Shedding Light Secrets

What do we get out of interacting photons? Well, for one, they could help with understanding matter's behaviour at the atomic scale. Even better? It's going to assist us in designing new materials with exotic powers for computation

by Dimitris G. ANGELAKIS

The Challenge

Imagine being able to design and fabricate an artificial substance where you can control all aspects of its underlying interactions between the huge numbers of atoms in its bulk. That dream material could, for example by the turn of a switch, shift its state from an insulator to a superconductor, allowing current to flow with no resistance. Accomplish that and you would have solved perhaps the most challenging problem in the interdisciplinary area spanning Physics, Computing, Engineering and Nanotechnology. Achieve that and you would have enabled the efficient understanding of the quantum properties of real materials.

This is an extremely important albeit difficult task for two reasons. Firstly, classical computers require enormous computing power and memory to simulate even the most modest of quantum systems. In layman terms, every time the simulation size needs to increase by including more atoms or electrons, the computational resources grow exponentially. In any realistic simulation we basically run out of memory from the stage of even defining the quantum problem to the computer! Secondly, if we resort to direct experimental observation, manipulation technologies far beyond our era would be required because extremely short scales both in time and in space are involved in the dynamics of most quantum phenomena. With these issues, we still have several hurdles to overcome in our race to gain a deeper understanding

into the of Matter

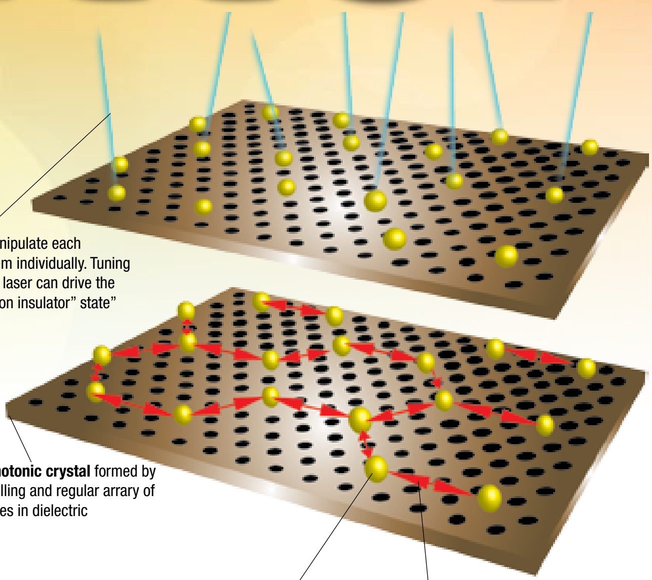

Figure 1: A quantum simulator made out of photons. Light is trapped in the cavity defects–circular yellow areas- which are doped with atoms. A crystal of light is thus formed that can simulate (mimick) the behaviour of complex real crystals made of atoms. By tuning external fields the properties of various complex phases of matter like insulators, and superconductors, can be probed and understood with high efficiency.

of fundamental properties of matter's behaviour at the atomic scale, and for the design of new materials with special "order on design" properties.

The First Innovator

It was 1982 Nobel Prize winner Richard P. Feynman who first acknowledged the scale of the problem and conjectured a possible solution. He ingeniously realised that in order to understand and predict the properties of complex materials, instead of using classical computers, one could try simulating the quantum effects using another, perhaps artificial but highly controllable quantum system. Intense research efforts in the last decade have led to a variety of proposals for quantum simulators ranging from ions in electromagnetic traps to really cold atoms trapped by lasers in optical lattices. However, all of these schemes have their limitations. Optical lattices although extremely promising in preparing regular arrays of thousands of atoms, suffer from serious drawbacks in allowing the necessary local manipulation. The main problem is, atoms are simply trapped too close to each other to be able to be probed individually. Ion traps proposals on the other hand, while promising for small-scale applications of Quantum Information Processing, remain difficult to scale up to larger schemes due to a variety of different technical problems. In other words, using particles of matter in either of the above formats – neutral atoms or ions – does not seem to work in the long term. Take matter out, and you are left with photons. Can we do better with them?

Interacting Photons?

The typical response from open-minded colleagues back in Cambridge when confronted with our suggestion was mixed – "Interacting photons could possibly solve it but…" Although they like the idea in principle, they were eagerly pointing out that first, we would need to figure out how to efficiently trap and manipulate photons. The latter is undoubtedly an extremely difficult task as photons are ghost-like beings. They are famous as one of the most arrogant and unsociable of Nature's particles, always busy zooming off at the speed of light from the moment they come into existence. When they encounter one of their own on the way, they simply go through each other like ghosts, never showing even the slightest acknowledgment of each other's presence! Getting them to form a well-ordered material, mimicking the role of the atoms sitting in specific points in the crystal would definitely be an extremely interesting and challenging task.

