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Engineering bandstructures of light interacting with sound

Light and sound can interact via radiation forces. This interaction becomes particularly strong when both light and sound are confined to micron-scale dimensions. Such a situation can be realized nowadays in photonic crystals, i.e. slabs of dielectric material with a periodic pattern of holes. The main idea is to introduce artificially engineered defects into the pattern. These give rise to localized optical modes. At the same time, localized vibrational modes will develop at the same defect sites. The vibrations will couple to the light field via radiation pressure, and the tight localization leads to strong interactions. A displacement by about a nanometer can give rise to an optical frequency shift of 100 GHz. Such setups have been employed recently in the field of cavity optomechanics to laser-cool a nanomechanical vibrational mode to near the quantum ground state and to investigate other quantum effects.

In our research, we are exploring the possibilities that could be realized in the future, based on this platform. We imagine going from the situation of a single optical and vibrational mode to a whole array (or circuit) of such modes, realizing "optomechanical arrays" (Figure 1a). Photons and phonons are able to 'hop' between the localized modes, because the evanescent tails of those nearby modes have a non-vanishing overlap. At the same time, at each localized site, they feel the mutual interaction. The appropriate conceptual framework to describe this situation would be a tight-binding model, as it is known from condensed matter physics (but replacing electrons by photons). In contrast to the situation in solids, however, the optomechanical array is strongly out of equilibrium, being continuously driven by a laser. This basic model of interacting photons and phonons on a lattice has a very rich phenomenology, which will be addressed in this talk.

The radiation pressure interaction is initially nonlinear (with the force depending on the light intensity instead of the amplitude). However, in many cases, it is possible to focus on the small intensity fluctuations. These fluctuations of the light field can couple coherently to the phonons, and the coupling strength can be tuned by the overall laser power. In this sense, an optomechanical array becomes similar to optical lattices for atoms, i.e. a periodic lattice whose properties can be tuned via the laser beam.

We have explored the tuneable bandstructure of photons interacting with phonons on such a lattice. For example, polaritons can form, i.e. hybrid excitations made from light field fluctuations and phonons. In addition, interesting instabilities can arise that eventually lead to nonlinear behaviour. When one allows the lattice structure to go beyond a simple Bravais lattice, it is possible to encounter other situations reminiscent of important condensed matter phenomena. On a honeycomb lattice, both photons and phonons produce the type of bandstructure known for electrons in graphene. That is, at special points the bandstructure resembles that of massless relativistic particles (Fig. 1(b)), such that energy vs. momentum forms a Dirac cone. We have started to describe the transport of photon-phonon Dirac polaritons, analyzing both edge states and Klein tunneling.

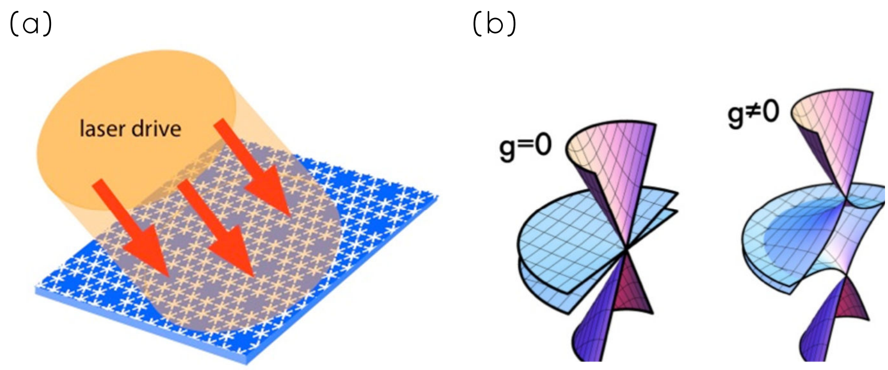

Figure 1: (a) optomechanical array. (b) bandstructure with and without optomechanical coupling.

When the laser field is allowed to be time-dependent, it can be used to engineer an artificial magnetic field for photons or phonons, based on the optomechanical interaction. That means, photons (or phonons) start to feel arbitrary phase factors when hopping from site to site. This gives rise to quantum-Hall effect type edge states, which in this case turn out to be robust against disorder. Other situations can be engineered as well, based on these laser-tuneable phase factors for phonons or photons hopping between different sites.

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