1.3.14 Light-matter interaction in metamaterials and opto-mechanical systems

The use of artificial photonic materials and micromechanical elements allows the ultimate degree of control of light, which can be finely tuned to achieve peculiar regimes (time-reverse lasing), dynamically modulated for fast and arbitrary operations or used to reach complex nonlinear mechanical and optical states.

The possibility of precisely controlling the parameters of electromagnetic waves (intensity, phase, polarization) is becoming the cornerstone of light-based technologies, which find broad and diverse applications in areas ranging from telecommunications to high-precision measurements and quantum/classical computation. Most successful approaches to light control originate from the field of artificial materials, where the first results in reproducing the optical properties of natural materials through nano-structuration quickly led to their recognition as powerful elements for photonic applications. A different approach sees the combination of light-based devices with nano-mechanical elements; the ability of integrating phonon resonators and photonic crystals inaugurated a new era where mechanics is used to control light and vice-versa, leading to unprecedented levels of mass, velocity, acceleration sensitivity, to the observation of quantum effects in macroscopic systems and to new avenues for hybrid systems which use vibrations as connecting elements [1].

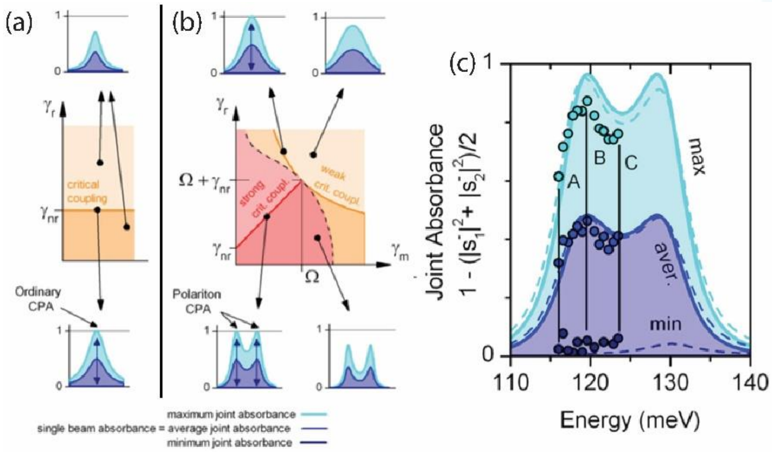

Figure 1. (a): Multi-beam coupling in a simple cavity system, where only the radiative loss rate (γ_r) can be controlled. (b): Multi-beam coupling in a polaritonic system, where also the light-matter coupling can be tuned. (c): Experimental realization of CPA in a polaritonic system.

Our activities explore different topics in this vast field, with interest in both fundamental and applied research.

A first front of investigation deals with the possibility of tuning the material absorbance through multi-beam interference. As recently demonstrated, it is possible to achieve perfect energy feeding into a lossy system (CPA – Coherent Perfect Absorption) or perfect Transparence (CPT) by controlling the relative phase of two light beams impinging on the device [2]. We extended this concept to strongly-coupled resonant systems, showing that also polaritonic excitations [3-5] can be “perfectly fed” from the outside free-space (Fig. 1) [6]. Furthermore, we investigated coherent absorption in 2D systems exploiting multilayer graphene grown on silicon carbide [7]. For a proper interpretation of such experimental results, a general theory of CPA in linear two-port systems has been constructed, without any symmetry requirements except for reciprocity [2]; this model has also allowed defining fundamental limits to the operation of interferential light-light switches [8].

A different approach to light control uses mechanical elements combined with photonic devices. Light can be modulated by mechanical vibrations; conversely, light can exert (back) action on the mechanics via radiation pressure or thermal forces. These simple concepts have led to the field of optomechanics, where we have been showing novel schemes for hybrid opto-electro-mechanical systems [9,10] and devices based on silicon nonlinearities to achieve ~GHz coherent phonon emission at room temperature [11]. In particular, we used this basic element to investigate nonlinear mechanical effects such as chaos and synchronization [12], with the future goal of creating nonlinear networks of optomechanical devices. While most optomechanical systems rely on exploiting light intensity and phase to achieve the desired effects, a different avenue aims at exploiting all the degrees of freedom of electromagnetic waves for novel results and applications. Our contribution in this direction sees the combination of chiral metasurfaces with mechanical elements to create novel polarization modulators.

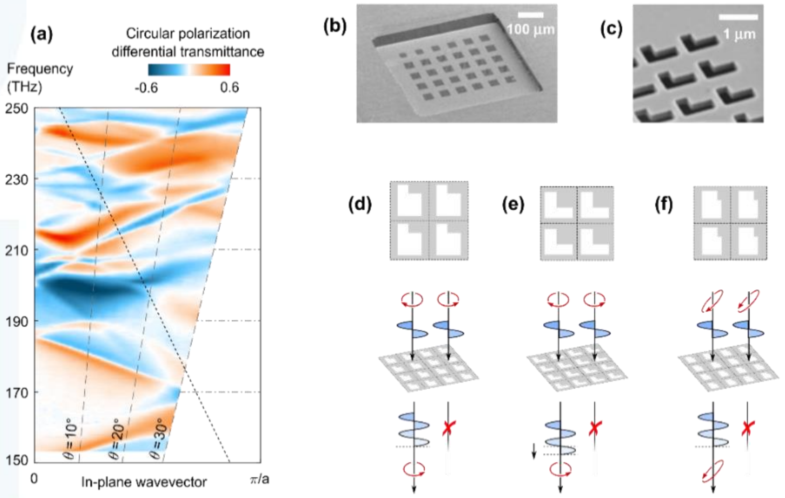

Figure 2. (a) Circular polarization differential transmittance (i.e., circular dichroism for transmitted intensities) measured at oblique incidence. The sample is a dielectric membrane metasurface (b), patterned with L-shaped holes (c). By means of an inverse-design technique we have shown that general wave operations can be performed by design (d-f).

