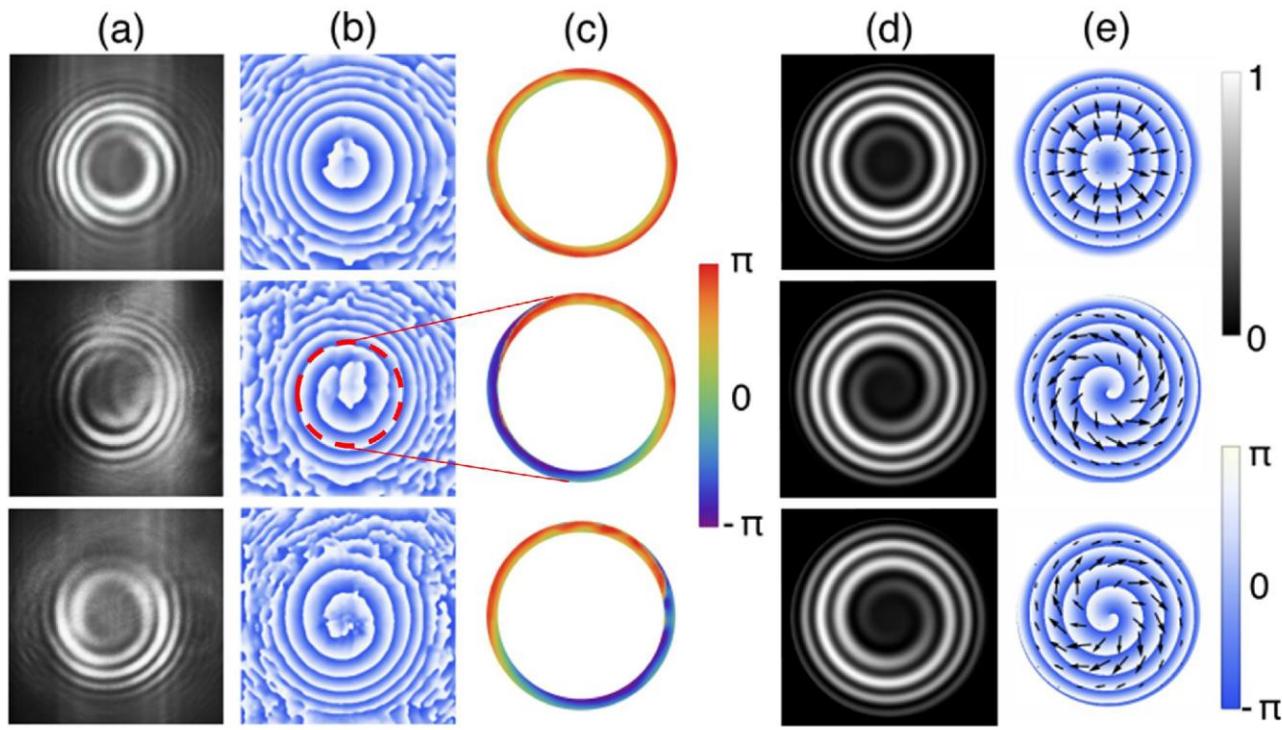
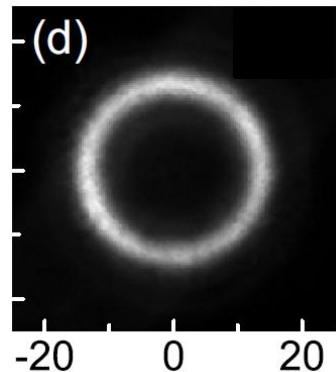
Mapping of the oscillations to the Bloch sphere



