

Viewpoint

Optical Transistor Flips On with One Photon

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Researchers have used interactions between highly excited atoms to make an optical transistor that can be activated by a single photon.

Subject Areas: **Atomic and Molecular Physics, Optoelectronics****A Viewpoint on:****Single-Photon Transistor Using a Förster Resonance**

Daniel Tiarks, Simon Baur, Katharina Schneider, Stephan Dürr, and Gerhard Rempe

Physical Review Letters **113**, 053602 2014 – Published July 28, 2014**Single-Photon Transistor Mediated by Interstate Rydberg Interactions**

H. Gorniaczyk, C. Tresp, J. Schmidt, H. Fedder, and S. Hofferberth

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A computer based entirely on optical components could perform some tasks much faster than existing computers, which rely on electronic components whose speed is limited by heat generation. However, a fundamental limitation to making the components for an all-optical processor is that photons do not interact: unlike electrons that interact strongly and therefore can easily be used to manipulate other electrons, interactions between photons are generally too weak for one or several photons to be able to block or redirect others. However, recent experiments have shown that highly excited atomic states could mediate the necessary coupling between photons [1–3]. Experimentalists have used these states to make a single-photon source [2], a single-photon phase shifter [3], and now, as reported by two independent research groups in *Physical Review Letters*, a single-photon transistor [4, 5]. Gerhard Rempe and his colleagues at the Max Planck Institute of Quantum Optics and Sebastian Hofferberth and his colleagues at University of Stuttgart, both in Germany, have succeeded in making the first single-photon transistors with high gain—a measure of efficiency—which is a key step to their being used to build more complex optical circuits.

Analogous to their electronic counterparts, photon transistors act as amplifiers for light, in which a few photons control the destiny of many. These optical transistors have two components: a switchable optical medium and a photon “gate” that controls the optical properties of the medium. After a gate photon is absorbed by the optical medium, a certain number of subsequent photons encountering the medium can be either blocked (or transmitted); the ratio of the number of blocked (or transmitted) photons to the number of gate photons defines the gain for the device.

Experiments using single molecules as optical transistors have shown that the gate can function with as few as 20 incoming gate photons [6]. The low-power limit of optical transistors, however, corresponds to the incoming gate pulse having only one photon. And an optical transistor that is responsive to a single photon could be used to perform quantum computations and to detect single quanta with high efficiency. Previous studies have achieved all-optical switching in an atomic system with a single gate photon, but this transistor had a low gain of only 0.24 [7]. Yet many devices, such as amplifiers and repeaters, work by feeding the output of one transistor into the input of another transistor. Such devices require transistors with gains above unity.

The key to achieving gains above unity is creating strong photon-photon interactions. To make these interactions, the single-photon transistors demonstrated by the Rempe and Hofferberth groups rely on optically excited atoms in high-excitation states, called Rydberg states, and an effect called Rydberg blockade that occurs in clouds of identical atoms. An atom excited to a Rydberg state has a large electric dipole, which induces shifts in the energy levels of neighboring atoms within a so-called “blockade radius.” As a result, these neighboring atoms become opaque or transparent to a subsequent light source, depending on how this source’s wavelength is tuned relative to the light that excited the Rydberg atom. This interaction persists within a so-called “blockade radius,” within which other Rydberg excitations are prevented from occurring (Fig. 1). The Rydberg blockade effect accordingly mediates a strong interaction between the excitation photon and the source photons.

The interaction between two Rydberg atoms can be many orders of magnitude larger than the interaction

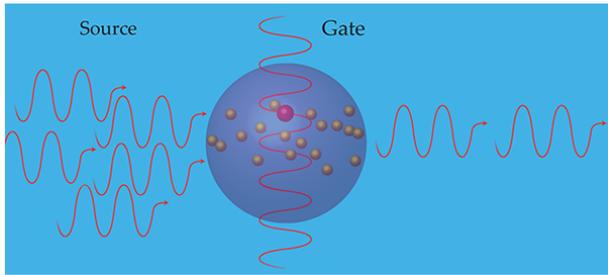


FIG. 1: A photon transistor uses a light source to modulate a medium’s opacity to subsequent photons. To make a medium whose opacity can be switched with a single photon, researchers used highly excited atoms in an atom cloud. When an incoming photon (red) excites an atom to a Rydberg state (red sphere), the excited atom perturbs the atoms within a certain “blockade radius” (purple volume) rendering them either opaque or transparent to a subsequent light source. (APS/Joan Tycko)

between two ground-state atoms. And if photons are mapped into Rydberg excitations, the interaction between Rydberg atoms can provide an extremely large effective photon-photon interaction [3]. The “nonlocal” effect of Rydberg blockade allows one to envision a device where one photon switches many photons in spatially separate optical channels.

Rempe and his collaborators prepared Rydberg states in an ultracold (0.33 microkelvin) gas of rubidium (Rb) atoms confined in an optical trap. The team fired 795-nanometer photons—gate photons—at the gas cloud, exciting one of the Rb atoms into a Rydberg state. The gate photons could be effectively “held” as long as the Rydberg state persisted, which was on the order of microseconds. The resulting energy shift of the Rydberg levels of nearby atoms within the blockade radius rendered the gas opaque to additional source photons. Rempe and his colleagues observed that a single 795-nanometer photon fired into the Rb gas was able to suppress the transmission of 20 target photons—equating to a gain of 20 for their photon transistor. This gain is significantly higher than other gains observed for single-photon transistors. The researchers also mapped out how the interaction between the gate and source scaled with the principal quantum number of the Rydberg state, showing that the gain of the transistor is a maximum where the Rydberg block-

ade is enhanced by a so-called Förster resonance.

Hofferberth and his team also experimentally verified a single-photon transistor using Rydberg states in an ultracold (0.40 microkelvin) gas of Rb atoms. Like the Rempe team, researchers successfully used one gate photon to control multiple source photons, achieving an optical gain above 10. The researchers also showed that single Rydberg atoms can be nondestructively detected, which paves the way for sensitive studies of Rydberg interaction physics, including spatially resolved imaging of systems in Rydberg states [8].

Researchers hope to someday realize a quantum internet where all of the signals are at the single-photon or single-quanta level. Such a quantum internet could offer better security, energy efficiency, and speed than current networks. The work by Rempe and Hofferberth and their collaborators shows that functional single-photon transistors are possible, and illustrates the general power of Rydberg quantum optics for designing prototype photonic devices.

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About the Author

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Professor Charles Adams received his Ph.D. from the University of Strathclyde in Glasgow, Scotland. He completed postdoctoral work in Germany and the United States before starting a research group at Durham University in 1995. He is Director of the Joint Quantum Centre (JQC) Durham-Newcastle and was awarded the 2014 Institute of Physics Thomson medal for his pioneering work in the field of Rydberg quantum optics.