Chiral metasurfaces offer advanced control on the polarization state of near infrared light; our minimal metasurfaces are composed by patterned single GaAs layers (see Fig. 2 (b)). By defining a chiral geometry, as a simple "L-shape" (Fig. 2 (c)), we obtain strong linear and circular dichroisms, as shown by the differential transmittance reported in Fig. 2 (a) [13]. The polarization, intensity and phase of the reflected and transmitted waves can be arbitrarily controlled by changing the shape of the holes, as demonstrated by numerical simulations based on inverse-design of which special cases are reported in Fig. 2 (d)-(f). A further tuning knob of the metasurface properties can be added considering the tunability given by mechanical actuation of the suspended membrane that hosts the chiral pattern.

Thanks to the high phase sensitivity of the metasurface and to the underlying substrate, tiny displacements from the equilibrium position lead to strong modifications of the state of the transmitted/reflected waves, see Fig. 3 (a). Using the ~350 kHz fundamental membrane mode (Fig. 3 (b)), we can obtain a fast, dynamic modulation along non-trivial paths on the Poincaré sphere, as shown by the colored lines in Fig. 3 (c), which represent different laser wavelengths and are superimposed on the static metasurface response (dotted line) [14]. Exploiting the back-action of light on the mechanics induced through thermal effects (Fig. 3 (d)), we can use the same device as a fast polarimeter, where we can uniquely associate to each input polarization state an amplitude and frequency of the mechanical resonance (the latter shown in Fig. 3 (e)) [15].

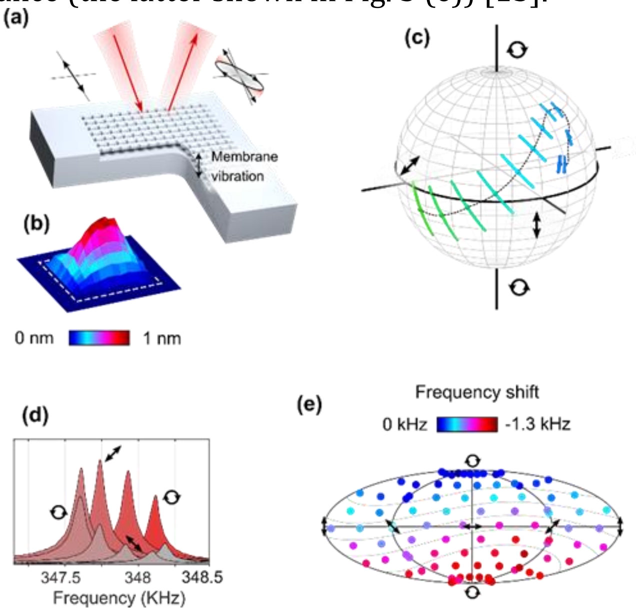

Figure 3. (a): sketch of the investigated device. (b): interferometric measurement of the fundamental drum-like mode. (c): Static (dotted line) and dynamic polarization modulation paths on the Poincaré sphere. If the structure is illuminated with different polarizations, the mechanical resonance frequency and transduction amplitude are affected (d); this effect has a peculiar fingerprint when plotted on the projected Poincaré sphere (e).

The potential of increasing the operating frequencies exploiting overdamped resonances makes our system particularly appealing for fast light modulation technology. Surface acoustic waves (SAW) could be also used to activate ~GHz mechanical modes defined by the same lattice generating the photonic resonances, naturally exploiting the GaAs natural piezoelectricity. First encouraging results of SAW coupled into a silicon nanostring [17] offer interesting insights for RF control of optomechanical systems, with spillovers in fields such as microwave photonics. Similar concepts such as the ones employed in the near infrared can be extended to the more challenging THz spectral range. Adding external or internal mechanical degrees of freedom to quantum cascade lasers would offer additional tuning knobs to control the device emission, mode locking and high-frequency wavelength sweeping, for novel and powerful spectroscopic sources. The route we followed for achieving THz optomechanics starts by coupling silicon nitride trampoline membranes with external lasers, from NIR laser diodes to THz QCLs via self-mixing interferometry [18,19]. After first experiments detecting the membrane motion via the feed voltage oscillations, next steps will see the linking of more lasers in a master-slave configuration via a commonly coupled membrane resonator. In a different approach, we imagined to embed an oscillating string within a QCL cavity itself. To this end, we designed and demonstrated new designs based on a "LC" approach, which show impressive performance in terms of device footprints, CW emitted power and focused far-field emission [20]. Leveraging on the already existing suspended element, next steps will see the full investigation of optomechanical features in the laser emission characteristic.

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