Experiment: Persistent circular polariton currents in pillar microcavities



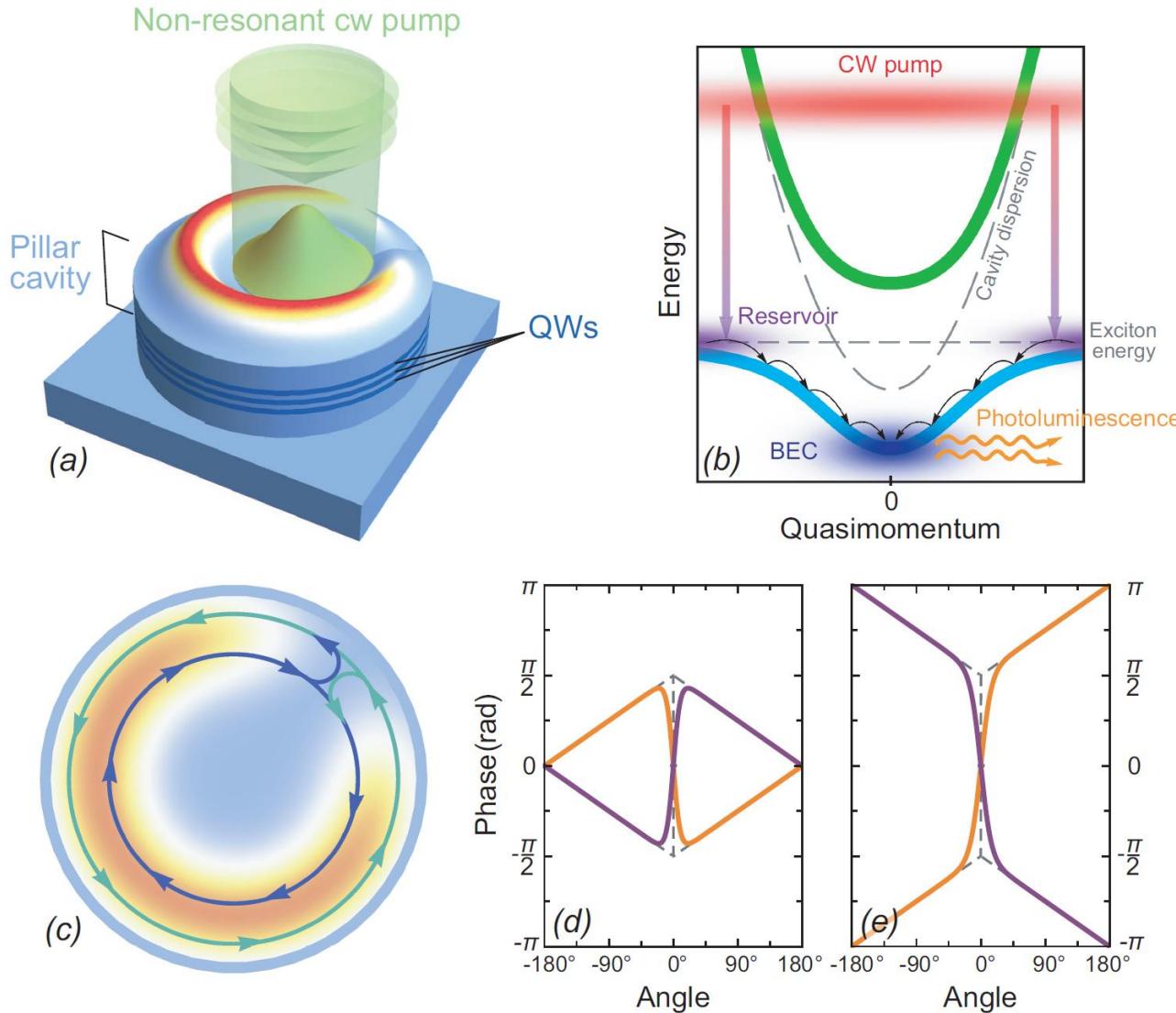
Circular current in a pillar



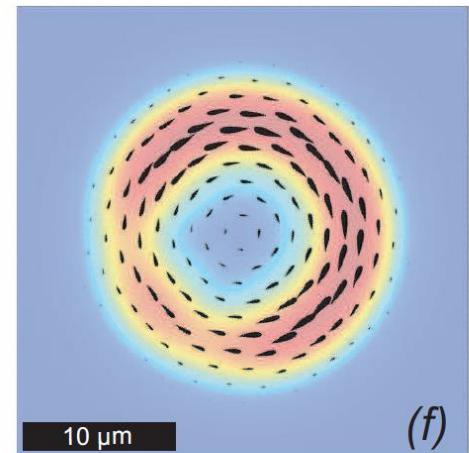
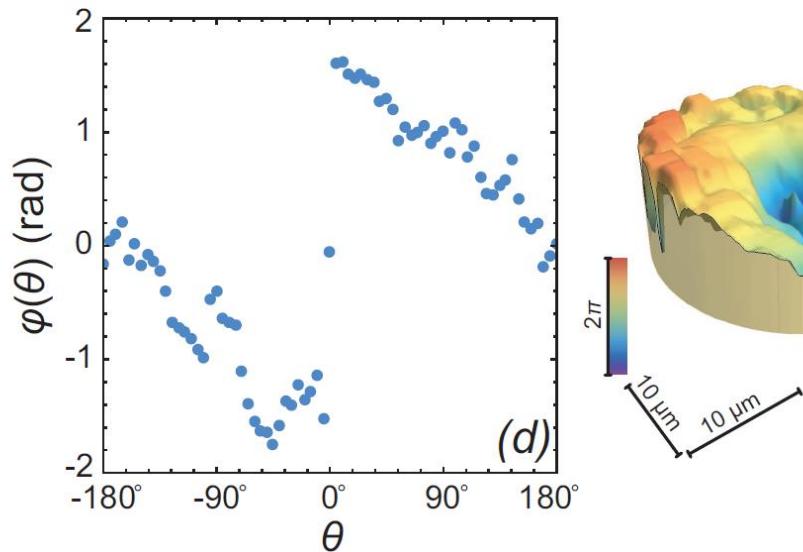
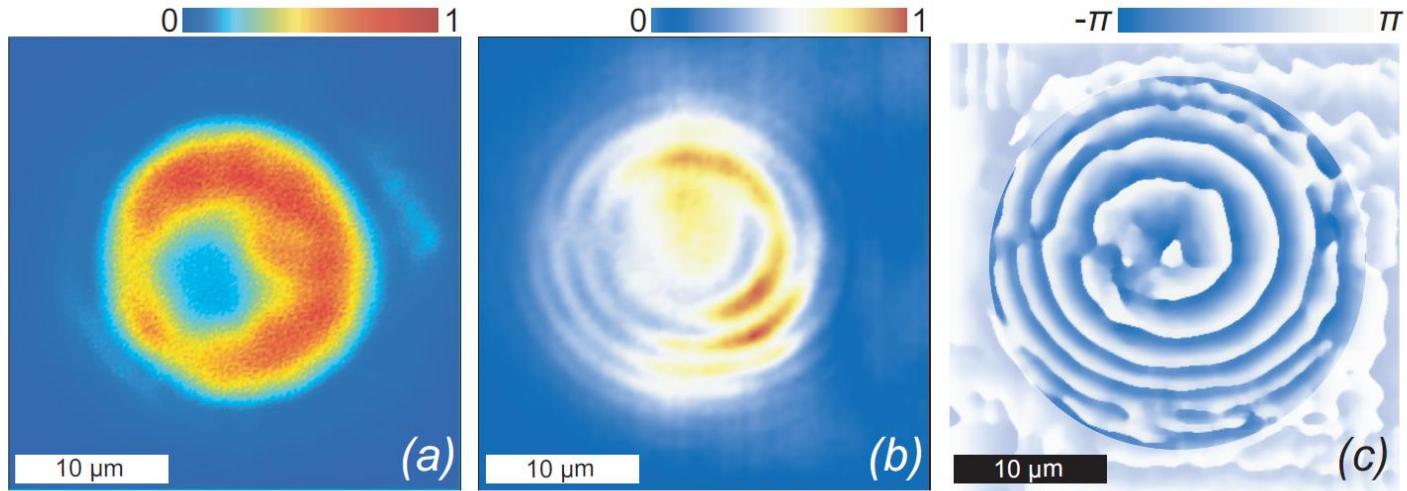
Persistent circular currents of exciton-polaritons in cylindrical pillar microcavities

V. A. Lukoshkin, V. K. Kalevich, M. M. Afanasiev, K. V. Kavokin, Z. Hatzopoulos, P. G. Savvidis, E. S. Sedov, and A. V. Kavokin, Phys. Rev. B **97**, 195149 (2018).

