Quantum acousto-optics of hybrid nanosystems

In the pursuit of miniaturization of electronic devices, physicists and engineers are looking for ever smaller physical systems and structures that will have the desired optical and electronic properties. One such system is the semiconductor quantum dot. Semiconductors are materials with an ordered internal structure, which can be given different desired properties through various physical and chemical processes. They play a vital role in almost all of today's electronic technologies. They are used in Blue-Ray players, computers, smartphones, car electronics and many other places in our daily life. Today, physicists are able to produce semiconductor structures in the range of a few nanometers, called quantum dots. "Dots" because they are very small structures: the size of the quantum dot in relation to a soccer ball is the same as the size of this ball in relation to the entire soccer field. As the name suggests, the characteristic properties of these structures are governed by quantum effects, especially the wave nature of the electrons trapped in them, which is one of the basic ideas of quantum mechanics. Analogous to the vibration of a guitar string, quantum mechanics allows electrons to be in very specific vibrational states that are associated with specific energy values, or energy levels. These quantum properties make quantum dots very similar to ordinary atoms in which the discovery of energy quantization led to the development of quantum theory, hence quantum dots are often referred to as artificial atoms. One can go even further and look for structures that are actually the size of atoms. It turns out that among such structures are some point defects in the structure of solids, e.g. diamond. Although “defect in a diamond” sounds daunting (despite the fact that they give the shine of diamonds beautiful colors), it turns out that these structures have a very interesting system of energy levels and the structure of quantum transitions between them, which can be used to create devices in the smallest available today scale.

Trying to use smaller and smaller systems to process information in a quantum manner, physicists realized that it is most often not enough to limit oneself to one physical phenomenon and one information carrier. Clearly, the transmission of information must be done by propagating waves, as it is in everyday life. However, the fundamental laws of physics say that the length of such a wave is related to its frequency, and this in turn to the difference in energy between the quantum levels of the emitting or absorbing system. In the case of the aforementioned defects, but also, for example, of superconducting artificial atoms, these energies and frequencies are small, and the lengths of the corresponding electromagnetic waves are in the centimeters range. They cannot be contained in a micrometer structure, creating a resonator, necessary to strengthen and control the interaction of such a wave with an artificial atom. There is a solution (used in everyday electronics, e.g. in smartphones): instead of electromagnetic waves, sound waves should be used. The speed of sound is much lower than the speed of light, hence the sound waves are much shorter at the same frequencies. However, this solution has a certain limitation: in practice, acoustic communication over long distances does not exist.

Here we come to the concept of a hybrid system that uses, for example, sound to communicate between elements of a quantum system, and light to transmit information over long distances. We would like this to happen without losing the fine quantum properties of the information. So we need acoustic resonators in which we can maintain quantum states of sound waves. We also need a system that will allow us to transform quantum information stored in sound into electromagnetic waves, such as light. It turns out that both quantum dots and defects in crystals can perform this function. These systems not only 'see' certain colors (react physically to light of a certain wavelength), but they can also feel or 'hear' sound. Weak sound waves seem irrelevant to our macroscopic world, but to tiny quantum dots or atomic diamond defects they are like an earthquake. The system vibrates back and forth, stretches and compresses, and this modifies the color of the light it absorbs, emits, or effectively scatters. Therefore, we believe that these systems are ideal for the construction of a quantum transducer between an acoustic and an optical information carrier.

Before we can do that, we need to understand the basic physical laws that govern the interaction of quantum systems with light and sound simultaneously, i.e. the quantum acousto-optics. In this project, we will apply a combination of theoretical methods to understand these basic physical laws and develop methods to actively use mechanical vibrations associated with an acoustic wave. In our research, we will deal with surface acoustic waves and vibrations of crystalline membranes. If the applied tone of sound is carefully selected, its properties can be transferred to the quantum state of photons emitted from a quantum dot or a defect. This acoustic-to-optical conversion effect can potentially be used to encode information in the light field. Our research will therefore represent an important step towards applications that are important for everyday life.