Photonic Quantum Simulators

Bugged by curiosity as most scientists are, we decided that even if it was going to be a long shot, we should give it a try. We got stuck for a few long months in frustrating dead ends, which is the usually the case with new ideas in physics. Then, we got lucky! A new long calculation involving a specific type of silicon-based system showed that a crystal made of light might be possible indeed.

To illustrate the basic ideas, let us imagine a hair-thin membrane of a dielectric material, with an orderly array of microscopic holes drilled into it (see Figure 1). Each hole, when slightly deformed, creates a so-called defect cavity structure. This is a tiny area measuring only one thousandth of a millimetre in diameter. It is something like a tiny cage made of perfect mirror-like surfaces, and it can keep photons inside it for a long time. Single photon trapping accomplished, we then tried getting many of these defect cavities together in some sort of regular crystal-like structure to see what we would get. The answer? The photons, while spending most of their life bouncing around in their tiny cage, would sometimes tunnel or hop to the closest available cavity hole in the neighbourhood.

This was an interesting result but we were still only half-way in our quest. The photons, although now localized, still continue to ignore each other even while occupying the same space. There was no interaction or bouncing and repulsion as yet. They could still simply pile up by the gazillions in each hole (see figure 1). To get repulsion, we somehow needed to get a "mediator". A mediator is a piece of nonlinear matter, basically an atom or even a bunch of atoms that are placed in this area. The interaction of the photons with the atoms calls the photon blockade effect into action. Basically, as soon as a photon enters the defect area where an atom is placed, an endless cycle of absorptions and emissions begins. This leads to the formation of a new state of matter

Shedding Light into the Secrets of Matter known as an atom-photon dressed state which transforms the available photonic energy levels of the defect cavity area. This in turn leads to the repulsion of any extra photons trying to sneak in as they simply do not fit in the cavity now (this is perhaps parallel to how only a single sperm usually enters and fertilizes the egg while thousands of others are kept outside and rejected afterwards). Once the cavity is filled with a photon and an atom, any other photon will have to keep hopping around until they find a different, empty defect to fill in.

By extrapolating the photon blockade effect in a case of a large two-dimensional array of holes, we have managed to show that a so-called Mott Insulator State can be created in this system. Here photons behave exactly like electrons in the crystal of an insulator material. They get stuck in specific places; repel each other and persistently refuse to flow when pushed by an external field! What is even more amazing is that the simple switching of an external electric field controls the atom-photon interaction and thus makes the system change its physical state! We note here that one of the hallmarks of any real material – and thus of a material quantum simulator – is the ability to change its state, just as liquid water turns into solid ice when frozen. These processes are known as a phase transitions. When they occur in zero temperature, they are termed quantum phase transitions. In our case, our photonic simulator could change its state from an insulator to a conductor and even a superconductor in a very efficient and controllable way. In contrast to the atoms in optical lattices, individual manipulation was not a problem as defect cavities could be etched far enough from each other with relative ease.

Optical quantum computer

In addition to displaying novel quantum phases of many-body states, strongly interacting photons can offer great opportunities for quantum information processing. Photons in a Mott insulating state can be viewed as a natural quantum register. In these cases, the existence of each quantum bit (qubit) is represented by the presence of a single photon in each hole. The Mott insulator state can therefore be used to initialize a large set of qubits in a single experimental step. The next step is to construct quantum logic gates between the photons that are localized in different cavities. We recently showed that this is possible by using external fields to control the flow of photons in the array. Moreover the model of quantum computation that can be implemented here is the so-called measurement based one. This is currently believed to be the most efficient model as all necessary quantum links between the photon qubits can be set up from the start of the experiment. The corresponding quantum algorithm is then implemented by making a series of measurements on the existence or not of a photon in each hole.

In conclusion getting photons to interact provides a solid framework for the understanding the structure of materials. Understanding the inner workings of substances offers the possibility of designing new materials with exotic properties and a chance at building super fast quantum computers which will solve currently intractable problems. One may say that these new photonic simulators will not only help improve our understanding of the physical world – by making unimaginable "light era" technologies available, it might even change the world and civilization itself.

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Quantum simulator	An artificial but highly controllable physical system mimicking and simulating the complex behaviour of real materials
Optical lattice	An 'egg-cell' structure created by counter-propagating laser beams with really cold atoms sitting in the cells
Quantum phase transition	A massive change in the phase and the quantum properties of a substance in zero temperature. One example is water to vapour or an insulator to a conductor or a superconductor
Photonic Mott Insulator	A state of the photonic quantum simulator where photons are locked in position and are not allowed to flow in the material