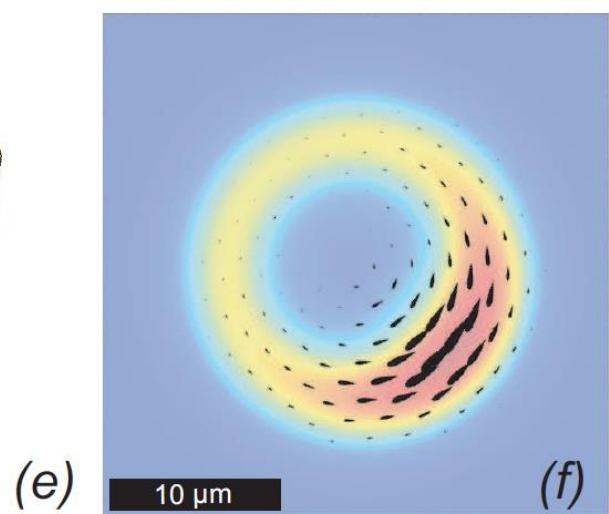
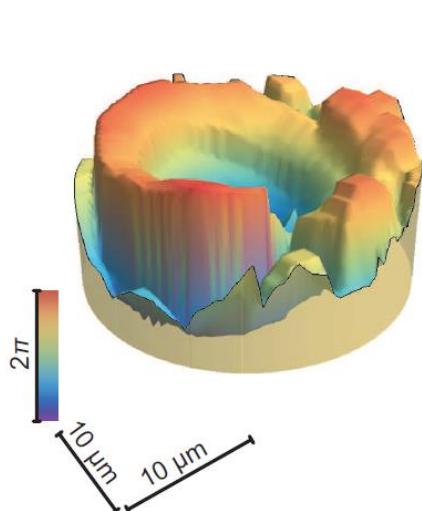
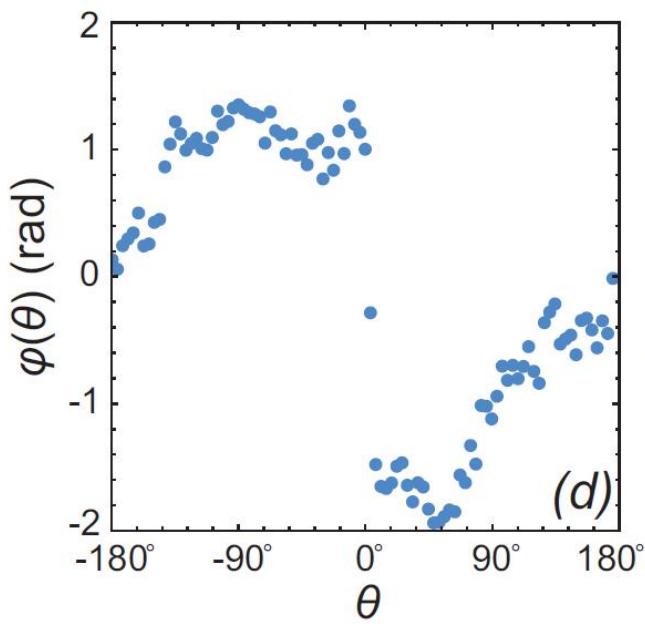
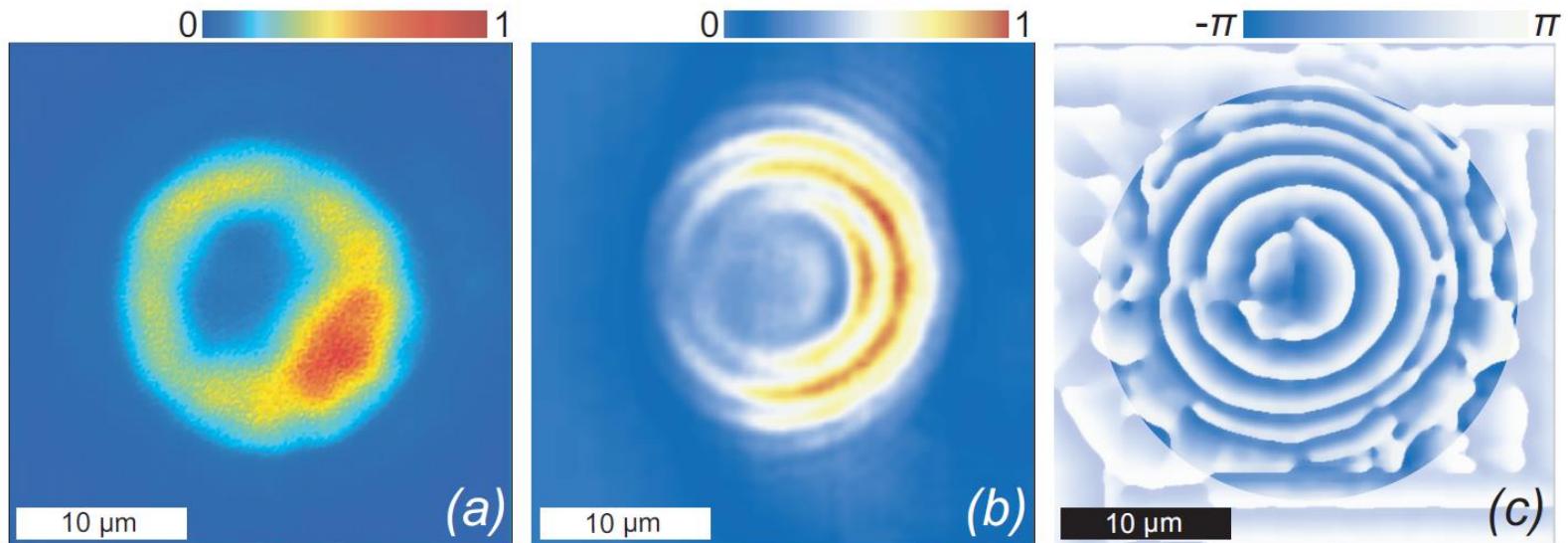
Split-ring condensates sustain currents with half-integer orbital momenta



