Strongly Nonlinear Acousto-Optical Modulation in a Periodic Array of Resonant Nanophotonic Cavities

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Abstract: We investigate theoretically acousto-optical coupling in a planar array of nanoscale asymmetric photonic cavities defined by metal ridges supported by a piezoelectric substrate. The metal ridges form an interdigital transducer that excites resonant elastic vibrations. A strongly nonlinear modulation of optical transmission, of optomechanical origin, is predicted.

The development of the field of optomechanics has renewed the way acousto-optics can be implemented at the nanoscale. Generally speaking, optomechanical structures rely on the coupling of optical waves and mechanical vibrations in a resonant photonic cavity. Optomechanical interaction can be made large if the cavity is doubly resonant – for photons as well as for phonons – and if the optical resonant frequency is highly sensitive to mechanical vibrations. Hence, as opposed to traditional bulk acousto-optics relying on the elasto-optical effect in crystals, optomechanical interaction depends on the structural properties of the device, which in turn provides guidelines for design. In general, there is a dual situation were the coupling mechanism between optical waves and mechanical (elastic) waves is due both to bulk contributions (photoelasticity, dynamical electrostriction) and to surface or interface contributions (moving interface effect, radiation pressure) [1].

In this contribution, we investigate a nanophotonic structure with a large optomechanical coupling that can in principle be measured by a simple transmission experiment. More precisely, we consider a planar structure composed of a structured metal layer (silver, Ag) patterned on an optically transparent piezoelectric substrate (lithium niobate, $LiNbO_3$), as depicted in figure 1. The considered periodic structure has two basic characteristics. First, the optical resonance can be interrogated under normal incidence. Second, the metal pattern itself forms an interdigital transducer for elastic waves propagating at the surface of the substrate, that could be used either for acousto-optical experiments (with the transducer acting as a source of coherent phonons) or for optomechanical experiments (with the transducer acting as a detector of mechanical vibrations in the structure). As we explain in the following, the optical transmission is highly sensitive to mechanical deformations, providing the mechanism for optomechanical coupling in the structure.

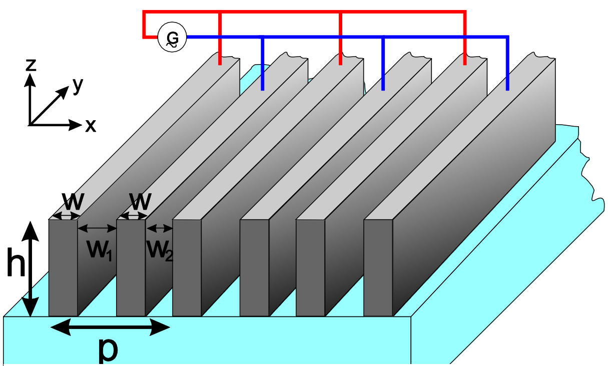

Figure 1 Schematic of the array of asymmetric resonant nanophotonic cavities.

The period of the structure shown in figure 1 is 640 nm and the design is performed for operation around the optical wavelength of 1550 nm. In order to obtain a cavity mode that can be excited with normal incidence, we use an asymmetric air cavity composed of two slits with relatively high aspect ratio (about 3:1). Thanks to uneven slit widths, a Fano resonant mode is created with a loaded quality factor Q ~ 700. This quality factor is related to enhancement of the optical wave field in the region of the cavities and to optical losses. On the transmission profile, this Fano resonance creates a sharp dip that is used for acousto-optical modulation. Optical transmission computations are performed using a home-made finite-difference time-domain (FDTD) code implementing periodic boundary conditions on the sides of the unit-cell and perfectly matched layers (PML) at the bottom and top of the computation domain [2]. The complex permittivity of silver and thus optical losses are accounted for using the critical points model.

When the metal strips are subjected to an alternated potential difference oscillating at a given radio frequency, surface acoustic waves (SAW) are excited in the piezoelectric substrate. These SAW are coupled mechanically to the natural resonances of the metal strips. Rather large amplitude mechanical oscillations of the ridges can thus be induced providing the radio frequency is tuned to resonance. A finite element model (FEM) is devised to obtain the frequency response of the transducer, implementing piezoelectricity of the substrate and a PML at the substrate bottom to simulate radiation at infinity [3]. From the FEM computation, the exact motion of the metal ridges within an acoustic period is obtained. Four different mechanical resonances are thus identified and characterized, at 0.5 GHz (mode 0), 2.2 GHz (mode 1), 2.3 GHz (mode 2), and 4.9 GHz (mode 3). The deformation of the structure is illustrated in figure 2 for the fundamental (m=0) elastic mode.

Acousto-optical modulation of the optical transmission is evaluated for the different mechanical resonances. In the limit of small vibrations, corresponding in principle to classical perturbation analysis of acousto-optics, it is found that the response is much larger for modes 0 and 2, and that it is due mostly to the moving interface effect (the photoelastic contribution is negligible). The moving interface response is evaluated by deforming adiabatically the optical structure as a function of time, within an acoustic period, and monitoring the modulation of the optical transmission [4]. Even for small vibrations, the modulation is found to be nonlinear. Further increasing the vibration amplitude up to maximum displacements of the order of 10 nm, the modulation of the transmission reaches a large dynamical range and becomes very strongly nonlinear. Though these results are only numerical at this point, we will discuss why and how they could be observable experimentally, but also what could be the influence of detrimental factors such as imperfect periodicity, finite width, or viscoelastic losses.

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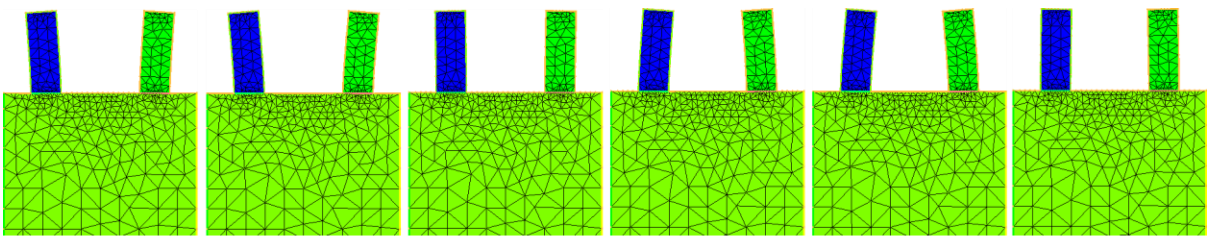

Figure 2 Deformation of the nanophotonic cavity for the fundamental elastic mode at 0.5 GHz. Six instantaneous frames taken evenly inside one acoustic period are shown. Flexural motion is here dominant.