The phase extracted from the interferometry images



The opposite sign of the current



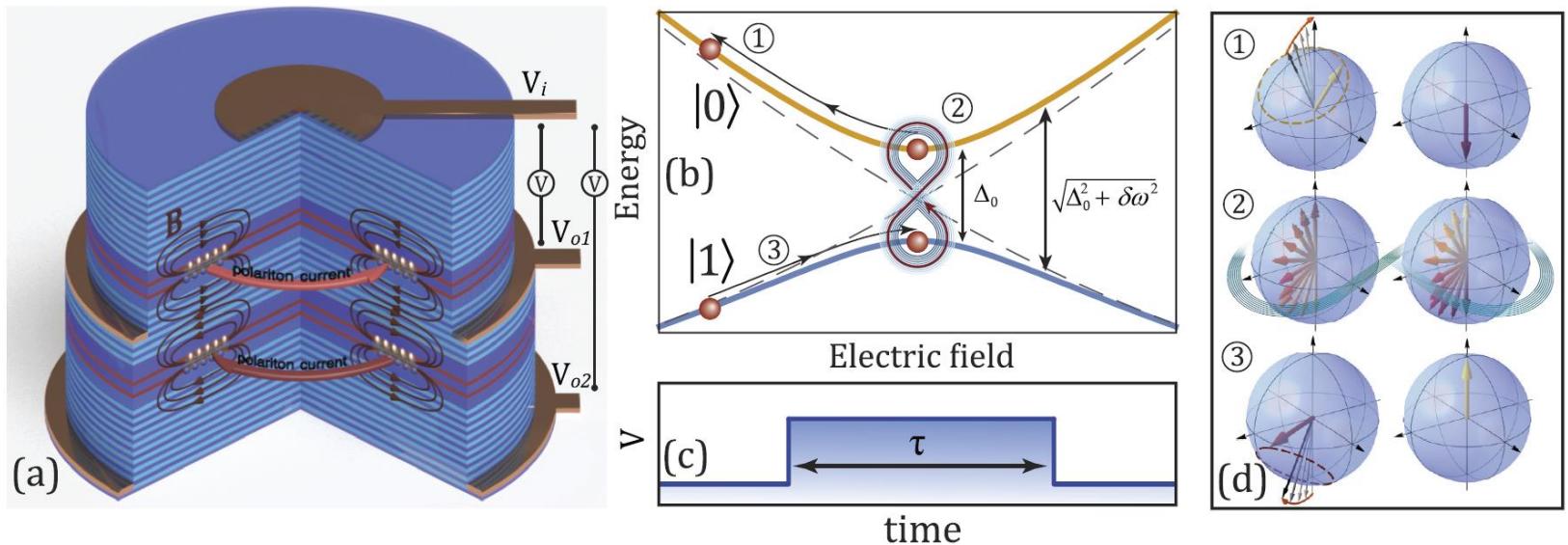
GATE	CIRCUIT REPRESENTATION	MATRIX REPRESENTATION	TRUTH TABLE	BLOCH SPHERE
I Identity-gate: no rotation is performed.		$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	Input Output $ 0\rangle$ $ 0\rangle$ $ 1\rangle$ $ 1\rangle$	
X gate: rotates the qubit state by π radians (180°) about the x-axis.		$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	Input Output $ 0\rangle$ $ 1\rangle$ $ 1\rangle$ $ 0\rangle$	
Y gate: rotates the qubit state by π radians (180°) about the y-axis.		$Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$	Input Output $ 0\rangle$ $i 1\rangle$ $ 1\rangle$ $-i 0\rangle$	
Z gate: rotates the qubit state by π radians (180°) about the z-axis.		$Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$	Input Output $ 0\rangle$ $ 0\rangle$ $ 1\rangle$ $- 1\rangle$	
S gate: rotates the qubit state by $\frac{\pi}{2}$ radians (90°) about the z-axis.		$S = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{2}} \end{pmatrix}$	Input Output $ 0\rangle$ $ 0\rangle$ $ 1\rangle$ $e^{i\frac{\pi}{2}} 1\rangle$	
T gate: rotates the qubit state by $\frac{\pi}{4}$ radians (45°) about the z-axis.		$T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{4}} \end{pmatrix}$	Input Output $ 0\rangle$ $ 0\rangle$ $ 1\rangle$ $e^{i\frac{\pi}{4}} 1\rangle$	
H gate: rotates the qubit state by π radians (180°) about an axis diagonal in the x-z plane. This is equivalent to an X-gate followed by a $\frac{\pi}{2}$ rotation about the y-axis.		$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$	Input Output $ 0\rangle$ $\frac{ 0\rangle + 1\rangle}{\sqrt{2}}$ $ 1\rangle$ $\frac{ 0\rangle - 1\rangle}{\sqrt{2}}$	

Suppose we have a qubit. What do we do with it?

Quantum logic gates

We need to be able to adiabatically switch on and off effective magnetic fields

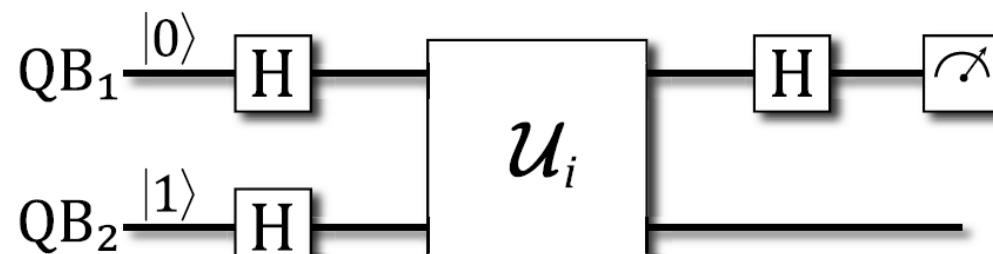
Two-qubit quantum gates for CNOT and iSWAP operations



Being detuned from the point of view of the polariton energy, two qubits are matched from the point of view of their energy gaps. Using of the spatially indirect excitons formed in coupled quantum wells endows polaritons with the permanent dipole moment aligned perpendicular to the cavity plane. A single inner (V_i) and a couple of outer (V_{o1} and V_{o2}) electrodes generate the radial electric field, which in combination with the perpendicular external magnetic field introduces an artificial gauge potential required for the selective tuning of the qubits' energy gap. (b)

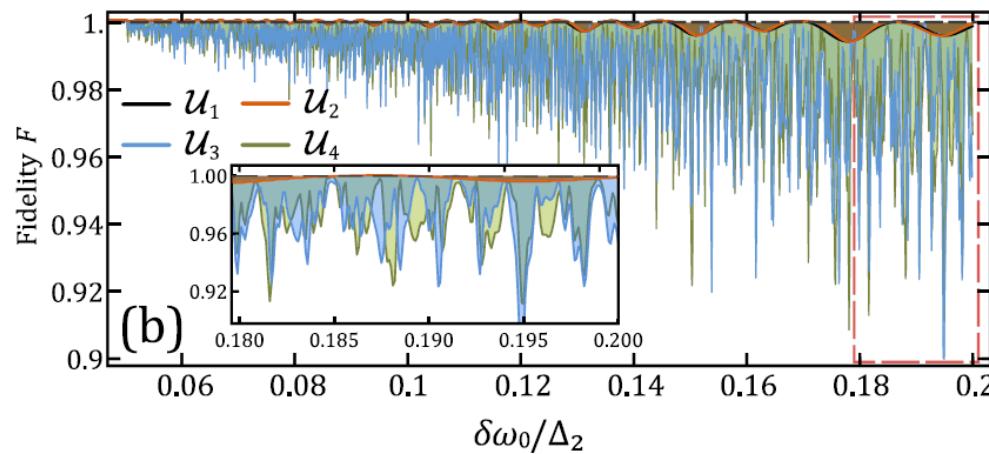
The implementation of the Deutsch algorithm

(Collaboration with the group of Aleksey Fedorov, RQC)



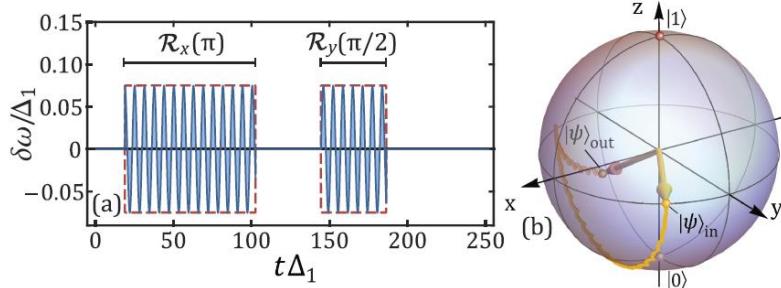
(a)

H denotes the Hadamard transform.

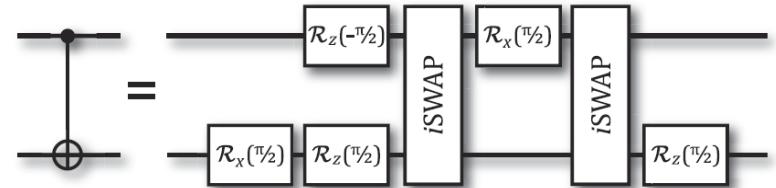


(b)

Polariton quantum protocols

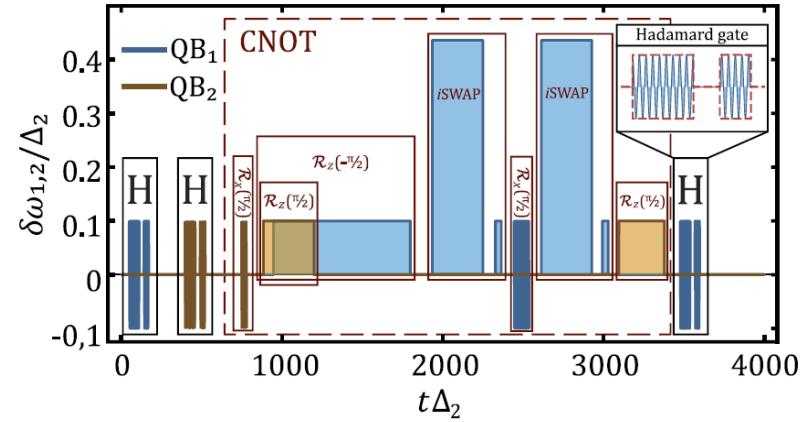


Realization of the Hadamard gate



Realization of the CNOT gate

Constant functions		Balanced functions	
\mathcal{U}	Logic gate	\mathcal{U}	Logic gate
\mathcal{U}_1	Identity	\mathcal{U}_3	CNOT
\mathcal{U}_2	Bit-flip	\mathcal{U}_4	Z-CNOT



The control pulse sequence for a single run of the Deutsch algorithm with the Oracle U_3

Conclusions

- Superfluid polariton circuits are analogous to superconducting flux qubits
- We demonstrate a coherent coupling of over 1000 condensates
- Next steps: two-qubit quantum gates, implementation of Deutsch and Grover algorithms
- Semiconductor platform: scalability, low cost
- Potentially, room temperature operation

PHYSICAL REVIEW RESEARCH 3, 013072 (2021)

Circular polariton currents with integer and fractional orbital angular momenta

E. S. Sedov^{1,2,3,*}, V. A. Lukoshkin^{1,4,5}, V. K. Kalevich^{1,4,5}, P. G. Savvidis,^{1,2,6} and A. V. Kavokin^{1,2,5,7}

PHYSICAL REVIEW RESEARCH 3, 013099 (2021)

Split-ring polariton condensates as macroscopic two-level quantum systems

Yan Xue^{1,2,3,*}, Igor Chestnov^{1,3,4,†}, Evgeny Sedov,^{1,3,4} Evgeniy Kiktenko,^{5,6} Aleksey K. Fedorov,^{5,6} Stefan Schumacher,⁷ Xuekai Ma,^{7,‡} and Alexey Kavokin^{1,3,5,§}